INTEGRATED WEED MANAGEMENT IN AUSTRALIAN CROPPING SYSTEMS

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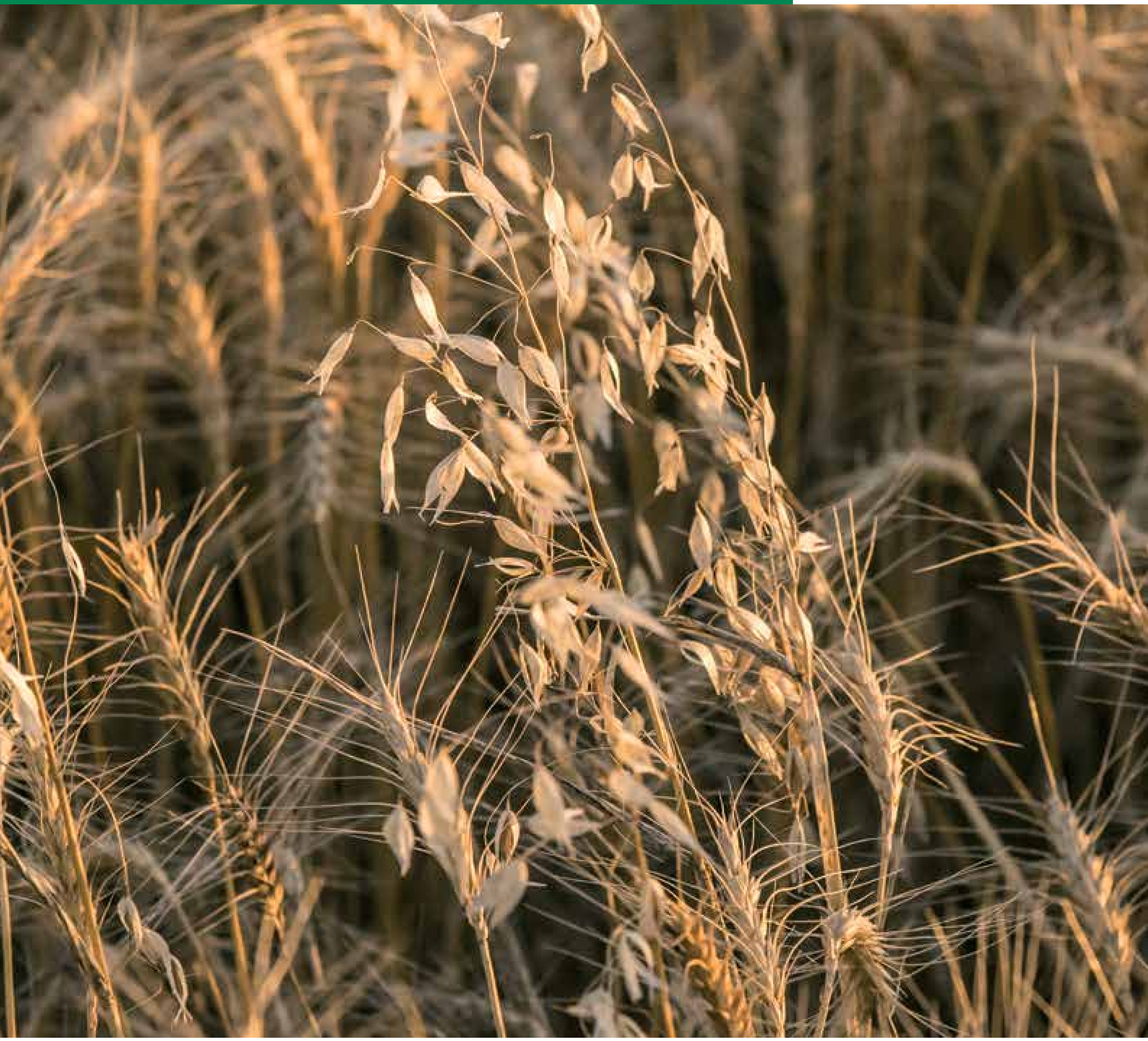

A NATIONAL REFERENCE MANUAL FOR GROWERS

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Original concept: The editor acknowledges Andrew Storrie, editor of the previous edition of this manual, on which this update is based. The editor also acknowledges Vanessa Stewart and team members of the 'Integrated Weed Management' project (Department of Agriculture and Food, Western Australia), the Cooperative Research Centre for Australian Weed Management (Weeds CRC) and the Grains Research and Development Corporation (GRDC) for their original vision to produce a technical guide specifically for cropping industries in Australia. This manual was seen as a critical step towards more effective weed management nationally and supported the education of farm advisers across all states. Strong collaboration between a nationally distributed team ensured that the original Western Australian concept was developed further to become the Integrated weed management in Australian cropping systems manual, tailored to meet the needs of farm advisers and growers throughout the cropping zones of Australia.

With the conclusion of the Weeds CRC in 2008, the GRDC saw value in updating the manual so that it remains a relevant reference and training resource for these rapidly changing times. This is the third edition of that original ground-breaking document.

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Published November 2019

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ISBN 978-1-921779-61-9

This report should be cited as: Preston A L (ed) 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

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Foreword

Arguably one of the toughest challenges currently facing Australian grain growers is the management of weeds.

The issue costs the industry an estimated $3.3 billion every year or $146/ha in control costs and lost revenue making the battle to overcome weeds a major priority for both growers and researchers.

Since 2002/03 the Grains Research and Development Corporation (GRDC) has invested more than $115 million in weeds research with additional funding committed until 2022.

Working together the grains industry has made significant advancements in weed management during the past 20 years, such as the evolution of harvest weed seed control and the prevalence of the double-knock control strategies, but the impact of weeds will continue to be problematic without an integrated approach.

Weeds continue to be challenging often as a result of selection for certain undesirable traits, such as, herbicide resistant biotypes or weeds which have changed their germination requirements and now germinate later during crop growth.

The emergence of 'new' weed challenges in different geographic regions has also occurred through changing management practices or other environmental shifts. Hence, weeds continue to be a major impediment to crop profitability.

The capacity of weed populations to evolve and adapt requires growers to continually deploy a range of control strategies in an integrated weed management approach. With access to herbicides with new modes-of-action likely to be limited in the near future, and growing herbicide resistance it is critical growers maintain the efficacy of those chemical controls currently available.

There is no simple solution to weed control in this complicated environment, instead we need an approach that combines integrated tactics, such as mechanical, chemical and cultural farm-management techniques.

Available strategies include mixing and rotating herbicides with different modes of action, harvest weed seed control, crop competition, hay making and farm hygiene. The research into and development of novel management tactics such as robotics, engineering, allelopathy and weed competitive crop types is also critical.

The GRDC has and will continue to investigate the most effective integrated weed management tactics for the grains industry. This research will help inform grower decision-making and equip them with the knowledge and tools to increase on-farm profitability and productivity in an environment of increasing herbicide resistance.

Transforming research outcomes into on-farm management strategies, like the revised and updated *Integrated Weed Management* (IWM) manual, is designed to guide and support growers and advisers in tackling this major constraint to farm business profitability.

The manual provides information on the latest tools and techniques to help manage current weeds and weeds of emerging economic importance, and at the same time maintain our arsenal of herbicide modes-of-action into the future.

Additions to the manual include information on five new weeds – cutleaf mignonette, Noogoora burr, Paterson's curse, wild mustard and yellow burrweed – details on the harvest weed seed control tools of chaff lining and chaff decks, as well as updated information on the extent of herbicide resistance.

This manual, in conjunction with other industry-driven extension efforts, will help growers make informed decisions to effectively manage and sustain a viable industry into the future.

GRDC also invest in WeedSmart which offers growers and advisers a wealth of information on weed management including 'The Big 6' core points.

The Big 6 are:

1. Rotate crops and pastures
2. Double-knock
3. Mix and rotate herbicides
4. Stop seed set
5. Crop competition
6. Harvest weed seed control

Dr Jason Emms
GRDC Manager - Weeds

Introduction

In 2016 the total cost of weeds to Australian grain growers was estimated to be $3.3 billion per annum. Overall, this equates a reduction to crop yields of about $33/ha, with growers spending $113/ha on weed control. This high cost of management is in part due to herbicide resistance, the cost of additional herbicides, and the use of other control tools to manage these weeds. Herbicide resistance has continued to become more widespread, reducing or eliminating the effectiveness of some herbicide mode of action (MOA) groups. This coupled with the dwindling development of new herbicide chemistries or MOA to replace ineffective herbicides means that concerted efforts are needed to maintain effective weed control whilst preserving herbicide longevity.

Losing these herbicides is of particular concern to farmers, especially glyphosate. A 2016 study found that herbicide resistance affects 43% of cropping land on average, with 64% of growers identifying some herbicide resistance on their farm. To date, 49 weed species in Australia have confirmed resistance to herbicides, 17 of which are resistant to glyphosate. This is an increase from the six species with glyphosate resistance as reported in the previous edition of this manual.

Integrated weed management (IWM) is a system for managing weeds over the long term, particularly the management and minimisation of herbicide resistance. There is a need to combine herbicide and non-herbicide methods into an integrated control program. Given that there are additional costs associated with implementing IWM, the main issues for growers are whether it is cost-effective to adopt the system and whether the benefits are likely to be long-term or short- term.

Is integrated weed management cost-effective?

IWM is definitely cost-effective in the longer term. In the short term, many farms don't adopt IWM because of the added costs and perceived complexity; however, research and farmer experience have shown that failure to adopt IWM leads to herbicide resistance.

In a 2004 survey of Western Australian grain growers it was realised that the adoption of IWM practices was associated with the herbicide resistance status of a farm. Although farms without resistance also used IWM, practices were more likely to be used when herbicide resistance was present. For example, IWM tactics such as the use of crop-topping was three times greater on farms with resistance than on those without. On average, farms with herbicide resistance used a greater number of weed control practices (nine) than farms without herbicide resistance (six). For most Australian farming systems, adopting IWM is often an outcome of identifying herbicide resistance.

There are four key factors that influence the adoption (or non-adoption) of IWM:

1. **Expectation of new herbicide technology**

Herbicides are regarded as having greater weed control efficacy than non-herbicide controls. While current herbicides remain effective there is reduced incentive to adopt alternative control options. The development of herbicide resistance indicates a reduction in the future effectiveness of herbicide options, and should increase the attractiveness of IWM. A 2016 study found that the majority of growers agreed that new selective and non-selective herbicides will be available within the next 10 years to control current resistant weeds, which may reduce the incentive to adopt IWM. At time of publishing, several new herbicides are in development and are undergoing registration. New MOA groups offer the opportunity to delay resistance to any one herbicide; however they do not prevent the eventual development of resistance. Current and any future herbicides need to be used in an integrated weed control strategy to best preserve their effectiveness and maintain superior control of weeds.

2. **Regression and mobility of resistance**

A 2002 study surveyed growers' perceptions of whether herbicide resistance will disappear of its own accord (when herbicides are no longer used and the less fit of the resistant plants fail to maintain their proportion in the population) and how easily herbicide resistance will spread (via means such as pollen flow, seed movement and contaminated seed and fodder).

The survey found that:

- Up to 46% of growers thought that resistance would disappear of its own accord.
- Nearly 14% thought self-disappearance to be highly likely.
- Fifty-four per cent of growers thought importation of resistance after 10 years was likely.
- Twenty-one per cent believed importation to be highly likely.

A 2006 study found similar trends among farmers and agronomists in the northern grains region (northern New South Wales and Queensland), where 30% of respondents thought herbicide resistance only lasted up to five years while a further 10% did not know.

A 2016 study of growers across Australia recorded mixed responses on the likelihood of gaining glyphosate resistance in one of their paddocks through grain or pollen movement. Results showed 42% of surveyed growers agreed that they would have a glyphosate-resistant weed population in 10 years, even if they stopped glyphosate use, compared with 39% who disagreed.

3. **Efficacy of alternative IWM options**

When herbicide resistance is absent, post-emergent selective herbicides are perceived by growers as having the highest reliability and efficacy among available IWM options. In contrast, some 'traditional' control methods such as stubble burning and cultivation are regarded as having much lower efficacy and large variances. Although it is recognised that each control tactic has its own impact on weed mortality and/or seed set, an increasing number of growers realise that very effective weed control can only be achieved with a targeted combination of a wide range of strategies. As control tactics are imposed at different times, their combined impacts are multiplicative rather than additive. For example, the combined effect of two control tactics each with 40% survival is 16% survival.

4. **Growers' attitudes to short-term profit versus long-term returns**

IWM is widely regarded as providing a long-term approach to weed management, in which there are likely to be initial upfront costs to achieve longer-term gains from reduced weed populations. In some circumstances growers may make suboptimal weed management decisions due to their specific planning objectives. For example, where there are short-term financial pressures (e.g. debt servicing requirements) growers may make decisions that increase current period profits but that may have negative long-term consequences (e.g. herbicide resistance). Since the last edition of this manual in 2013 there have been increased seasonal variations and fluctuating crop yields in many cropping districts, which have reduced growers' interest in increasing their costs through the introduction of non-herbicide management techniques.

Returns of an individual enterprise in the short-term are usually measured through a gross margin budget, which is determined by factors such as crop yield, price, the costs of both herbicide and non-herbicide weed control, and other inputs such as seed and fertiliser. Crop yield is directly influenced by weed density, which itself is a function of weed control. For short-term decision making the goal of the grower managing a weed problem is to determine the optimal level of herbicide and non-herbicide inputs for a given weed density that will maximise the crop gross margin.

However, this approach to measuring returns from weed management ignores a critically important economic factor, namely the carryover of the weed seedbank and its impact on returns in future years.

A weed control decision not only has an impact on returns for the current crop, but also affects yields in later years (for good or bad) due to its impact on the weed soil seedbank. Calculating returns over the longer term, such as a period of 20 years, is a better approach for determining the value of the economic benefits of IWM.

A longer-term approach is also able to account for important economic factors such as changes to weed seedbanks from one year to the next due to weed management actions and the impact of herbicide resistance. The role of good agronomic practices such as more competitive crops, alternative crops in a rotation and pasture phases should be valued along with weed management tactics.

Adopting the concept of tactic groups (see below) supports this longer-term view of weed management. This approach coordinates weed control practices with the life cycle of weeds, and emphasises the need to avoid any practices which may add viable weed seeds to the seedbank.

Management of weeds using tactic groups

Integrated weed management in Australian cropping systems approaches weed management in a novel manner by introducing the concept of tactic groups. This concept creates new options and opportunities for weed management and has been designed to change the focus of growers and advisers from crop yield to weed life cycle.

Individual weed management tactics are packaged into tactic groups according to the target growth stage of the weed. The tactic groups are based on the five key objectives of all weed control strategies (see table below).

Tactic Group	Aim
1	Deplete weed seed in the target area soil seedbank.
2	Kill weeds in the target area.
3	Stop weed seed set.
4	Prevent viable weed seeds within the target area being added to the soil seedbank.
5	Prevent introduction of viable weed seed from external sources.

In a well-integrated weed management plan each target weed will be attacked by a number of tactics, each from a different tactic group. They should be combined in the same way herbicides from different MOA groups are rotated. Integrating tactic groups and MOA groups will reduce weed numbers, stop replenishment of the seedbank and minimise the risk of herbicide-resistant weeds populations developing.

When selecting a tactic, consider the aim of the group to which each tactic belongs, and evaluate the suitability of the activity to the target weed and the weed's growth stage. Some weed management tactics such as manuring significantly reduce crop production or yield, often producing a dramatic reduction in gross margin for that paddock. Instead of excluding such tactics, consider using them as a one-off solution in problem situations. Tactics used in this way can be highly effective, reducing weed seedbank numbers by up to 95% in a single year.

Taking control of weed management

Significant or subtle changes in agronomy can enhance the effectiveness of weed management tactics. Increases in sowing rate, reducing row spacing, adjusting fertiliser application rates and changes in crop variety choice can significantly improve crop competition, which in turn improves weed control results. More substantial changes, such as choosing a different crop type, allows additional tactics to be included and expands the opportunities for highly effective weed control.

Most importantly, get out and have a look! Useful knowledge of the weed species in the target area includes observations of population density, distribution across the paddock, growth cycle and the growth stages when the weeds are most vulnerable to weed management tactics.

Knowing the problem that is to be faced is essential to solving the weed management dilemma.

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Aaron Preston and Andrew Storrie

Manual outline

The manual is divided into six sections, to provide the reader with a simple process to follow for developing an integrated weed management (IWM) plan.

Section 1 **Economic benefits of adopting IWM**	Outlines the economic benefits of IWM in Australian cropping systems using computer model simulations.
Section 2 **Profiles of common cropping weeds**	Details the characteristics of 29 key annual cropping weeds across Australia. Information includes characteristics for basic identification, distribution and traits that make the weed a significant problem in cropping systems. For each weed, the most suited weed management tactics for control is also recommended.
Section 3 **Herbicide resistance**	A knowledge resource clarifying aspects of herbicide resistance in weed populations. It is crucial to understand the basics of herbicide resistance when managing weed populations that are resistant to one or more herbicide groups, or are at risk of becoming resistant.
Section 4 **Tactics for managing weed populations**	Provides detailed information on available weed management tactics and presents trial results from across Australia. The tactics, sorted by Tactic Group, are addressed individually. Where a tactic can fall into two Tactic Groups because it impacts on two stages of the weed's life cycle, it has been grouped according to its major aim.
Section 5 **Agronomy to enhance the implementation and benefits of weed management tactics**	Discusses a range of agronomic practices that can be used to enhance the results of the specific weed management tactics used. It includes many simple and cost-effective management changes that can be made to improve the competitive ability of the crop.
Section 6 **Implementing an IWM program using tactic groups**	The 'doing' part of the manual, outlining how best to assess the on-farm situation and implement the IWM plan on-farm. The information that should be collected for each paddock is listed, so that an effective weed management plan can be prepared.

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SECTION 1: ECONOMIC BENEFITS OF INTEGRATED WEED MANAGEMENT

Introduction

Integrated Weed Management (IWM) involves a systems approach, coordinating agronomic, economic, social, and environmental issues with short-term costs to achieve short- and long-term benefits. Adopting IWM practices will reduce weed numbers and enhance crop production, which is economically beneficial. Not only is IWM essential for managing herbicide resistance, it also plays an important role in minimising weed seedbank size over time. There are also clear benefits for managing weed control failure risk from adverse seasonal conditions. Using a range of tactics in an IWM plan is essential for effective, long-term weeds management. The challenge is to realise and estimate the long-term benefits, both physical and fiscal, rather than focus on the short-term financial pressures.

Short-term returns in individual enterprises are usually measured by a gross margin budget. This is determined by subtracting factors such as the cost of weed control (both herbicide and non-herbicide) and other inputs (e.g. seed and fertiliser) from gross income (calculated as crop yield multiplied by grain price). Crop yield is directly influenced by weed density, which itself is a function of weed control.

With the widespread and increasing problem of herbicide resistance, growers are forced to change both their short- and long-term view of weed management. The new paradigm has weed populations managed to ensure a decrease in the weed seedbank over time, and the actions taken now to reduce the weed seedbank will affect crop profitability for years to come. As small numbers of weed survivors are often sufficient to increase the weed seedbank, few surviving weeds can be tolerated. As a result, it is irrelevant to only use economic thresholds of weed numbers based on their yield impact in the current crop!

Key finding #1

Weed seed carryover in the soil seedbank has a huge impact on returns in future years

Determining the optimal level of herbicide and non-herbicide inputs for a given weed density to maximise the crop gross margin does not consider the longer term effects of weed seedbanks on profitability. Each weed control decision not only affects returns for the current crop, but can cause changes in the weed seedbank. Any change in the weed seedbank that results from decisions made in the current year also affect future crop options, yields and the cost of weed management.

Key finding #2

Calculating returns over the long term (e.g. 10 years) will help determine the real value of weed management options

Net present value (NPV) is one measure of calculating returns over the long term. In this instance, future gross margins are summed and discounted back to a present day value. The discounted average annual return, obtained by dividing the NPV by the time period, can also be used. The term ‘discounting’ means converting future gross margins to a present day dollar value to account for factors such as inflation and the opportunity cost of capital.

This approach is able to account for important economic factors such as changes to the weed seedbank from one year to the next in response to weed management actions and herbicide resistance. The benefits of agronomy targeting weed control (e.g. a change in crop sequence) and IWM tactics (e.g. green manuring where there is a loss of income in the year of activity) can be included.

Estimating the economic benefits and costs of IWM

Guidelines illustrating the economics of individual IWM practices can be provided based on a realistic IWM scenario, although the true economics will vary significantly between and within regions, farms and seasons. A summary of the elements of the economic costs and benefits of the IWM tactics identified in this manual is presented in *Table E1*.

The net value of individual tactics is the difference in the 20-year equivalent annual profit for the base IWM strategy. This is calculated by including or excluding that particular tactic. A series of model simulations based on ryegrass integrated management (RIM) identified a base IWM strategy, which was the most profitable combination of tactics over a 20-year period.

For further information on the RIM model, see the Australian Herbicide Resistance Initiative (AHRI) website (www.ahri.uwa.edu.au/RIM), related publications (Pannell et al 2004; Lacoste 2013; Lacoste and Powles 2014) and *Simulation model 3: RIM model – herbicide resistance, annual ryegrass and IWM*.

Key finding #1

Herbicides are the most cost-effective weed management option, providing the most reliable weed control

When considering the economic value of individual tactics (*Table E1*) using herbicides was by far the most economically valuable. Herbicides are currently the backbone of weed management in the Australian conservation crop production system. In this system, effective weed management without herbicides is inconceivable in the short term. However, the problem is that many of these selective herbicides are no longer effective in many regions.

Both high-intensity pasture grazing and high crop sowing rates also proved to be profitable tactics. Furthermore, windrowing; inversion ploughing; delayed sowing and pasture spray-topping; seed collection at harvest and encouraging seed predation; and crop-topping to prevent seed set were all of positive value, as most provided very effective weed control. All other tactics were slightly unprofitable, with green manuring and silage/hay crops the least valuable.

This is consistent with the findings of Monjardino et al. (2004b), who concluded that non-cropping phases, such as haying and manuring crops, generally reduced profits due to the high cost of sacrificing the entire crop, despite excellent weed control. The most promising prospects for such tactics appear to be in cases of well-established herbicide resistance where all selective herbicides are ineffective, which is becoming more common. Here, a simple break-even analysis on the sale price of hay indicates that it would have to increase from $40/tonne to $85/tonne for the hay scenario to be as profitable as the base strategy.

See *Section 4 Tactic 3.3: Silage and hay – crops and pastures* and *Tactic 3.4: Manuring, mulching and hay freezing* for real life examples of where these tactics are being used to manage resistance while still making a profit for the grower.

Table E1 Elements of the economic costs and benefits for some individual tactics

Tactic Group	Tactic	Average annual application cost ($/ha)	Elements of economic cost	Element of economic benefit^
1. Deplete weed seed in the target area soil seedbank	1.1 Burning residues	12	Fire risk, high erosion risk, nutrient and moisture losses	20–90% weed control; reduce viable weed seed numbers
	1.2 Encouraging insect predation on seed	#	Stubble management, reduced tillage practices,	20–80% reduced seedbank
	1.3 Inversion ploughing	100	Mechanical operation, high erosion risk	Up to 100% weed control, increased soil fertility and crop yield if soil constraints removed
	1.4 Autumn tickle	6	Mechanical operation, erosion risk, moisture loss, crop sowing	Stimulate weed emergence; up to 60% seedbank depletion
	1.5 Delayed sowing	#	Mechanical operation, 5–30% crop yield penalty for each week of delay, herbicides	Increase early weed control
2. Kill weeds in the target area	2.1 Fallow and pre-sowing cultivation	3	Mechanical operation, soil degradation, moisture loss	80% weed control, decrease the reliance on knockdown herbicides, pupae busting (e.g. cotton)
	2.2a Knockdown (non-selective) herbicides for fallow and pre-sowing control	12	Herbicide use, spray pass	95% weed control, easy weed control
	2.2b Double knockdown or 'double knock'	20	Herbicide use, spray pass	90% weed control, delay resistance risk
	2.2c Pre-emergent herbicide	10–40	Herbicide use, spray pass, resistance risk, phytotoxicity, incorporation, crop rotation	50–90% weed control, extended period of control, prevent resistance development
	2.2d Selective post-emergent herbicides	20–40	Herbicide use, spray pass, high resistance risk, phytotoxicity, adjuvants	90-95% weed control, flexible
	2.3 Weed control in wide-row cropping	#	Herbicide use, mechanical operation, low resistance risk, root pruning or crop damage	50-90% weed control, small yield loss
	2.4 Inter-row shielded spraying and crop-row band spraying	#	Herbicides, drift damage, crop injury	20-90% weed control
	2.5 Spot spraying, chipping, hand roguing and wiper technologies	#	Herbicide use, mechanical operation, low resistance risk	Target weed control/eradication, avoid herbicide resistance development
	2.6 Weed detector sprayers	#*	Machinery investment, herbicide use, spray pass, potential herbicide residue patches	High levels of control on low density, difficult to control weeds, reduces fallow spray costs by 80–95% and drift issues

* Values vary between systems.
^ Weed control ranges correspond to the average percentage weed kill/seedset reduction across a range of weeds, crops and pasture types.
# No specific cost item.

Tactic Group	Tactic	Average annual application cost ($/ha)	Elements of economic cost	Element of economic benefit^
3. Stop weed seed set	3.1a Spray-topping with selective herbicides	5–20	Herbicide use, spray pass, high resistance risk, phytotoxicity, harvest withholding periods	Up to 90% weed control
	3.1b Crop-topping with non-selective herbicides	18	Herbicide use, spray pass, yield loss, phytotoxicity, 5% yield loss (e.g. pulses)	Approximately 75% weed control, low resistance risk
	3.1c Wiper technology	8	Herbicide use, mechanical operation, phytotoxicity	50–98% weed control, low resistance risk
	3.1d Crop desiccation and windrowing	3–5	Machinery investment, herbicide use, mechanical operation, fire risk (if burn dumps on rows), shattering seeds (e.g. canola)	15–60% weed control
	3.2 Pasture spray-topping	20	Herbicide use, spray pass	75–90% weed control, low resistance risk
	3.3 Silage and hay – crops and pastures	#*	Herbicide use, mechanical operation, spray pass, contract labour, crop loss	90–98% weed control, fodder value, harvest savings
	3.4 Manuring, mulching and hay freezing	#*	Herbicide use, mechanical operation, spray pass, crop loss, contract labour	80–95% weed control, increased soil fertility, 10% yield boost in next crop, fodder value
	3.5 Grazing – actively managing weeds in pastures	#*	Running sheep, seed burial/spread, soil compaction and erosion	10–45% weed control
4. Prevent viable weed seeds within the target area being added to the soil seedbank	4.1 Weed seed control at harvest (e.g. narrow windrow burning, chaff carts, seed impact mills, narrow header trail, chaff tramlining and chaff lining)	2–25	Initial investment, mechanical operation, harvest delays, fire risk	60–95% weed seed removal of some weeds, reduced spread of resistant weeds, contain weed seedbank
	4.2 Grazing crop residues	#	Running sheep, seed burial/spread	10–45% weed control, fodder value
5. On-farm hygiene	5.1a Sow weed-free seed	#*	Preventing new weed infestations requires extra time and labour	Minimise new species or resistant weeds being introduced to the farm
	5.1b Manage weeds in non-crop areas	#*		
	5.1c Clean farm machinery and vehicles	#*		
	5.1d Manage livestock feeding and movement	#*		
	5.1e Monitor paddocks following flood for new weed incursions	#*		

* Values vary between systems.
^ Weed control ranges correspond to the average percentage weed kill/seedset reduction across a range of weeds, crops and pasture types.
\# No specific cost item.

Estimating the economic benefits of IWM using simulation models

This example discusses a number of published studies that have considered the economic benefits of IWM and their key findings. There is a strong Western Australian focus in these case studies due to the high incidence of herbicide resistance in that state.

Simulation model 1: Net present value of adding crop competition and seed destruction

Key finding #1

Net present value (NPV) was determined by modelling a wheat–lupin rotation with different inputs and assumptions on resistance (Gorddard et al. 1995)

A continuous cropping system was assumed until the herbicide-resistant weed population increased to a point where cropping was no longer economically feasible, at which time the system converted to pasture production. The study did not consider issues such as rotating herbicide groups or rotating crop and pasture between years.

The results of the analysis were reported for herbicide-resistant and herbicide-susceptible scenarios, and for chemical-only control (non-IWM) and non-chemical plus chemical control (IWM), as shown in *Table E2*. The results are reported in terms of NPV calculated over 30 years using a five per cent real discount rate. In addition to the economic returns, the number of years before cropping was abandoned in favour of pasture (*Table E2*).

The model suggests that the presence of resistance at the rate of one plant per million (for annual ryegrass) in the first year substantially reduces the NPV by $678/ha for non-IWM after seven years and $594/ha for IWM scenarios after 12 years. Where resistance does not exist, cropping can continue indefinitely.

A large number of strategies involving combinations of these tactics with post-emergent herbicides were examined. Of the control strategies investigated, a strategy that integrated six different tactics provided the highest NPV (*Table E3*).

The strategies with the highest average NPV included a broader combination of tactics than is currently used in mainstream agriculture. The final two strategies in *Table E3* highlight the importance of employing a combination of several non-chemical control methods.

Table E2 Benefits of non-chemical weed control options (Gorddard et al. 1995).

Weed control option	NPV[a] ($/ha)	Years of cropping[b]
Herbicide susceptible weeds, chemical-only control	1,445	30
Herbicide susceptible weeds, non-chemical and chemical control	1,445	30
Resistant, chemical-only control	767	7
Resistant, non-chemical and chemical control	851	12

[a] Net present value (NPV) over 30 years using 5% real discount rate.

[b] Number of years before resistance reaches a level where cropping is less profitable than pasture.

Table E3 Net present values (NPV) of alternative weed control strategies in a 20-year continuous cropping (wheat–lupin) rotation in the central wheatbelt of Western Australia (Schmidt and Pannell 1996).

Modelling (target weed – annual ryegrass)	NPV ($/ha)
Model 1	985
• pre-sow glyphosate in wheat • simazine in lupins • increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2) • crop-top lupins with paraquat • windrow lupin and wheat crops • burn windrows in autumn	
Model 2	955
• pre-sow glyphosate in wheat • simazine in lupins • increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2) • crop-top lupins with paraquat • windrow lupin and wheat crops • collect crop residue (seed-catch) at harvest	
Model 3	159
• pre-sow glyphosate in wheat • simazine in lupins • crop-top lupins with paraquat • windrow lupin and wheat crops • burn windrows in autumn	
Model 4	255
• pre-sow glyphosate in wheat • simazine in lupins • increase crop plant densities (lupins from 40 to 60 plants/m^2, wheat from 100 to 200 plants/m^2) • total autumn burn	

Simulation model 2: Combining a range of IWM tactics targeting annual ryegrass

Key finding #1

A strategy which integrated six different tactics provided the highest NPV according to the simulation model developed by Schmidt and Pannell (1996)

Key finding #2

Growers who wish to remain in a continuous cropping system must include a wide range of weed control methods, as no single method provides the optimal solution

The RIM simulation model included a much larger number of IWM tactics than was considered in Simulation model 1. The weed control tactics included delayed sowing, shallow cultivation, cutting crop for hay to remove weed seed-heads, green manuring, seed-catching at harvest, crop-topping and increased crop densities.

Simulation model 3: RIM model – herbicide resistance, annual ryegrass and IWM

Key finding #1

The benefits of IWM extend beyond herbicide resistance management, also applying to the case of long-term weed population management

The RIM model was developed from the earlier simulation models, 1 and 2, and is described by Pannell et al. (2004). This model expanded the number of chemical and non-chemical tactics available and also included the effects of different pasture phases on herbicide resistance and economic returns. The model allowed for resistance to herbicides with different modes-of-action, represented by the herbicide groups. Each group was allocated a number of applications, or 'shots', before full herbicide resistance was assumed to have developed.

A number of scenarios with differing levels of availability of a selective herbicide were evaluated over a 10-year period for a wheat–lupin rotation in Western Australia (*Table E4*). Included in the results are the non-herbicide options of:

- increasing crop sowing rates
- seed-catching at harvest
- shallow cultivation with delayed sowing
- crop-topping (a non-selective application of the herbicide paraquat to lupins during grain fill).

As herbicide availability increases, the total number of weed treatments using other than selective herbicides falls. However, it is apparent from the results that IWM options are economical in the long term, when herbicide resistance is not an issue, to achieve a high level of control of weed populations.

Table E4 Consequences of restricting selective herbicide usage over 10 years (assuming a Western Australian lupin–wheat rotation) (Pannell et al. 2004)

Applications of selective herbicide available	Profitable treatments (other than selective herbicide) forming part of the integrated strategies[a]	Equivalent annual profit ($/ha)
2	• Use high crop sowing rates (10) • Crop-top lupins with paraquat (5) • Use seed-catching cart, burn dumps (10) • Delay seeding 20 days and apply glyphosate (10)	64
4	• Use high crop sowing rates (10) • Crop-top lupins with paraquat (5) • Use seed-catching cart, burn dumps (10) • Delay seeding 20 days and apply glyphosate (6)	76
6	• Use high crop sowing rates (10) • Crop-top lupins with paraquat (4) • Use seed-catching cart, burn dumps (10) • Delay seeding 20 days and apply glyphosate (2)	83
8	• Use high crop sowing rates (10) • Crop-top lupins with paraquat (2) • Use seed-catching cart, burn dumps (10) • Delay seeding 20 days and apply glyphosate (1)	91
10	• Use high crop sowing rates (6) • Crop-top lupins with paraquat (1) • Use seed-catching cart, burn dumps (10)	93

[a] The number of years in which this treatment was applied is shown in parentheses.

Simulation model 4: Multi-species (annual ryegrass and wild radish) RIM model

Key finding #1

The most promising of the strategies examined appeared to be three years of pasture ('phase farming' in Western Australia), rather than the more commonly practiced one year of pasture between crops

Monjardino et al. (2003) extended the original single species (annual ryegrass) RIM model to include wild radish and added additional weed management practices to control that species (i.e. a multi-species RIM model).

The implications of several rotational sequences with different crop–pasture phases where the level of selective herbicide availability was held constant, were evaluated (*Table E5*). The first two rotations are continuous cropping based on wheat (with either lupin or canola), and the last rotation is a wheat–wheat–lupin sequence with a three-year French (pink) serradella pasture phase in years 9–11 of a 20-year simulation.

The IWM options were selected as optimal for each rotation system considered. All three rotations provided good weed control. The control methods selected for the two cropping-only rotations were broadly similar, although practices such as delayed sowing, windrowing and seed-catching were slightly less attractive in the lupin rotation. The rotation that included pasture had a different mix of control options, as the pasture phase itself allowed for grazing as an additional weed control method. Importantly, including a pasture phase with these extra weed control options made it economically optimal to use fewer applications of selective herbicide.

In a different study by Monjardino et al. (1999), including pasture in a cropping rotation increased the attractiveness of a long-term herbicide conservation strategy (versus rapid exploitation of the same selective herbicide) by reducing the early net losses that occur when cropping is continued with minimal herbicides use.

Monjardino et al. (2004a) evaluated the net value of a broader range of crop–pasture sequences against different factors such as initial weed seed densities, level of herbicide use, pasture phase length and frequency. The most promising sequence examined appeared to be the so-called 'phase farming', involving occasional three-year phases of pasture rather than shorter, more frequent and regular pasture phases. This approach was competitive with the best continuous cropping rotation in a number of scenarios, particularly where herbicide resistance was at high levels.

Table E5 Choice of crop–pasture rotation sequence and weed control practices over a 20-year period in Western Australia (Monjardino et al. 2003)

Rotation[a]	Profitable control options other than selective herbicides[b]	Equivalent annual profit ($/ha)
WWL	• delayed sowing (1) • high sowing rates (19) • crop spray-topping (6) • windrowing (3) • seed-catching + burning (11) • windrowing + burning (6)	137
WWC	• delayed sowing (2) • high sowing rates (19) • crop spray-topping (0) • windrowing (6) • seed-catching + burning (10) • windrowing + burning (9)	114
WWL+PPP	• delayed sowing (0) • high sowing rates (16) • crop spray-topping (9) • seed-catching + burning (10) • windrowing + burning (3) • burning (1) • grazing (1) • high-intensity grazing (2)	124

[a] Abbreviations: W – wheat; L – lupin; C – canola; P – pasture (French serradella).
[b] The number of years in which this treatment was applied is shown in parentheses.

Simulation model 5: Multi-species (annual ryegrass and wild radish) RIM model and GM glyphosate resistant canola crop

Key finding #1

In the absence of glyphosate-resistant weeds, the value of glyphosate-resistant canola as a break crop to manage weeds is significantly higher than that of triazine-resistant canola

Key finding #2

The glyphosate-resistant canola technology package needs to be highly effective in order for its use to be justified in managing annual ryegrass and wild radish infestations

The multi-species RIM model was again used, this time to evaluate the economic value of including a genetically modified (GM) crop in the system. The example used was glyphosate-resistant canola to replace triazine-resistant canola in a typical Western Australian cropping system (Monjardino et al. 2005). The analysis focused on a continuous cropping rotation of wheat–wheat–canola–wheat–lupin.

The assumption was that glyphosate can be sprayed in-crop once or twice, and that this might reduce reliance on, and thus help prolong the life of, selective herbicides to which annual ryegrass and wild radish can be highly resistant. Glyphosate-resistant canola was also assumed to have a yield advantage compared with triazine-resistant canola, although its seed is likely to cost more due to a technology fee.

Evaluating these trade-offs led to the conclusion that the value of glyphosate-resistant canola is significantly higher than that of triazine-resistant canola, which currently dominates Western Australian plantings (*Table E6*). The benefits of glyphosate-resistant canola accrue from its yield advantage relative to triazine-resistant canola (10–20%) and from the inexpensive, effective weed control obtained with glyphosate.

Table E6 Equivalent annual profits and weed densities for two scenarios, and net value of glyphosate-resistant canola ($/ha/year), for a wheat–wheat–canola– wheat–lupin rotation over a 20-year period in Western Australia

	Equivalent annual profit ($/ha/yr)	Annual ryegrass density (plants/m^2)	Wild radish density (plants/m^2)
Scenario with glyphosate resistant canola	153	<1	1
Scenario with triazine resistant canola	142	<1	2
Net value of glyphosate resistant canola	11		

Note: the presence or selection of glyphosate-resistant weeds was not considered in this modelling.

However, the results of this analysis indicate that the glyphosate-resistant canola technology package needs to be highly effective to justify its use in managing annual ryegrass and wild radish infestations. This estimate would be higher if wild radish alone had been considered in the analysis, and lower if the focus were on annual ryegrass.

Adopting glyphosate-resistant canola could result in a substantial increase in farm profit, as well as greater flexibility in managing weeds, and possibly extending the life of selective herbicides.

Despite public debate on the potential effects from genetically modified crops, the risks of gene flow from glyphosate-resistant canola, the development of ‘super weeds’ and the potential problems with volunteer weeds have all been found to be very low or negligible (Busi and Powles 2016). Furthermore, the effect on the environment from growing glyphosate-resistant canola is likely to be positive due to less use of residual triazine herbicides in favour of glyphosate.

However, if glyphosate-resistant canola is widely adopted, there is a threat of increased evolution of glyphosate resistance in a range of weed species, as glyphosate will be used in-crop as well as during the fallow phase, thus reducing its profitability and availability to farmers over time.

The effect of GM canola products on human health is not expected to be significant, as no traces of GM material are usually found in canola oil. Nevertheless, ongoing risk assessment research is required in these areas.

Grower and adviser experience with early releases of glyphosate-resistant crops, which have a limited application window for glyphosate, have found issues with later season weed germinations. If these are not addressed at harvest by seed capture or other means, there will be an unacceptable increase in the weed seedbank for following crops.

Simulation model 6: Brome RIM and barley grass RIM allows growers to look at long-term IWM management strategies

Key finding #1

The benefits of IWM extend long-term weed population management, change crop rotations, herbicide use patterns and increase crop competition

CSIRO used the original RIM model, developed by the Australian Herbicide Resistance Initiative (AHRI), to develop the new brome RIM and barley grass RIM model. These models allow users to quickly set up crop/pasture management sequences and test a full range of crop, brome grass and barley grass management options for their effect on crop yields, weed populations and profitability for up to 10 years. This model also expanded options for better planning, harvest weed seed control, changing crop rotation, herbicide use pattern, and non-chemical tactics for long-term brome grass control in low to medium rainfall zones. The model also allowed for reduced reliance on group B herbicides and use of greater crop competition for weed seed set suppression.

Monjandino and Llewellyn (2018) used a brome RIM and barley grass RIM scenario to analyse the long-term value of a practice change that increases crop competition. Options to improve crop competition on sandy soils include using soil wetting agents on non-wetting soils, on-row seeding options, new seeding systems or more competitive varieties. Here researchers considered the value of a seed-placement innovation such as near-row sowing that could increase cereal establishment on non-wetting sandy soils to the equivalent of increasing wheat seeding rates from 60 kg/ha to 90 kg/ha but without additional seed cost.

Over a 10-year wheat–barley–wheat–lupin crop sequence, the scenario assumed only one brome or barley grass plant per square metre set seed in the previous year. Sowing was at a standard seeding rate in a no-till system, one week after the break in cereals and dry in lupins. Cereal herbicides were glyphosate knockdown (double-knock in the first wheat) and pre-emergent trifluralin (trifluralin + metribuzin) in barley. Lupin herbicides were pre-emergent simazine, post-emergent clethodim and crop-topping.

The high cereal crop competition scenario resulted in an overall average net benefit (gross margin) of $23 ha/year for brome, $16 ha/year for barley grass and was able to maintain low weed numbers

Simulation model 7: WeedRisk model – inclusion of variability and uncertainty

The simulation studies already discussed assume certainty with regarding the efficacy of the weed control options. However, variability in seasonal conditions is an important source of risk to farmers in terms of yields and potential effects on weed control efficacy.

Key finding #1

Using multiple weed management tactics seeks to spread the risk of control failure and increase the probability of success

Farming and weed management practices both have elements of seasonal risk and are affected by seasonal conditions. Jones and Medd (2005) used a climate and biological simulation model (WeedRisk) to determine the effect of IWM options on weed seedbanks, plant densities and crop yields for different population densities of wild oats and wild radish.

The strategies in this simulation model involved using a post-emergent herbicide plus various combinations of the IWM options of pre-season tillage (e.g. autumn tickle), increased competition (e.g. increased sowing rate, competitive crops) and late-season herbicide application (e.g. crop-topping, selective spray-topping).

Key finding #2

IWM options that stop weed seed set had the greatest effect on reducing weed seedbanks

Using post-emergent herbicides was found to be critical when trying to minimise wild oats density and maximise crop yields in any given year. Similar results were obtained with wild radish.

Using the same mix of weed control options, Jones et al. (2006) estimated the economic IWM benefits under deterministic (i.e. zero risk) and stochastic (i.e. full risk) assumptions. The benefits of a non-IWM scenario (i.e. post-emergent herbicide only) for wild oats over a 20-year simulation period were a six per cent gain in NPV. However, when variability in seasonal conditions and the efficacy of the alternative options were taken into account, the IWM scenario NPV was 80 per cent greater than the non-IWM scenario.

Key finding #3

The benefit of the IWM scenario was largely due to options that reduced the seedbank (e.g. crop-topping, selective spray-topping). These tactics compensated for post-emergent herbicide failure due to adverse seasonal conditions

To explore the benefits of IWM further, the WeedRisk model was tested for a range of rotational and IWM options over 20 years for three key cropping weeds: wild oats, wild radish and annual ryegrass (*Table E7*). The systems included a continuous cropping system and a rotation involving a four-year crop phase followed by a three-year perennial pasture phase for a southern New South Wales cropping system. The calculated benefits from IWM are conservative, as the analysis does not consider effects developing from herbicide resistance due to continual post-emergent herbicide use.

Wild radish effectively 'crashes the system' when relying solely on herbicides in a continuous cropping system. This is due to the difficulty in controlling the staggered wild radish germinations throughout the year, along with its ability to set viable seed whenever conditions are favourable. Wild radish seed will be harvested each year and re-sown with farmer-saved seed.

Key finding #4

The economic returns averaged over a 20-year period for IWM are greater than for non-IWM in all cases, usually by a considerable margin, primarily due to lower seedbank numbers in IWM systems.

Table E7 The economic impact ($/ha) of different crop and IWM systems on mean[a] annualised discounted returns for wild oats, wild radish and annual ryegrass in a southern New South Wales cropping system.

	Economic return ($/ha)					
	Wild oats		Wild radish		Annual ryegrass	
Continuous cropping						
No IWM	268	± 35	−9	± 27	284	± 34
IWM	332	± 38	315	± 37	335	± 38
Crop + pasture rotation						
No IWM	288	± 29	157	± 25	284	± 28
IWM	319	± 32	300	± 30	320	± 31

[a] The values following ± are the standard deviation.

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References

Busi R and Powles SB 2016. Transgenic glyphosate-resistant canola (*Brassica napus*) can persist outside agricultural fields in Australia. *Agriculture, Ecosystems & Environment*, vol 220, pp.28–34.

Gorddard RJ, Pannell DJ and Hertzler G 1995. An optimal control model for integrated weed management under herbicide resistance. *Australian Journal of Agricultural Economics*, vol. 39, pp. 71–87.

Hashem A, Blackwell P and Collins M 2004. Excellent weed control in wide row-lupins. *Crop Updates 2004, Western Australian Department of Agriculture*.

Hashem A, Nicholson D, Bowran D and Pathan S 2005. Non-selective herbicide molecules for inter-row weed control in wide row lupins. In '*Crop Updates, Technical Information for Agribusiness*'. pp. 32–34. (Department of Agriculture: Perth, Western Australia).

Jones RE and Medd RW 2005. A methodology for evaluating risk and efficacy of weed management technologies. *Weed Science*, vol 53, pp. 505–514.

Jones RE, Cacho O and Sinden J 2006. The importance of seasonal variability and tactical responses to risk on estimating the economic benefits of integrated weed management. *Agricultural Economics*, vol. 35, pp. 245–256.

Lacoste M 2013. *RIM, Ryegrass Integrated Management – User guide*. Australian Herbicide Resistance Initiative, University of Western Australia, Perth.

Lacoste M and Powles SB 2014. Upgrading the RIM Model for Improved Support of Integrated Weed Management Extension Efforts in Cropping Systems. *Weed Technology*, vol. 28, pp. 703–720.

Monjardino M and Llewellyn R 2018. Newly-developed RIM models for integrated management of brome and barley grass. *Weed Biosecurity – Protecting our future: 21st Australasian Weeds Conference*. Manly, Australia, (eds S Johnson, L Weston, H Wu and B Auld), pp. 164–167, The Weed Society of NSW Inc.

Monjardino M, Pannell DJ and Powles S 1999. Managing herbicide resistance: should you conserve or exploit your herbicides? *Proceedings of the 43rd Australian Agricultural and Resource Economics Society and 6th New Zealand Agricultural Resource Economics Society Conference*, 1999, Congress Centre, Christchurch, New Zealand.

Monjardino M, Pannell DJ and Powles SB 2003. Multispecies resistance and integrated management: a bioeconomic model for integrated management of rigid ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*). *Weed Science*, vol. 51, pp. 798–809.

Monjardino M, Pannell DJ and Powles SB 2004a. The economic value of pasture phases in the integrated management of annual ryegrass and wild radish in a Western Australian farming system. *Australian Journal of Experimental Agriculture*, vol. 43, pp. 265–271.

Monjardino M, Pannell DJ and Powles SB 2004b. The economic value of haying and green manuring in the integrated management of annual ryegrass and wild radish in a Western Australian farming system. *Australian Journal of Experimental Agriculture*, vol. 44, pp. 1195–1203.

Monjardino M, Pannell DJ and Powles SB 2005. The economic value of glyphosate-resistant canola in the management of two widespread crop weeds in a Western Australian farming system. *Agricultural Systems*, vol. 84, pp. 297–315.

Pannell DJ, Stewart V, Bennett A, Monjardino M, Schmidt C and Powles SB 2004. RIM: a bioeconomic model of integrated weed management of *Lolium rigidum* in Western Australia. *Agricultural Systems*, vol. 79, pp. 305–325.

Schmidt CP and Pannell DJ 1996. Economic issues in management of herbicide-resistant weeds. *Review of Marketing and Agricultural Economics*, vol. 64, pp. 301–308.

Further reading

Australian Herbicide Resistance Initiative (AHRI), Brome RIM: www.ahri.uwa.edu.au/research-brome-rim/. Viewed 30 Nov 2018

GM Canola Technical Working Group 2001. *Genetically Modified Canola in Western Australia: Industry Issues and Information – A summary of Western Australian canola production in relation to biotechnology and genetic modification issues*. GM Canola Technical Working Group, Perth.

Jones R, Alemseged Y, Medd R and Vere D 2000. The distribution, density and economic impact of weeds in the Australian annual winter cropping system. *Technical Series No. 4*, CRC for Australian Weed Management, Adelaide.

Llewellyn RS, Lindner RK, Pannell DJ and Powles SB 2002. Resistance and the herbicide resource: perceptions of Western Australian grain growers. *Crop Protection*, vol. 21, pp. 1067–1075.

Llewellyn RS, Lindner RK, Pannell DJ and Powles SB 2004. Grain grower perceptions and use of integrated weed management. *Australian Journal of Experimental Agriculture*, vol. 44, pp. 993–1001.

Neve P, Diggle AJ, Smith FP and Powles SB 2003a. Simulating evolution of glyphosate resistance in *Lolium rigidum*. I. Population genetics of a rare resistance trait. *Weed Research*, vol. 43, pp. 404–417.

Neve P, Diggle AJ, Smith FP and Powles SB 2003b. Simulating evolution of glyphosate resistance in Lolium rigidum. II. Past, present and future glyphosate use in Australian cropping. *Weed Research*, vol. 43, pp. 418–427.

Pannell DJ and Zilberman D 2000. Economic and sociological factors affecting growers' decision making on herbicide resistance. SB Powles and DL Shaner (eds). *Herbicide resistance and world grains*. CRC Press Inc., Boca Raton, Florida, United States of America, pp. 251–277.

Peltzer SC, Hashem A, Osten VA, Gupta ML, Diggle AJ, Riethmuller GP, Douglas A, Moore JM and Koetz EA 2009. Weed management in wide-row cropping systems: a review of current practices and risks for Australian farming systems. *Crop and Pasture Science*, vol. 60, pp. 395–406.

Rieger MA, Potter TD, Preston C and Powles SB 2001. Hybridisation between *Brassica napus* L. and *Raphanus raphanistrum* L. under agronomic field conditions. *Theoretical and Applied Genetics*, vol. 103, pp. 555–560.

Rieger MA, Preston C and Powles SB 1999. Risks of gene flow from transgenic herbicide-resistant canola (*Brassica napus*) to weedy relatives in southern Australian cropping systems. *Australian Journal of Agricultural Research*, vol. 50, p. 115.

Sinden J, Jones R, Hester S, Odom D, Kalisch C, James R, Cacho O and Griffith G 2005. The economic impact of weeds in Australia. *Plant Protection Quarterly*, vol. 20, pp. 25–32.

SECTION 2: PROFILES OF COMMON CROPPING WEEDS

Weed (page)	Common name	Scientific name
Weed 1 (page 14)	Annual ryegrass	*Lolium rigidum*
Weed 2 (page 18)	Barley grass	*Hordeum* spp.
Weed 3 (page 22)	Barnyard grass	*Echinochloa* spp.
Weed 4 (page 26)	Black bindweed	*Fallopia convolvulus*
Weed 5 (page 29)	Bladder ketmia	*Hibiscus* spp.
Weed 6 (page 32)	Brome grass	*Bromus* spp.
Weed 7 (page 36)	Capeweed	*Arctotheca calendula*
Weed 8 (page 39)	Common sowthistle	*Sonchus oleraceus*
Weed 9 (page 42)	Cutleaf mignonette	*Reseda lutea*
Weed 10 (page 44)	Doublegee	*Emex australis*
Weed 11 (page 47)	Feathertop Rhodes grass	*Chloris virgata*
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Weed 14 (page 57)	Liverseed grass	*Urochloa panicoides*
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Weed 18 (page 69)	Paradoxa grass	*Phalaris paradoxa*
Weed 19 (page 72)	Paterson's curse	*Echium plantagineum*
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Weed 22 (page 82)	Turnip weed	*Rapistrum rugosum*
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Weed 25 (page 96)	Windmill grass	*Chloris truncata*
Weed 26 (page 99)	Wild mustard	*Sinapis arvensis*
Weed 27 (page 102)	Wild turnip	*Brassica tournefortii*
Weed 28 (page 105)	Wireweed	*Polygonum* spp.
Weed 29 (page 108)	Yellow burrweed	*Amsinckia* spp.

Weed 1 **Annual ryegrass (*Lolium rigidum*)**

Common names

Annual ryegrass, Wimmera ryegrass, ryegrass.

Distinguishing characteristics

Annual ryegrass (*Lolium rigidum*) is hairless and has bright green, narrow leaves that are shiny, especially on the back of the blade. Annual ryegrass has a wide ligule and long auricles, and the emerging leaf is folded. The base (below ground) is often reddish–purple, and seedlings exude a clear sap when crushed.

Mature plants are erect and up to 900 mm in height. The inflorescences (flowering stems) are flat and up to 300 mm long. Spikelets have three to nine flowers and the husk is almost as long as the spikelet.

Seeds are relatively flat, 4–6 mm long, 1 mm wide and straw-coloured, with the seed embryo often visible through the outer layers. They are held securely to the flower stem, and significant force is needed to detach them either as individual seeds or as part of the flower stem.

Figure W1.1 Mature plant of annual ryegrass.
Photo: Andrew Storrie

Figure W1.2 Seedling of annual ryegrass.
Photo: Andrew Storrie

Other weeds that can be confused with annual ryegrass

Perennial ryegrass (*Lolium perenne*) is very similar to annual ryegrass. However, the two species can be differentiated at the flowering to seeding stage.

Annual ryegrass has three to nine flowers in each spikelet, and the husk on the outer edge of the spikelet is generally a similar length to the spikelet. Perennial ryegrass has four to 14 flowers, and the outer husk is approximately half as long as the spikelet.

Paradoxa grass (*Phalaris paradoxa*) and lesser canary grass (*Phalaris minor*) can sometimes be mistaken for annual ryegrass at the seedling stage. Both *Phalaris* species have a reddish–purple pigmentation at the base of the plant but they lack the shiny surface on the back of the leaf blade. Rather, the leaves tend to be a dull silver–green. If the base of paradoxa is pinched at the 1- to 2-leaf stage the resultant sap will be red, unlike the clear sap in annual ryegrass.

Annual ryegrass can also be confused with silver grass (*Vulpia* spp.), bulbous meadow grass (*Poa bulbosa*) and toad rush (*Juncus bufonius*) at the seedling stage. Annual ryegrass has a shiny back to the leaf while both silver grass and bulbous meadow grass have the same shine on both leaf surfaces. Bulbous meadow grass leaves end in a hood. Toad rush is not a grass and can be distinguished by the absence of a ligule.

Factors that make annual ryegrass a major weed

Annual ryegrass is one of the most serious and costly weeds in annual winter cropping systems in southern Australia.

Annual ryegrass produces an extremely high number of seeds per plant.

Survivors of control measures (in-crop and in pastures) can tiller well and produce high numbers of viable seed. This rapidly leads to large seedbanks and, subsequently, high weed numbers at emergence. Dense stands (greater than 100 plants/m^2) can produce up to 45,000 seeds/m^2 under ideal conditions.

Annual ryegrass is highly competitive.

When annual ryegrass emerges before or with the crop it can compete for nitrogen as early as the 2-leaf crop stage, and appears to have a greater competitive advantage in later sown crops. Conversely, there is good evidence to suggest that annual ryegrass plants that germinate after the crop are poor competitors and far less likely to influence crop yield.

Annual ryegrass is a host for the bacteria *Clavibacter* spp. that causes annual ryegrass toxicity (ARGT).

ARGT is a serious disease that causes sheep and cattle death in southern Australia.

Annual ryegrass can be infected by ergot fungus.

Ergot fungus can infect annual ryegrass heads in coastal regions, leading to grain contamination. Ergot is toxic to both livestock and humans.

Many populations of annual ryegrass have developed resistance to both selective and non-selective herbicides.

In 2018 in Australia annual ryegrass had developed resistance to nine herbicide mode-of-action (MOA) groups (A, B, C, D, J, K, L, M and Q). Repeated use of herbicides from the same MOA group (particularly the high-risk Groups A and B) is likely to select for herbicide-resistant individuals that will produce large numbers of seeds and quickly become a serious and significant weed problem.

There are many populations of annual ryegrass resistant to glyphosate (Group M) on the Liverpool Plains of northern New South Wales (NSW). These populations formed following repeated glyphosate use for winter fallow weed control. Glyphosate-resistant populations are now found from NSW to Western Australia and at the time of writing there were 858 documented cases. (Refer to the Australian Glyphosate Sustainability Working Group under ‘Further information’ in *Section 3 Herbicide resistance for details*).

Environments where annual ryegrass dominates

Since its deliberate introduction as a pasture species in the early 1900s annual ryegrass has become widespread across the temperate areas of southern Australia. Its distribution has increased northward and westward in NSW to become a serious problem in winter cropping.

Annual ryegrass is considered a winter fallow and crop weed due to its soil moisture preference and effect on crop yield loss. It is well adapted to most soil types in the winter rainfall regions of southern Australia, which are characterised by hot, dry summers and mild, wet winters.

Seasonal conditions that favour annual ryegrass

Annual ryegrass grows over winter to spring and can emerge from late autumn through to early spring. The number of emergence flushes and the density of plants that emerge are related to initial seedbank levels and frequency and amount of rainfall.

Conditions that favour annual ryegrass germination and establishment

Newly-formed annual ryegrass seeds are typically dormant, with seeds losing dormancy during the first six months after dispersal. Ideal conditions for annual ryegrass germination include a significant autumn to winter rain event of at least 20 mm, and seeds located 20 mm deep in the soil. Germination reduces with increasing seed depth, ceasing at about 100 mm.

The optimum temperature for annual ryegrass germination is much lower for buried seeds in darkness (11 °C) compared with seeds in the light (27 °C).

The majority of shallowly buried seed will germinate in autumn and early winter, when undisturbed conditions favour seedling survival. Peak germination (80% of seeds) occurs at the break of season after the first two falls of rain that exceed 20 mm. Seed burial (darkness) can trigger a secondary state of dormancy for 10–20% of the seed.

Annual ryegrass seeds are mostly dormant when they develop, and slowly lose dormancy over the summer. However, some can still be dormant at the break, which limits the proportion of the seedbank that can emerge.

Table W1.1 Tactics to consider when developing an integrated plan to manage annual ryegrass (*Lolium rigidum*).

Annual ryegrass (*Lolium rigidum*)		Most likely % control (range)	Comments on use
Tactic 1.3	Inversion ploughing	95 (80–99)	Bury seed greater than 100 mm deep. Using skimmers on the plough is essential for deep burial.
Tactic 2.2b	Double knockdown or 'double-knock'	95 (80–99)	Reduces the likelihood of glyphosate resistance. Use glyphosate followed by paraquat or paraquat + diquat 3 to 10 days later.
Tactic 2.2d	Selective post-emergent herbicides	90 (80–95)	Apply as early as possible after the ryegrass has two leaves to reduce yield losses in cereals.
Tactic 3.4	Manuring, mulching and hay freezing	90 (70–95)	Most commonly used where there is a mass of resistant annual ryegrass growth. Follow up with herbicides or heavy grazing to control regrowth.
Tactic 5.1a	Sow weed-free seed	85 (50-99)	Reduces the risk of introducing resistant annual ryegrass to the paddock with crop seed.
Tactic 3.1a	Spray-topping with selective herbicides	80 (60–90)	Apply before milk dough stage of annual ryegrass.
Tactic 3.3	Silage and hay – crops and pastures	80 (50–95)	Most commonly used where there is a mass of resistant annual ryegrass growth. Follow up with herbicides or heavy grazing to control regrowth.
Tactic 3.2	Pasture spray-topping	80 (30–99)	Graze heavily in spring to synchronise flowering.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (30–95)	Avoid overuse of the one herbicide MOA group. Wait until ryegrass has more than two leaves.
Tactic 2.2c	Pre-emergent herbicides	70 (50–90)	Note incorporation requirements for different products and planting systems.
Tactic 3.1b	Crop-topping with non-selective herbicides	70 (50–90)	Note stage of crop compared to stage of annual ryegrass. Often not possible to achieve without crop yield loss. Most likely to occur with a quick finish to season.
Tactic 4.1	Weed seed control at harvest	65 (40-80)	Best results when crop is harvested as soon as possible before ryegrass lodges or shatters.
Tactic 2.1	Fallow and pre-sowing cultivation	60 (0–90)	Cultivation may lead to increased ryegrass in the crop. Use in combination with a knockdown herbicide. Use cultivators that bury seed.
Agronomy 2	Improve crop competition	50 (20–80)	Optimum sowing rates essential. Row spacing >250 mm to reduce crop competitiveness. Sow on time.
Tactic 3.5	Grazing – actively managing weeds in pastures	50 (20–80)	Graze heavily in autumn to reduce annual ryegrass plant numbers. Graze heavily in spring to reduce seed set.
Tactic 1.1	Burning residues	50 (0–90)	Avoid grazing crop residues. Use a hot fire back-burning with a light wind.
Tactic 1.4	Autumn tickle	15 (0–50)	Only effective on last year's seed set. Use in conjunction with delayed sowing (*Tactic 1.5*).

Emergence at the break the following year will be greater if:

1. Spring (when the seeds were produced) has above average temperatures, and even better if conditions are dry. These conditions produce seeds with less dormancy than usual.
2. Summer is very hot, and even better if there are also several heavy rain events. These conditions result in faster dormancy release.
3. There is a late break to the growing season. This gives the seeds more time to lose dormancy and be ready to germinate when the rains begin.

If the above factors occur in combination, then the proportion of the annual ryegrass seedbank that will germinate at the break of season will be greater.

If all three conditions occur in the one year, delaying seeding to allow maximum annual ryegrass germination and kill pre-sowing will be the most beneficial strategy in terms of reducing seedbank numbers.

Seed survival in the soil

Seed survival in the soil is reduced if the soil is not disturbed, whereas deep cultivation prolongs seed life.

In undisturbed soil less than one per cent carryover of viable residual seed remains after late winter, indicating that the seed is relatively short-lived. In a Western Australian study viable annual ryegrass seed persisted in undisturbed soil for at least four years, but the rate of decline was as much as 70–80% per annum. Similar results were found in a South Australian study, which found seed decay rates were higher under low soil disturbance systems.

Contributors

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Weed 2 **Barley grass (*Hordeum* spp.)**

Common names

Barley grass is a widely used name for *Hordeum glaucum* and *Hordeum leporinum*, although *H. glaucum* is referred to as northern barley grass in Western Australia. Until recently *H. glaucum* was described as a subspecies of *H. leporinum*. Accurate differentiation of the two species *H. glaucum* and *H. leporinum* requires a microscope and taxonomic skills.

H. leporinum is referred to as common foxtail and hare barley in some localities. *Hordeum marinum* is widely referred to as sea barley grass around the world, and *Hordeum hystrix* is known as Mediterranean barley grass.

Given the confusion that exists with common names for individual species and the recent differentiation between certain species, the scientific name will be used in the following text when referring to one species or another, while the term 'barley grasses' will be used where the information applies to several or all species.

Figure W2.1 Barley grass seedling (*Hordeum leporinum*).
Photo: Di Holding

Distinguishing characteristics

Barley grasses are annual species known for rapidly germinating in autumn to provide valuable stock feed soon after breaking rain. This speedy establishment is a useful clue for early identification.

Small barley grass seedlings can be identified by looking for seed remnants, which can often be found attached to the root system.

Both *H. glaucum* and *H. leporinum* have very prominent auricles and a membranous ligule. Auricles are absent in *H. marinum* and *H. hystrix*.

Leaves are 1.5–12.0 mm wide and up to 200 mm long. They are sparsely covered with soft hairs and taper to a point. Leaves tend to be a paler green than other common annual grasses. Barley grasses grow to about 450 mm high.

The inflorescence is a cylindrical spike-like panicle that is often partly enclosed by the sheath of the flag leaf. The spikelet is made up of three florets, the central one being fertile and the lateral ones sterile.

Glumes and awns are rough and sharp. When they are ripe the spikelets fall off the plant as units.

H. marinum is a common indicator plant for shallow clay and/or saline soil.

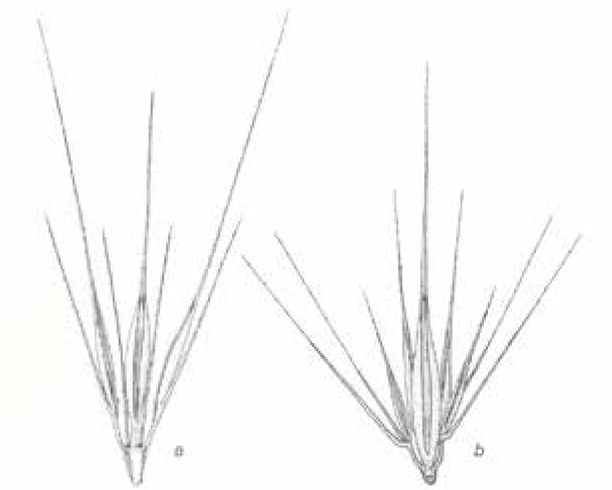

Figure W2.2 Spikelet groups of *H. leporinum* (a) and *H. marinum* (b).
Source: Cunningham et al 1992

Other weeds that can be confused with barley grass

Barley grasses are unlikely to be confused with other grasses once they reach the boot (floral stages) and later stages of development. However, they can be confused with other grasses such as brome grasses (*Bromus* spp.), wild oats (*Avena* spp.) and volunteer cereals in early stages of development.

The following features help to distinguish barley grasses from other grass species in the early stages of growth:

- Seeds germinate rapidly after the autumn break.

- Seed remnants are often still attached to the roots after germination, frequently with the characteristic multiple awns clearly visible.
- Leaf colour tends to be a lighter green than other species such as great brome (*Bromus diandrus*), which tends to be a darker green with a dull purplish tinge.
- Leaves tend to be quite twisted in growth, and the leaf tips often show signs of frost damage.
- Auricles are present.

Figure W 2.3 Mature barley grass (*Hordeum leporinum*) seed-head.
Photo: Andrew Storrie

Factors that make barley grasses a major weed

Barley grasses act as an alternate host for a number of cereal diseases.

Barley grasses germinate rapidly after rain, which provides the potential for the species to act as a 'green bridge' for cereal root diseases. They are major hosts of the disease take-all (*Gaeumannomyces graminis* var. tritici), with possible yield losses of up to 80% under ideal conditions. Barley grasses harbour scald and net blotch of barley, and also host a type of stripe rust, although it is not yet clear what affect this rust may have on cereals.

Barley grass seeds cause stock health problems.

The seeds are a problem in pasture, hay and silage, causing eye injuries to sheep, reduced live-weight gains and reduction in wool quality.

Post-emergent herbicide control is limited in cereals.

There is a limited range of post-emergent herbicides available for the control of barley grasses in wheat and other cereals. However, pyroxasulfone (Sakura®) is an effective pre-emergent herbicide in wheat, chickpeas, field peas, lentils, lupins and triticale.

Barley grasses are readily dispersed.

The seeds can be carried on animals and fabric, and are a common contaminant of hay and feed grains. Barley grass seeds are also often shed before crop harvest, limiting the effectiveness of harvest weed seed control methods.

Barley grass populations can develop resistance to herbicides.

Many barley grass populations have been found with resistance to Group A, B and L herbicides, and recently resistance to Group M has been confirmed in the Yorke Peninsula in South Australia.

Environments where barley grasses dominate

Barley grasses tend to be more dominant in the winter rainfall (southern) areas of the cropping belt. They flourish on a wide range of soil types, particularly in lightly grazed, fertile, ley pasture paddocks.

Barley grasses are commonly a problem in low rainfall cropping environments where cereals are grown in long succession and dry sowing is routinely practiced. In these environments barley grasses are becoming more problematic as an increasing number of populations have evolved increased seed dormancy. This enables barley grasses to escape knockdown herbicides pre-sowing and they can germinate in-crop where there are limited herbicide options.

Barley grasses have the potential to be most problematic in ley pasture crop systems, especially when the pasture phase is more than three years. Without intervention, barley grasses tend to build up as fertility increases. While low grazing pressure leads to increased density, high stocking rates can be used to reduce levels of the weed in a pasture. A higher stocking rate of merinos (4.9 compared with 2.5 wethers/ha) at Trangie, NSW, resulted in a decline in *H. leporinum* levels.

Seasonal conditions that favour barley grasses

Increasing soil fertility is a commonly recognised factor favouring barley grasses, as evidenced by their prevalence in animal camp areas. Their presence is favoured by bare soil such as that found in thinning lucerne stands.

In fact, barley grasses have been shown to establish on a bare surface more rapidly than annual ryegrass (*Lolium rigidum*). In cropping systems low disturbance disc systems favour barley grasses compared with knife point and conventional sowing systems that have increased soil disturbance. This is the opposite situation to annual ryegrass. While stock will enthusiastically graze the weed in its vegetative phase, under low grazing pressure they will avoid it almost completely once the early boot stages begin. Therefore, in good spring conditions barley grasses can produce large amounts of seed.

Conditions that favour barley grass germination and establishment

Barley grasses will germinate over a wide range of temperatures (7–32 °C) although the optimum range is 10–15 °C. The seeds germinate more rapidly in response to autumn rain than other grasses (such as *Lolium* spp.) and are able to establish before the soil surface dries out. Slightly saline conditions favour establishment mainly because barley grasses have a greater tolerance to higher osmotic potentials at germination than most other pasture species. They have low levels of hard seed and most of the seed formed in the spring will germinate in the following autumn.

A very high proportion of barley grass seeds will germinate on the autumn break and it is unusual for further significant germinations to occur during the year. Populations in cropping systems possess increased seed dormancy compared with those from non-crop situations. This increase in seed dormancy may be a response to an increase in cropping intensity, and allows barley grass to avoid early weed control tactics. Seed dormancy in these populations is broken by exposure to cold stratification. Therefore, seeds of these cropping populations tend to germinate in late autumn to early winter when conditions are moist and temperatures are cooler.

Figure W 2.4 Mature barley grass plant (*Hordeum leporinum*).
Photo: Sheldon Navie

Seed survival in the soil

There is limited evidence indicating that barley grasses produce a persistent seedbank. Over 99% of seeds germinate in the first year after seed set. Where persistence has been greater than one year, this has been attributed to greater seed dormancy. Where activities such as pasture spray-topping are correctly timed, field observations indicate that control (as evidenced by autumn germinations) will be very high.

Table W 2.1 Tactics to consider when developing an integrated plan to manage barley grass (*Hordeum* spp.).

Barley grass (*Hordeum* spp.)		Most likely % control (range)	Comments on use
Tactic 2.2d	Selective post-emergent herbicides	90 (80–95)	Several 'fop' herbicides provide good control in broadleaf crops. Sulfosulfuron provides suppression in wheat.
Tactic 1.3	Inversion ploughing	90 (70–99)	Use skimmers to ensure deep burial.
Tactic 2.2c	Pre-emergent herbicides	85 (75–99)	Pyroxasulfone provides good control in wheat.
Agronomy 1	Crop choice and sequence	85 (0–95)	Avoid planting barley in infested areas.
Tactic 2.2b	Double knockdown or 'double-knock'	80 (60–95)	Works best if delayed until the 2- to 4-leaf stage after good opening rains.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (50–90)	Works best if delayed until the 2- to 4-leaf stage after good opening rains.
Tactic 3.1b	Crop-topping with non-selective herbicide	80 (50–90)	Timing is aimed at maximising weed seed kill and minimising effect on the crop.
Agronomy 3	Herbicide tolerant crops	80 (40–95)	Triazines and imidazolinone herbicides provide useful control in triazine and imidazolinone tolerant crops respectively.
Tactic 3.4	Manuring – green and brown, mulching and hay freezing	75 (50–90)	Graze heavily to induce more uniform emergence of heads. Timing is critical. Graze or spray regrowth.
Tactic 1.5	Delayed sowing	60 (50–90)	Level of control depends on break. Use in combination with Tactic 2.2a.
Tactic 3.2	Pasture spray-topping	60 (50–90)	Graze heavily or winter-clean with 'fop' herbicides to induce more uniform emergence of heads. Timing is critical. Graze or spray regrowth.
Tactic 2.1	Fallow and pre-sowing cultivation	50 (30–80)	Requires dry weather following cultivation.
Tactic 3.3	Silage and hay – crops and pastures	50 (30–80)	Silage provides better control than hay making. Heavily graze or spray regrowth.
Tactic 1.1	Burning residues	50 (0–75)	Dropping chaff and straw into windrows improves control.
Tactic 3.5	Grazing – actively managing weeds in pastures	30 (0–50)	Use high stocking rates early in the season to reduce numbers, and late in the season to reduce seed set on infested paddocks.

Contributors

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Weed 3 **Barnyard grass (*Echinochloa* spp.)**

Two of the top five weeds considered the most troublesome to world agriculture belong to the genus *Echinochloa*: awnless barnyard grass (*Echinochloa colona*) and barnyard grass (*Echinochloa crus-galli*).

Figure W3.1 *Echinochloa* inflorescences; *E. colona* (L) and *E. crus-galli* (R)
Photos: Andrew Storrie

Weed 3a *Echinochloa colona*

Common names

Awnless barnyard grass, barnyard grass, water grass, jungle rice, wild millet.

Due to the confusing similarity of the first two common names, the scientific names will be used in the following text when referring to one species or the other, while the term 'barnyard grasses' will be used where the information applies to both species.

Distinguishing characteristics

E. colona is a smooth, tufted annual, 300–750 mm high, with an inflorescence of short spikes in an alternate arrangement on the main axis. It grows erect or sometimes lying along the ground, enabling rooting at lower nodes.

Purple-tinged leaf sheaths and blades (often), awnless spikelets (usually) and absence of a ligule are distinguishing characteristics of the species.

It is the flowers that principally distinguish *E. colona* from *E. crus-galli*. The flowering part and branches of *E. colona* are shorter, and the sharp pointed spikelets do not end in a bristle. The spikelets of *E. colona* are crowded on the stem in two to four regular rows, rather than being irregularly arranged.

Figure W3.2 *Echinochola colona* seedling.
Photo: Andrew Storrie

Other weeds that can be confused with *E. colona*

E. crus-galli, prickly barnyard grass (*Echinochola muricata* var. *microstachya*) and hairy millet (*Echinochola oryzoides*) can be confused with *E. colona*.

Factors that make *E. colona* a major weed

E. colona is an important weed in five of the world's major crops. In Australia it is a serious weed in rice, sugarcane, maize, sorghum and summer fallow.

E. colona germinates over a range of soil temperatures and grows rapidly.

E. colona can germinate from September to March in southern Australia and at any time in northern Australia. Multiple cohorts will establish in any one season assuming sufficient rainfall. *E. colona* can establish under winter crops in spring. Most seed produced in one season will not germinate until the next season.

E. colona grows rapidly when air temperatures are greater than 24 °C and soil moisture is sufficient.

E. colona is a very competitive plant.

As *E. colona* has a prostrate growth habit in early seedling stages (rooting at the nodes to gain space and assuming an erect posture when light is limited) it is a very competitive weed in most crops.

One plant may produce up to 42,000 seeds.

E. colona seeds are readily spread by irrigation or river water and often enter rice fields with crop seeds or transplants. In Australia it is suspected that wild ducks might have been important in the initial distribution of the weed.

E. colona **hosts a number of diseases.**

It is an alternate host for the viruses that produce mosaic diseases.

E. colona **has evolved resistance to herbicides.**

In 2007 glyphosate resistance was documented in *E. colona* populations in NSW. As of 2018 there were 103 documented glyphosate-resistant *E. colona* populations across NSW, Queensland and Western Australia.

Overseas research has reported that *E. colona* has evolved resistance to a number of herbicides with different mode-of-action (MOA) including Groups A, B, C, I and J.

Environments where *E. colona* dominates

E. colona is a significant cropping weed in northern, central and southern NSW, southern and central Queensland, the Northern Territory and the Ord River Irrigation Area in Western Australia.

E. colona is more widespread than *E. crus-galli* and is common along streambanks, levees and irrigation channels, around waterholes and in gilgai country (land surface with irregular mounds and depressions, usually in grey to black vertosols).

The species is found on a wide range of soils, particularly heavy grey and black soils that are periodically flooded.

Seasonal conditions that favour *E. colona*

E. colona is an annual species that grows rapidly during the spring to autumn period in southern Australia and all year in northern Australia. Flowering occurs during summer and autumn, particularly in response to rain.

Conditions that favour *E. colona* germination and establishment

E. colona emerges mainly from September to February. The grass germinates in a number of flushes in response to rain of at least 20 mm. Most emergences will come from seed near the soil surface (0–20 mm), with little (1%) below a burial depth of 100 mm.

Seed survival in the soil

Seed burial experiments conducted on the Darling Downs, Queensland, have shown that seeds of *E. colona* remained viable after 12 months' burial, with 13%of seeds viable at 0 mm, 25% at 50 mm, and 40% at 100 mm.

Weed 3b *Echinochloa crus-galli*

Common names

Barnyard grass, wild millet, Japanese millet, barnyard millet, swamp barnyard grass.

Due to the confusing similarity of the first two common names, in the following text the scientific names will be used in the following text when referring to one species or the other, while the term 'barnyard grasses' will be used where the information applies to both species.

Distinguishing characteristics

E. crus-galli is a tall erect annual with thick roots and stout spongy stems. It has no ligule and has numerous racemes that are spreading, ascending or branched. Seed-heads are often purplish and consist of crowded spikelets with large seeds. The awns may be absent or present up to 25 mm long.

E. crus-galli is an extremely variable species which frequently has been split into different varieties and forms.

Other weeds that can be confused with *E. crus-galli*

Echinochloa crus-pavonis and *E. colona* can be confused with *E. crus-galli*.

Factors that make *E. crus-galli* a major weed

E. crus-galli **causes crop failures and yield reductions.**

E. crus-galli reduces crop yield and causes forage crops to fail by removing up to 80% of the available soil nitrogen. The high levels of nitrates it accumulates can poison livestock. In Australia, infestations of this weed in rice have reduced yield by 2–4 t/ha.

E. crus-galli **can produce over 40,000 seeds per plant.**

Seed production is highly variable and relates to growing conditions.

E. crus-galli **has evolved resistance to a range of herbicides.**

Globally, *E. crus-galli* populations have been found resistant to MOA groups A, B, C, D, I, J, K and Q, including a number of populations resistant to multiple MOA groups. No resistant populations had been confirmed in Australia at the time of writing.

***E. crus-galli* can cause problems at harvest.**

Heavy infestations of *E. crus-galli* can interfere with mechanical harvesting.

Contaminated seed is probably the most common dispersal method.

Water, birds, insects, machinery and animals will also spread *E. crus-galli*.

***E. crus-galli* is a disease host.**

E. crus-galli acts as a host for several mosaic virus diseases.

***E. crus-galli* is difficult to control as a mature plant.**

Pre-emergent herbicides are most effective as *E. colona* plants are highly susceptible at the seedling stage, whereas established plants are difficult to control with most selective herbicides. Post-emergent herbicides are often ineffective due to a combination of poor herbicide coverage and/or moisture or heat stress at the time of spraying.

Environments where *E. crus-galli* dominates

Photoperiod is one of the most important factors governing *E. crusgalli* distribution and competitiveness. It flowers quickly in response to shortening day length, and under favourable growing conditions and increasing day length it will produce very large competitive plants which eventually flower and produce many seeds.

It tolerates a wide variety of soil types. It commonly occurs along roadsides, in ditches and in disturbed areas, and can invade riverbanks and the shores of lakes and ponds. It is a principal weed in many agricultural crops including rice, cotton, maize, sorghum, vegetables and sugar cane, and in summer fallow.

The species can also continue to grow when partially submerged, making it a major weed of lowland rice.

Table W3.1 Tactics to consider when developing an integrated plan to manage barnyard grass (*Echinochloa* spp.).

Barnyard grass (*Echinochloa* spp.)		Most likely % control (range)	Comments on use
Tactic 2.5	Weed detector sprayers	99 (90–100)	Use in fallow (*Tactic 2.1*) with high rates of herbicide to 'spot' out larger survivors.
Tactic 2.2b	Double knockdown or 'double-knock'	95 (90–100)	Use with dense populations or where you suspect glyphosate-resistant populations. Ideally suited to treating plants no larger than the early tillering stage. Look at tank mixing pre-emergent herbicides for fallow use with second knock, e.g. Flame®.
Tactic 2.2a	Knockdown (non-selective) herbicides	95 (70–100)	Target small weeds (two to three leaves).
Tactic 2.2d	Selective post-emergent herbicides	90 (70–99)	Follow label directions carefully, especially on plant growth stages. Be mindful of herbicide resistance risks as these herbicides have a greater tendency for selecting resistant individuals. Ensure surviving plants do not produce seed.
Tactic 2.2c	Pre-emergent herbicides	90 (50–100)	Atrazine mixed with metolachlor gives more reliable control than atrazine alone. Reliant on good soil moisture.
Agronomy 1	Crop choice and sequence	90 (40–99)	Avoid grass summer crops such as sorghum. Choose a competitive broadleaf crop such as mung beans where a range of herbicide MOA groups can also be used. Short season of mung beans allows use of other tactics. See *Tactic 2.2a Non-selective knockdowns* and *Tactic 2.2b Double-knock* to control spring and early summer cohorts before planting. Wide row summer crops will allow the use of bipyridyl herbicides or cultivation along the inter-row area.

Seasonal conditions that favour *E. crus-galli*

E. crus-galli grows rapidly during the spring to autumn period. Flowering occurs during summer and autumn, particularly in response to rain.

Conditions that favour *E. crus-galli* germination and establishment

E. crus-galli requires warm summer days and abundant soil moisture to germinate. The optimum temperature range for germination is 27–31 °C, but seeds will also germinate from 13 °C to 40 °C. Compacted soil favours germination and emergence.

Seed survival in the soil

New seeds are dormant. Dormancy is often broken by exposure to low winter temperatures, alternating spring temperatures or spring flooding, but some seeds remain dormant much longer. Deeply buried seeds (over 80 mm) lose no viability for three years, and some seeds remain viable for up to 13 years.

Contributors

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Weed 4 **Black bindweed (*Fallopia convolvulus*)**

Common names

Black bindweed (NSW), climbing buckwheat (Queensland), fallopia.

Figure W4.1 Black bindweed climbing wheat.
Photo: Andrew Storrie

Distinguishing characteristics

Black bindweed (*Fallopia convolvulus*) is an annual herb with twining stems to 1 m long. Cotyledons are narrow-clubbed with rounded tips. Arrow-shaped leaves are hairless to slightly 'mealy' with a prominent mid-vein. The leaf margin has small, shallow, rounded 'teeth'. Flowers are greenish-white and the seed is dull black and tri-angled.

Other weeds that can be confused with black bindweed

Black bindweed can be confused with the following three species:

1. *Muehlenbeckia gracillima* is a native climber usually found on riverbanks and the margins of wet sclerophyll forests. Its leaf margins are very finely toothed and slightly wavy. The seed is black and spherical rather than tri-angled.
2. Field bindweed (*Convolvulus arvensis*) is a vigorous dark green perennial twiner with stems to 2 m, arising from a deep taproot with horizontal roots and rhizomes. The leaves are elongated, arrow-shaped, two-lobed at the base and sparsely hairy.
3. *Convolvulus erubescens* is a hairy prostrate perennial with twining stems to 1 m and a thick rootstock.

Figure W4.2 Black bindweed seedling.
Photo: Andrew Storrie

Table W4.1 Distinguishing characteristics of black bindweed compared with similar weed species.

Species	Leaf	Flower	Seed
Fallopia convolvulus	Arrow-shaped with prominent mid-vein. Small rounded teeth on margin.	Floppy spike-like inflorescence of greenish-white flowers.	Dull black, tri-angled, 4–5 mm long.
Muehlenbeckia gracillima	Triangular with very finely toothed margin.	Spike-like inflorescence.	Black and spherical.
Convolvulus arvensis	Elongated and arrow-shaped with two lobes at base. Smooth margin.	White to pink funnel-shaped single flower to 25 mm diameter.	Hanging globular capsule with a small point. Brown to black.
Convolvulus erubescens	Variable in shape and size, but similar to *C. arvensis*. Smooth margin.	Tubular with fused petals, pink to white, ~20 mm wide when open.	Egg-shaped capsule. Brown to black.

Factors that make black bindweed a major weed

Black bindweed is competitive in crops.

In Oklahoma, United States of America (USA), 32 black bindweed plants/m^2 reduced wheat yield by 50%.

Black bindweed produces a large number of seeds.

Seed production varies and depends on plant emergence and conditions. Plants in Oklahoma have produced up to 2,500 seeds/m^2 per season, with up to 1,000 seeds per plant, however approximately 30,000 seeds have been produced from black bindweed plants in Canada.

The twining habit of black bindweed causes blockages in tillage equipment and contamination in grain samples.

If black bindweed grows in summer fallows, the vine wraps around cultivator tynes, causing blockages in equipment and slowing operations. It readily becomes a grain contaminant; in milling grades of wheat up to 50 seeds per half-litre is permitted. Black bindweed can also be dispersed in contaminated seed and feed grain.

Black bindweed is tolerant of many herbicides, particularly once it has more than two true leaves.

This fact, together with the adoption of wider winter cereal row spacings (greater than 250 mm) to improve sowing into stubbles which reduces crop competitiveness, has made black bindweed a more significant problem weed. Wider row spacings often mean that full crop ground cover is never achieved, or is achieved late in the season, allowing the black bindweed to establish and develop into large twining plants.

Black bindweed has evolved resistance to herbicides

A population resistant to chlorsulfuron (Group B herbicide) was first recorded in 1993, west of Goondiwindi, Queensland. However, at the time of writing no other resistant populations have been identified in Australia. Black bindweed populations have evolved resistance to triazine herbicides (Group C) in Austria and Germany and Group B resistance in Canada.

Environments where black bindweed dominates

Black bindweed is found to some degree in all mainland states and territories. Although adaptable to a wide range of environmental conditions, it prefers self-mulching clay soils but will also grow on loam soils. It is unclear why it is not a problem in winter crops in more southerly areas with clay soils.

Black bindweed is a winter crop weed, particularly in pulses where no effective herbicides are available for its control. Germinating in mid-winter to spring, black bindweed avoids early post-emergent herbicide applications and survives harvest. With sufficient soil moisture it will continue to grow into summer, creating problems in fallows and no-till summer crops.

Figure W4.3 *Convolvulus erubescens* in flower.
Photo: Andrew Storrie

Seasonal conditions that favour black bindweed

In northern New South Wales and southern Queensland black bindweed germinates from July to September. Flowering starts late in spring and continues into summer. Plants will grow up to 1 m long during a wet summer.

A wet spring followed by a wet summer favours the weed. In farming systems where wide row spacings (>300 mm) are used and where cereal plant density is suboptimal, the black bindweed problem is intensified.

A wet spring decreases the period of residual control given by picloram (e.g. Tordon® 242).

Conditions that favour black bindweed germination and establishment

Black bindweed tends to germinate when the soil temperature at 50–100 mm depth reaches 11–13 °C. It is speculated that there is a cyclical dormancy, which is released in late winter and then reinstated as a secondary dormancy when temperatures begin to rise. Only 2.5% of the seed germinates each year. New seed is thought to have a primary dormancy that is broken by a period of low temperatures. Research in North Dakota, USA, in the 1980s found that temperatures between 2 °C and 10 °C for two months were required to break this primary dormancy.

Due to the lack of control options available in pulse crops, the black bindweed seedbank often increases dramatically when pulse crops are grown.

Seed survival in the soil

The survival of black bindweed seed in Australian soils is unknown. However, work in Alaska showed that less than 1% of seed was viable 10 years after burial.

Table W4.2 Tactics to consider when developing an integrated plan to manage black bindweed (*Fallopia convolvulus*).

Black bindweed (*Fallopia convolvulus*)		Most likely % control (range)	Comments on use
Tactic 2.2d	Selective post-emergent herbicides	95 (40–99)	Must be used with competitive crops and higher sowing rates.
Tactic 5.1	Sow weed-free seed	95 (0-100)	Ensure seed for sowing comes from black bindweed free areas or has been well graded.
Agronomy 2	Improve crop competition	90 (10–95)	Optimum sowing rates are essential. Row spacings >250 mm in winter cereals reduce crop competitiveness.
Tactic 3.5	Grazing – actively managing weeds in pastures	90 (0–95)	Unmanaged pastures are a major source of crop weed problems.
Agronomy 1	Crop choice and sequence	85 (0–95)	Do not sow pulses where black bindweed is a problem. Summer crop–winter fallow allows use of knockdown non-selective herbicides to control black bindweed.

Contributor

Andrew Storrie

Weed 5 **Bladder ketmia (*Hibiscus* spp.)**

Figure W5.1 Mature narrow-leaf bladder ketmia plant.
Photo: Andrew Storrie

Common names

Bladder ketmia, narrow-leaf bladder ketmia (*Hibiscus tridactylites*), wide-leaf bladder ketmia (*Hibiscus verdcourtii*), lantern hibiscus, flower-of-an-hour, rose mallow, wild gooseberry, Venice mallow (commonly used outside Australia).

Distinguishing characteristics

There are two species of bladder ketmia. The cotyledons of both species are similar in shape, with one leaf circular to broadly oval and the other circular with a slightly flattened base (*Figure W5.2*).

The two species can be distinguished by a number of characteristics (*Table W5.1*).
Wide-leaf bladder ketmia has two forms generally distinguished by the colour of the centre of the flower.

Table W5.1 Characteristics of the two species of bladder ketmia.

Characteristic	Wide-leaf bladder ketmia	Narrow-leaf bladder ketmia
Scientific name	*Hibiscus verdcourtii* (formerly *Hibiscus trionum* var. *vesicarius*).	*Hibiscus tridactylites* (formerly *H. trionum* var. *trionum*).
Introduced/native	Native	Previously thought to be introduced, but likely to be native
Plant height and habit	Always erect and up to 1.8 m high	Semi-prostrate to erect and up to 1.3 m high
Leaf appearance	Waxy and mid to dark green	Leaves less waxy, often with purple-tinged edges
	Leaves have three lobes, not deeply divided.	Leaves have three, sometimes five lobes, deeply divided.
	Margins not toothed (entire).	Margins are toothed.
Flower appearance	Cream petals with either yellow or crimson-red centres	Yellow-cream petals with deep purple centres
Cotyledon size (length × width)	20 × 18 mm (yellow-centred) 18 × 16 mm (red-centred)	14 × 14 mm
Leaf size (max. length × width)	138 × 94 mm (yellow-centred) 101 × 72 mm (red-centred)	90 × 95 mm
Time to flowering (glasshouse average)	37 days (yellow-centred) 40 days (red-centred)	30 days
Time to mature seed-heads (glasshouse average)	53 days (yellow-centred) 61 days (red-centred)	46 days
Seed-head appearance	Straw-coloured and rough in texture with raised ribs. Not see-through at maturity.	Light grey and papery with soft, raised purple ridges. Nearly see-through at maturity.
Seed appearance	Larger and black	Smaller and light to mid-grey
Total number of seeds per plant	2,300 (range 50–7,800)	5,600 (range 1,500–15,900)

Figure W5.2 Wide-leaf bladder ketmia seedling.
Photo: Andrew Storrie

Other weeds that can be confused with bladder ketmia

Wide- and narrow-leaf bladder ketmia are easily confused. The seedlings of bladder ketmia are also similar in appearance to native rosella (*Abelmoschus ficulneus*), a common broadacre weed in Queensland.

The various common names of ketmia may lead to some confusion with the *Physalis* species commonly called Chinese lantern or Chinese gooseberry.

Factors that make bladder ketmia a major weed

Bladder ketmia is an annual weed of summer crops and disturbed areas.

Both species of bladder ketmia are able to produce a large number of seeds.

Between approximately 2,000 and 5,500 seeds are produced on medium sized plants (*Table W5.1*).

Strong seed dormancy and a number of dense seedling flushes throughout spring and summer make bladder ketmia difficult to control.

While plants are generally killed by frost, narrow-leaf bladder ketmia will grow in sheltered stubble and fallow situations during winter.

Narrow-leaf bladder ketmia is tolerant of glyphosate.

Lower rates of glyphosate are ineffective on narrow-leaf bladder ketmia seedlings, especially where there is moisture and/or heat stress. As the plants get larger their tolerance of glyphosate increases.

Dense stands of bladder ketmia can cause localised yield loss.

Individual plants are not overly competitive.

The weed, which may be easily spread through poor farm and machinery hygiene, is a crop pathogen host.

Bladder ketmia is an alternative host to many insect pests.

Figure W5.3 Wide-leaf bladder ketmia.
Photo: Stephen Johnson

Environments where bladder ketmia dominates

Bladder ketmia is a problem in summer crops, particularly in cotton and grain sorghum.

It is a common weed in the northern grain zone and a minor weed in other areas.

Narrow-leaf bladder ketmia is common on the slopes, tablelands and coastal areas of NSW, and on the Darling Downs and coastal areas of southern Queensland.

Wide-leaf bladder ketmia is more common in the western areas of the plains in NSW and the Darling Downs in Queensland. The yellow-centred form of this species is common south of the Darling and Western Downs of Queensland where it coexists with the red-centred form, which is more common in central and western Queensland.

Bladder ketmia is common on heavy cracking clay soils.

Seasonal conditions that favour bladder ketmia

Both wide- and narrow-leaf bladder ketmia seedlings emerge in successive flushes after rain (at least 10 mm is needed) or irrigation throughout spring, summer and autumn. Narrow-leaf bladder ketmia can also emerge during winter.

Plants produce seeds within 46 to 61 days, depending on variety (*Table W5.1*). Only narrow-leaf bladder ketmia has been recorded as producing seed over winter.

Conditions that favour bladder ketmia germination and establishment

Cultivation increases the number of narrow-leaf bladder ketmia seedlings that emerge by two to four times over uncultivated situations. Narrow-leaf bladder ketmia can emerge from at least 5 cm deep but this decreases to less than 1% emergence at 10 cm.

Rain or irrigation before spring planting generally produces an early season flush that may be controlled by a knockdown herbicide. Periodic spring and summer showers encourage good seedling establishment.

Figure W5.4 Wide-leaf bladder ketmia flower (yellow-centred form).
Photo: Stephen Johnson

Seed survival in the soil

Narrow-leaf bladder ketmia seed has a relatively long viability in the soil. Summarising seedbank studies on vertosols, 70–80% of seed is viable after one year, decreasing to 40–70% after two years and 30% after three years. In contrast, wide-leaf bladder ketmia seed viability was 50% after one year and 15% per cent after two years. Seedling emergence is highest at 2 cm burial depth, but decreases progressively.

Table W5.2 Tactics to consider when developing an integrated plan to manage bladder ketmia (*Hibiscus* spp.).

Bladder ketmia (*H. tridactylites* and *H. verdcourtii*)		Most likely % control (range)	Comments on use
Tactic 2.1	Fallow and pre-sowing cultivation	95 (90–99)	Shallow cultivation may stimulate seedling emergence, followed by knockdown non-selective herbicides.
Tactic 2.2c	Pre-emergent herbicides	Variable	Dependent on herbicide used and available soil moisture for activation.
Tactic 2.2d	Selective post-emergent herbicides	Variable	Dependent on herbicide used. Target small weeds.

Contributor

Stephen Johnson

Weed 6 **Brome grass (*Bromus* spp.)**

The most common species in the genus *Bromus* in southern Australia are *Bromus diandrus* and *Bromus rigidus* (both short- and long-awned varieties).

Common names

B. diandrus is commonly called great brome but may also be known as ripgut brome, ripgut grass, giant brome, slands grass, jabbers, Kingston grass, spear grass and brome grass.

B. rigidus is usually known as rigid brome but sometimes ripgut brome, ripgut grass, spear grass, brome grass and also great brome, which causes confusion between the two species.

As a result, the scientific names will be used in the following text when referring to one species or the other, while the term 'brome grasses' will be used when the information applies to both species.

Distinguishing characteristics

It is difficult to distinguish between the two species (*Table W6.1*) because both have erect seedlings with dull, hairy leaves that display reddish–purple stripes following the leaf veins.

Figure W6.1 Mature *Bromus diandrus* plant.
Photo: Andrew Storrie

Figure W6.2 *Bromus diandrus* seed.
Photo: Andrew Storrie

Figure W6.3 *Bromus diandrus* seedling.
Photo: Andrew Storrie

Other weeds that can be confused with brome grasses

Brome grasses are difficult to distinguish from other brome species at the seedling or vegetative stage as they are very similar.

At the seedling stage brome grasses may be confused with wild oats (*Avena* spp.) because both have hairs on the leaves and stems and have large ligules and no auricles at the base of the leaf blade.

Table W6.1 Distinguishing characteristics of *Bromus diandrus* and *Bromus rigidus*

Character	*B. diandrus*	*B. rigidus*
Leaf appearance	10 mm wide leaves, which are rough and have some long hairs. The hairs on the leaf blade point upwards. There are usually prominent purple stripes on the leaf sheath.	10 mm wide leaves with sparse hairs and very erect panicle branches.
Inflorescence appearance	The inflorescence is loose and nodding and spikelet branches are longer than the spikelets.	The inflorescence is compact and stiff. Spikelets are often heavily pigmented with reddish to black colouring. The spikelet branches are shorter than the spikelets.
Seed appearance	The hardened scar on the seed is rounded.	The hardened scar on the seed is acute.

Figure W6.4 *Bromus diandrus* seedling showing seed in root system. This helps determine whether the plant is brome or wild oats.
Photo: Andrew Storrie

Figure W6.5 *Bromus diandrus* ligule. This is slightly shorter than in wild oats. Both species do not have auricles.
Photo: Andrew Storrie

Factors that make brome grass a major weed

Both *B. diandrus* and *B. rigidus* compete against pasture and crop species for nutrients and water.

Research in Western Australia found that *B. diandrus* and wild oats were the most competitive grass weeds in wheat. This research demonstrated that wheat yields decreased exponentially with increasing densities of *B. diandrus*. One hundred *B. diandrus* plants/m2 reduced wheat yields by 30%.

Brome grasses are more tolerant of drought and phosphorus deficiency and respond better to nitrogen than wheat. For this reason, adding nitrogen to a crop can aggravate a brome grass problem.

Brome grasses produce large numbers of seeds.

Seed production can range from 600 to more than 3,000 seeds per plant. The ability to shed a large proportion of seed before crop harvest is another important characteristic that makes brome grasses a major weed.

Brome grasses seeds cause contamination problems.

In cropping situations brome grasses contaminate grain. In pastures the seeds contaminate wool, damage hides and meat and cause injury to livestock by entering the eyes, mouth, feet and intestines.

Both *B. diandrus* and *B. rigidus* act as alternate hosts to cereal diseases.

Left uncontrolled in fallow or pasture phases, brome grasses will host and carry over cereal diseases and pests to new crops. Diseases include ergot (*Claviceps purpurea*), take-all (*Gaeumannomyces graminis*), powdery mildew (*Erysiphe graminis*), septoria glume blotch (*Leptosphaeria nodorum*), black stem rust (*Puccinia graminis*), brown rust (*Puccinia recondita*), barley net blotch (*Pyrenophora teres*), sharp eyespot (*Rhizoctonia solani*), bunt (*Tilletia caries*) and *cereal yellow dwarf virus*. Pests include cereal cyst nematode (*Heterodera avenai*) and root-knot nematodes (*Meloidogyne* spp.)

Both *B. diandrus* and *B. rigidus* have evolved resistance

A low incidence of resistance to Group A, B and M herbicides has been confirmed in *B. diandrus*. Similar resistance has been found in *B. rigidus* to Group A and B herbicides.

Environments where brome grasses dominate

Brome grasses are a widely distributed problem weed across southern Australia. They occur between latitudes 23 °S and 44 °S in areas with a mean annual rainfall greater than 250 mm and at least four months of growing season with a mean July temperature of less than 15 °C. In drier areas of Australia *B. diandrus* and *B. rigidus* are replaced by *Bromus madritensis* and *Bromus rubens*.

Both *B. diandrus* and *B. rigidus* have a diverse habitat range that includes croplands, pastures, fallows, wastelands, roadsides, hilltops, coastal sand dunes, national parks and reserves.

B. diandrus is spread from south-eastern Queensland to south-western Western Australia and tolerates a wide range of soil types (acidic or alkaline, sandy to loamy).

B. rigidus is more commonly found on calcareous, sandy soils along coastal areas (mostly limited to Geraldton, the Eyre Peninsula and a strip from Adelaide to the Victorian Mallee).

Brome grasses are frequently found on fallows and in cropping rotations that contain high numbers of cereal crops.

Brome grasses appear to proliferate in no-till crops. Seeds do not germinate until shallow burial by the sowing operation, prompting a larger in-crop flush of brome grasses. There are few selective in-crop herbicides that are effective against brome grasses, which can dominate under reduced competition situations that arise when other weeds are selectively controlled.

Seasonal conditions that favour brome grasses

Brome grasses germinate quickly after the autumn break, causing reduced tillering in cereals sown at low densities in low rainfall areas.

Moisture is the main requirement for brome grass germination, as seed will germinate over a wide range of temperatures. Rainfall therefore plays a prominent role in determining germination flushes, and the first flush following the opening rains in autumn to early winter is always the most prominent. In a dry start to the season, a greater proportion of the seeds show staggered germination which may continue until as late as August.

Conditions that favour brome grass germination and establishment

Brome grass seeds have an initial period of dormancy. Usually by the end of summer seeds move out of their dormant phase and many germinate with the autumn break. The release from dormancy is generally much slower in *B. rigidus* than in *B. diandrus*. However, recent unpublished research has identified *B. diandrus* populations with similar dormancy to *B. rigidus* which appears to be under strong hormonal control in the seed embryo. These populations appeared to respond to chilling, meaning that in the field dormant seed requires both moisture and a period of colder temperatures to germinate. As a consequence, large germinations of brome grasses are not expected until cooler moist conditions in late autumn and early winter.

This high dormancy and chilling requirement enables brome grasses to avoid knockdown herbicides and germinate in-crop where control options are far more limited.

Due to protracted germination and emergence from various soil depths, seedlings establish as cohorts throughout the season.

Seedlings can emerge from seeds buried up to 150 mm deep, although establishment rate is reduced at that depth. The best depth for germination and emergence is 10 mm.

B. rigidus germination appears to be strongly inhibited by exposure to light. However, seed germination resumes upon release from innate dormancy and placement in complete darkness caused by tillage or sowing operations.

B. diandrus establishment is more rapid and uniform when emerging from under wheat stubble than on bare soil and higher if seed is mixed with the soil by shallow cultivation.

Seed survival in the soil

A high proportion of dormant seeds survive hot, dry summers. Seed viability is lost within a year or two if exposed to humidity.

B. diandrus seeds can remain viable in the surface soil layer for two to three years, but little dormancy was found in *B. diandrus* in the southern areas of Western Australia.

Persistence of *Bromus* species could be prolonged on non-wetting soils, with high levels of seedbank carryover (30%) from one season to the next. Greater persistence of brome grass seeds means that control must be undertaken over successive years to deplete the weed seedbank.

Table W 6.2 Tactics to consider when developing an integrated plan to manage brome grass (*Bromus* spp.).

Brome grass (*Bromus* spp.)		Most likely % control (range)	Comments on use
Tactic 2.2d	Selective post-emergent herbicides	90 (75–99)	Apply when weeds have two to six leaves and are actively growing.
Tactic 3.4	Manuring, mulching and hay-freezing	90 (75–95)	Manuring works well if done before seed set. Any regrowth must be controlled.
Tactic 2.1	Fallow	80 (70–90)	Start the chemical fallow before weeds set seed (i.e. early spring).
Tactic 2.2c	Pre-emergent herbicides	80 (40–90)	Follow label directions, especially on incorporation requirements of some herbicides.
Tactic 2.2a	Knockdown non-selective herbicides for fallow and pre-sowing control	80 (30–99)	If possible delay spraying until full emergence and youngest plants have two leaves.
Tactic 3.2	Pasture spray-topping	75 (50–90)	Spray before viable seed set. Respray or graze survivors. Use this technique two years before going back to crop.
Tactic 1.1	Burning residues	70 (60–80)	Sufficient crop residues are needed.
Tactic 1.5	Delayed sowing	70 (30–90)	Best results with early seasonal break.
Tactic 4.1	Weed seed control at harvest	70 (10–75)	Highly variable due to shedding and lodging. Works best on early harvested crops if weeds are yet to drop their seeds.
Tactic 3.3	Silage and hay – crops and pastures	60 (40–80)	Silage is better than hay. Graze or spray regrowth.
Tactic 3.5	Grazing – actively managing weeds in pastures	50 (20–80)	Graze infested areas heavily and continuously in winter and spring. Unpreferred once seed heads emerge
Tactic 1.4	Autumn tickle	50 (20–60)	Depends on seasonal break. Seed burial through shallow cultivation enhances seed depletion through germination, especially in *B. diandrus* with its shorter dormancy and faster germination.

Contributors

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Weed 7 **Capeweed (*Arctotheca calendula*)**

Common names

Capeweed, cape dandelion.

Distinguishing characteristics

Capeweed (*Arctotheca calendula*) is a prostrate, stemless, sprawling annual herb that germinates during autumn and winter. It has hairless, club-shaped cotyledons. The first two leaves grow as a pair, are spear-shaped and may be scalloped. Subsequent leaves grow singly and are deeply lobed with a rounded apex. Leaves are succulent; the upper surface is hairy and the lower surface is covered with a mat of white hairs.

The solitary daisy-like flower heads have brilliant yellow ray florets with blackish-purple central disc florets. Seeds are covered in pinkish-brown, fluffy, woolly hairs.

Figure W7.1 Mature capeweed plant
Photo: Andrew Storrie

Figure W7.2 Capeweed seedling.
Photo: Andrew Storrie

Other weeds that can be confused with capeweed

During vegetative stages capeweed may be confused with dandelion (*Taraxacum officinale*), flatweed (*Hypochoeris radicata*), smooth catsear (*Hypochoeris glabra*), skeleton weed (*Chondrilla juncea*), fleabane (*Conyza* spp.), hawkbit (*Leontodon taraxacoides*), ox tongue (*Helminthotheca echioides*), prickly lettuce (*Lactuca serriola*), sowthistle (*Sonchus oleraceus*), prickly sowthistle (*Sonchus asper*), slender thistle (*Carduus* spp.), brassica weeds such as wild radish (*Raphanus raphanistrum*), and white arctotis (*Arctotis stoechadifolia*), a coastal sand-stabilising perennial weed.

Figure W7.3 Comparison of the underside of capeweed (left) and wild radish (right) leaves showing similar shape but different surface.
Photo: Andrew Storrie

Distribution

A native of southern Africa, capeweed is found in all Australian states and territories.

Factors that make capeweed a major weed

Capeweed is a competitive plant.

It competes with crops (cereals, pulses, canola) for water, nutrients and probably light, resulting in reduced yield. Plants emerging in early autumn become large before the crop is sown and compete strongly with the crop. A capeweed plant at rosette stage can reach 600 mm in diameter and can out-compete other plants. Such large plants are difficult to control with herbicides. They are often transplanted during the planting operation, and their re-emergence with crop plants can lead to population levels that decrease crop yield. In Western Australia 7–90 capeweed plants/m^2 may reduce wheat yield by 28–44% and net return by up to 76%.

Figure W7.4 Capeweed dominated pasture in Western Australia.
Photo: Andrew Storrie

A capeweed plant growing under favourable conditions can produce up to 4,300 seeds.

Seeds may be dispersed by human activity, animals, wind, water and movement of hay.

Capeweed is persistent.

Capeweed rapidly dominates overgrazed or poorer pastures. Capeweed seed will pass through the gut of rabbits and remain viable. Continuous high stocking rates will lead to capeweed dominance in annual pastures.

Capeweed can develop resistance to herbicides.

Capeweed has evolved resistance to diquat and paraquat (Group L) in lucerne hay crops in Victoria. Resistance to 2,4-D (Group I) has been detected in South Australia.

Capeweed can cause animal health problems.

It is often associated with scouring in sheep. It can also cause nitrate and nitrite poisoning of livestock, particularly sheep and cattle. This occurs more frequently in starved animals given access to potentially toxic plants, in stressed animals (during mustering, droving or other handling), or due to lack of acquaintance or adaptation. It can also occur under normal grazing in some seasons. Toxic levels of nitrate are only likely to be present in plants growing in high fertility soils, particularly around stock camps or in stockyards. In practice, capeweed growing on medium to light textured soils is unlikely to contain toxic levels of nitrate. Horses develop skin allergies to the pollen which they come across through contact when grazing and/or eating the weed.

Stock deaths may also occur after spraying with hormones and other herbicides that elevate nitrate content in the capeweed. This usually occurs from early season spraying, when temperatures are higher and overcast weather follows. Nasal granuloma may occur in cows that inhale air with high concentrations of capeweed pollen for long periods. Woolly seeds in unopened buds may cause hair balls and death in sheep. In humans capeweed can cause contact dermatitis and hay fever.

Capeweed is an alternate host for insects and diseases.

Capeweed is an alternate host for light brown apple moth and the larvae of 10 other species of *Lepidoptera*, as well as green peach aphid (*Myzus persicae*), blue green aphid (*Acyrthosiphon kondoi*), cowpea aphid (*Aphis craccivora*) and redlegged earth mite (*Halotydeus destructor*). It also carries the thrip-transmitted *tomato spotted wilt virus* and the aphid-transmitted *cucumber mosaic virus*.

Environments where capeweed dominates

Capeweed is a serious weed of cultivation across southern Australia.

In pasture the status of this species as a weed is less clear-cut. For example, in drier parts of the Western Australian wheatbelt capeweed is a useful forage plant, but in wet areas it is viewed as a weed because it occupies the area of more valuable and beneficial pasture species. In pastures it may have both positive and negative effects on both the pasture and stock production.

Seasonal conditions that favour capeweed

This species is favoured by 'false breaks'. These low rainfall events can favour capeweed germination before other species because the woolly seed cover attracts moisture and reduces desiccation. It can also survive periods of drought better than most crops and pastures, so a dry period following good germinating rains increases the proportion of capeweed.

Conditions that favour capeweed germination and establishment

Autumn rains induce capeweed germination if the soil surface remains wet for a few days. Subsequent rain and residual soil moisture continue to support seedling growth, and these will persist through winter crops if not killed before crop sowing. The woolly hair around the seed assists early germination.

Seeds are usually dormant at maturity, with an after-ripening period of two to three months. Dormancy is rapidly overcome by summer temperatures around 40 °C.

Secondary dormancy, a combination of embryo and seed coat-based dormancy, may be initiated by low winter temperatures. Long-term dormancy is dependent on regional adaptation. In Western Australia greater than 95% of capeweed seed from the southern agricultural area germinated on the soil surface at the break of the season. Only 5% of seed from the northern agricultural area germinated in the first year and 75% in the second season, with 20% remaining dormant for more than two years. Dormancy cycled to favour an autumn germination.

Capeweed seeds kept in the dark or buried will remain dormant for longer than those exposed to light. Again, this appears to be ecotype dependent as seeds in Portugal showed almost complete germination at 15 °C in continuous darkness, whereas in Australia seed burial prevented germination.

Optimal diurnal temperatures for germination were between 10 °C and 15 °C in research conducted in South Africa, but higher (25 °C) in Western Australian research. Germination is very low at temperatures above 30 °C.

All these results were recorded in strong autumn germination flushes in Mediterranean environments.

Seed survival in the soil

Capeweed seed survival in the soil is likely to be very strongly influenced by the ecotype or location and by the degree of burial that occurs. In Western Australia survival ranges from almost no carryover of seed from one season to the next, to in excess of 20% of seed set being carried over for at least two years.

Table W7.1 Tactics to consider when developing an integrated plan to manage capeweed (*Arctotheca calendula*).

Capeweed (*Arctotheca calendula*)		Most likely % control (range)	Comments on use
Tactic 2.2b	Double knockdown or 'double-knock'	90 (80–99)	Better control of hard-to-kill plants and those in dense infestations.
Tactic 2.2d	Selective post-emergent herbicides	90 (80–99)	Clopyralid, florasulam, florasulam + isoxaben, pyroxsulam and terbutryne provide good control, especially of hard-to-kill plants. Limited control options in leguminous crops. Spray-grazing is good for pastures.
Tactic 3.4	Manuring – green and brown, mulching and hay freezing	90 (80–99)	Graze heavily in winter to ensure uniform flower emergence. Graze or respray survivors.
Agronomy 3	Herbicide tolerant crops	90 (80–95)	Good control can be achieved in triazine, imidazolinone and glyphosate resistant crops.
Tactic 1.3	Inversion ploughing	90 (50–98)	Use skimmers to ensure deep burial of seed. Not suitable for some soil types.
Tactic 2.2a	Knockdown non-selective herbicides for fallow and pre-sowing control	80 (70–99)	Good control of actively growing unstressed weeds. Poor control of early germinated weeds that have lost leaves due to early season drought.
Tactic 2.2c	Pre-emergent herbicides	75 (70–85)	Diuron and picloram provide good control.
Tactic 3.2	Pasture spray-topping	70 (30–90)	Graze heavily in winter to ensure uniform flower emergence. Graze or respray survivors.
Tactic 1.5	Delayed sowing	60 (50–90)	Works best on undisturbed paddocks.
Tactic 2.1	Fallow and pre-sowing cultivation	60 (20–95)	Requires drying conditions following cultivation. Transplants are common in wet conditions. Burial of seed will lead to dormancy.
Tactic 3.5	Grazing – actively managing weeds in pastures	50 (30–80)	Rotationally graze pastures and use spray-grazing with MCPA or 2,4-D while terbutryn gives excellent control in clover based pastures. Flumetsulam plus diuron provides reasonable control in many other legume based pastures.

Contributors

Abul Hashem and John Moore

Weed 8 **Common sowthistle (*Sonchus oleraceus*)**

Common names

Common sowthistle, annual sowthistle, sowthistle, milk thistle.

Distinguishing characteristics

The cotyledons of common sowthistle (*Sonchus oleraceus*) are spoon-shaped and often have a greyish powdery film on their surface. Leaves are bluish-green and predominantly net-veined.

Adult leaves are characterised by their serrated appearance and are commonly deeply lobed with a major triangle-shaped lobe at the tip of the leaf. Adult leaves are characterised by auricles that clasp the stem, and the leaf margins are never spiny.

Stems are hollow and exude a milky sap when broken.

Seeds are flat and possess a wrinkled surface at maturity and a fine white pappus.

Other weeds that can be confused with common sowthistle

Common sowthistle can be confused with rough, spiny or prickly sowthistle (*Sonchus asper*). However, the leaves of prickly sowthistle are thicker and spiny at the margins, and its seeds are broader and lack the cross wrinkles present on common sowthistle seeds.

Figure W8.1 Mature prickly sowthistle plant
Photo: Andrew Storrie

Figure W8.2 Common sowthistle seedling.
Photo: Andrew Storrie

Figure W8.3 Prickly sowthistle seedling.
Photo: Wilson et al., 1995

Factors that make common sowthistle a major weed

Common sowthistle is a major fallow weed and uses vital stored soil moisture.

It is not seen as competing heavily with crops. However, in a poorly competitive crop common sowthistle contributes to green matter at harvest and can lead to grain quality problems.

Common sowthistle is a prolific producer of seed.

It can produce up to 68,000 seeds/m^2 in a fallow. In addition, the seeds possess a fine pappus that helps them disperse readily. The seeds possess no innate dormancy and are therefore able to germinate once dispersed from the parent plant.

Common sowthistle is difficult to control.

In northern Victoria, NSW, and southern Queensland resistance to Group B herbicides is common. Glyphosate resistance has been confirmed in northern NSW and southern Queensland, with 20% of samples tested in a 2018 survey showing resistance. Resistance to Group I (2,4-D) has also been found in populations in South Australia and Victoria. There are populations of *S. asper* that have evolved resistance to Group B herbicides in Canada and the USA and to Group C herbicides in France.

Common sowthistle is an alternate host for insects.

Common sowthistle is an alternate host for *Helicoverpa* species, and for aphids which can transmit viral diseases to economically important crops.

Environments where common sowthistle dominates

Although ubiquitous across Australia, common sowthistle is a major weed only in the northern grain region from central Queensland to northern NSW. The weed is most common in zero or reduced tillage systems and occurs in both fallow and cropped areas.

Common sowthistle can be found on most soil types but grows best in soils with a high water-holding capacity.

The weed is a problem in many different production enterprises including dryland and irrigated broadacre cereal production, horticultural crops, vineyards and tree crops. Also common in non-crop areas, it is frequently found on roadsides and in nature reserves.

Figure W8.4 Mature common sowthistle plant.
Photo: Andrew Storrie

Seasonal conditions that favour common sowthistle

Common sowthistle has long been considered a winter annual. However, it is common all year round in the northern region and capable of producing several generations in a favourable year. For this reason a high level of diligence is required to control this weed.

This species can emerge following minimal rain (5 mm). However, larger flushes emerge following significant rain (greater than 25 mm).

The weed is common in crops and fallows but most prevalent in fallows. In fallows, and before planting, it is common for this weed to be present at different stages of growth.

In a poorly competitive crop common sowthistle plants will grow and produce seeds. Escapees of the weed in such crops are most likely to set seed toward the end of the crop, or once the crop has been harvested.

Following harvest common sowthistle will regrow and flower, and at this stage it is difficult to control with commonly used rates of fallow herbicides.

A competitive crop such as barley will suppress common sowthistle and the number of plants reaching maturity will be dramatically reduced. On the Darling Downs in southern Queensland, common sowthistle was fully controlled in the absence of herbicides by growing barley at a density of 75 plants/m^2 at either a 250 mm or 500 mm row spacing. By comparison, it readily grew in wheat, even at a density of 150 plants/m^2 when grown in 500 mm rows.

Conditions that favour common sowthistle germination and establishment

Common sowthistle seed can germinate at temperatures in the range 5–35 °C. Germination is ultimately determined by moisture availability, as a moist environment is preferred.

Emergence is favoured under zero and reduced tillage systems where seeds remain close to the soil surface (top 20 mm). No seedlings emerge from below a depth of 20 mm.

Seed survival in the soil

The duration of seed persistence will depend on the depth at which the seed is buried, with up to 10% viable after two to three years burial at 5–10 cm. Generally, the seed of common sowthistle is short-lived in the surface soil (20 mm), with up to 99% gone after eight to 12 months in the absence of replenishment.

Table W8.1 Tactics to consider when developing an integrated plan to manage common sowthistle (*Sonchus oleraceus*).

Common sowthistle (*Sonchus oleraceus*)		Most likely % control (range)	Comments on use
Tactic 4.2	Grazing crop residues	95 (up to 100)	To control escapes in fallow before seed set. Common sowthistle is very palatable and is preferentially grazed.
Agronomy 2	Improve crop competition	95 (75–99)	Increased competition results in lower weed pressure. Competition improves herbicide efficacy.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	95 (75–99)	Better control is achieved when treating small weeds. A reduction in herbicide efficacy occurs when 2,4-D is tank-mixed with glyphosate due to antagonism within the plant.
Tactic 2.2d	Selective post-emergent herbicides	95 (75–99)	Better control is achieved when treating small weeds.
Tactic 3.1a	Spray-topping with selective herbicide	95 (75–95)	Seed reduction of escapes. Timing is critical to avoid crop damage.
Tactic 2.1	Fallow and pre-sowing cultivation	80 (30-90)	Cultivation or full disturbance sowing buries seeds and prevents their germination.

Contributor

Michael Widderick

Weed 9 **Cutleaf mignonette (*Reseda lutea* L.)**

Common names

Yellow mignonette, wild mignonette.

Figure W 9.1 Mature cutleaf mignonette plants.
Photo: Michael Moerkerk

Distinguishing characteristics

Cutleaf mignonette (*Reseda lutea* L.) is a perennial weed, frequently of disturbed agricultural area and is found in south-east Queensland, eastern NSW, south and north-west Victoria, Tasmania, South Australia and south-west Western Australia. The plant is erect up to 1 m high, with simple shiny alternate leaves with narrow pointed lobes between 20 mm and 60 mm long. Flowers are pale-yellow, closely packed and numerous, appearing at the ends of the main stem. Fruits are oblong angular pods approximately 10 mm long, containing numerous black smooth shiny seeds. It features an extensive root system and a deep tap root, allowing it to survive in dry conditions. Root fragments are regenerative, and can be spread by cultivation. Cutleaf mignonette lifespan can be indeterminate, existing as an annual, biennial or frequently perennial.

Other weeds that can be confused with cutleaf mignonette

Can be confused with rampion mignonette or corn mignonette. The two species can be distinguished by their growth habits, with cutleaf mignonette growing erect whereas rampion mignonette grows prostrate.

Factors that make cutleaf mignonette a major weed.

Cutleaf mignonette has a persistent root system

Cutleaf mignonette has very deep, persistent root system which allows it to survive drought and grow in areas with low rainfall. Regeneration of root fragments assists in persistence and spread of weed.

Cutleaf mignonette is competitive.

Cutleaf mignonette is an effective competitor against crops, with cereal yield losses between 9% and 61%. The cost to the South Australian grains industry is estimated at $1.5 million per annum.

Cutleaf mignonette is an host for a number of diseases.

Watermelon mosaic virus and the *cucumber mosaic virus* can be found in cutleaf mignonette.

Cutleaf mignonette can be easily spread.

Root fragments can be spread by cultivation, and are more vigorous after pasture than following cultivated crops. Seed can be spread over a wide area via stock, contaminated seed and fodder.

Figure W 9.2 Cutleaf mignonette pods.
Photo: Geoff Sainty

Environments where cutleaf mignonette dominates

Cutleaf mignonette is native to Eurasia and northern Africa, and has naturalised in southern and eastern Australia. Although found in each Australian state, cutleaf mignonette is most common in South Australia, particularly in Yorke Peninsula growing well on calcareous or alkaline soils. Cutleaf mignonette thrives on disturbed sites, and can endure a range of rainfall conditions (100–625 mm).

Seasonal conditions that favour cutleaf mignonette

Cutleaf mignonette prefers to emerge between September and the end of November or between March and the end of April.

Conditions that favour cutleaf mignonette germination and establishment

Cutleaf mignonette can germinate at any time of the year between the range of 10 °C and 35 °C when provided with adequate soil moisture. Lights inhibits germination; thus cultivation that may bury seed enhances it. Seedlings from buried seed can emerge from a depth of 80 mm, with greatest emergence at 5 mm (57%). Taproot development in seedlings is rapid, growing as much as 350 mm in one month. As seedling recruitment is low however, shoot regeneration from perennial roots is a main source of cutleaf migonette. Little is known about the limit of root fragment regeneration in field, although under laboratory conditions shoots were able to form from root fragments 10 mm long and 1 mm thin.

Seed survival in the soil

Seed can remain viable for at least four years in soil, with viability affected by burial depth. A study in South Australia showed that after 48 months, seed taken from 50 mm had 33–63% germination, and seed taken from 150 mm had zero germination. These results indicate that even with good seed set control,it will take four to five years to significantly reduce seed banks.

Table W 9.1 Tactics to consider when developing an integrated plan to manage cutleaf mignonette (*Reseda lutea* L.).

Cutleaf mignonette (*Reseda lutea* L.)		Most likely % control (range)	Comments on use
Tactic 2.2d	Selective post-emergent herbicides	90 (80–90)	Use in combination with competitive crops. Good to excellent control achieved with glyphosate and chemicals registered in South Australia for cutleaf mignonette control including products containing 2-4D, MCPA, and Metsulfuron-methyl. 2-4D products should only be used on seedlings and young plants.
Tactic 2.2c	Pre-emergent herbicides	80 (70–90)	Works best when combined with competitive crops.
Tactic 3.5	Grazing- actively managing weeds in pasture	80 (0–95)	Heavy grazing can remove seedlings; however can be toxic if excessively consumed. Subsequent crop choice may be limited after treatment.
Agronomy 2	Improving Crop competition	Variable	Higher cropping seeding rates and higher crop nutrition restrict plant development. Competitive pastures also provide good suppression.

Contributors

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Weed 10 **Doublegee (*Emex australis*)**

Common names

Doublegee, spiny emex, three-cornered jack, cat-head, prickly jack, giant bull head, Tanner's curse, bindii, Cape spinach.

Distinguishing characteristics

Doublegee (*Emex australis*) is a vigorous annual herb with a strong tap root and a long, fleshy, hairless stem. The cotyledons are hairless, elongated and club-shaped. Subsequent leaves are alternate, hairless and triangular with undulating margins.

Ovate leaves form a prostrate rosette at early stages of growth but can assume a semi-erect habit in dense crop or pasture.

Round, ribbed stems branching from the centre of the rosette may grow up to 600 mm in length. Clusters of very small, inconspicuous white flowers produce hard woody achenes with three sharp spines radiating from the apex.

Figure W10.1 Mature doublegee plant.
Photo: Andrew Storrie

Other weeds that can be confused with doublegee

Doublegee is easily confused with *Emex spinosa*, an uncommon weed found at a few sites in the northern wheatbelt of Western Australia and also in some areas of southern Australia. *E. spinosa* has more erect stems but the fruits and achene spines of are half the size of those of *doublegee*.

Factors that make doublegee a major weed

Doublegee was brought to Australia in 1830 as the vegetable called Cape spinach and has become a significant agricultural weed in temperate Australia. A recent study by Llewellyn et al. (2016) found that doublegee losses equated to $1.4 million in lost yield, covering over 170,000 ha.

Figure W10.2 Doublegee seedling.
Photo: Abul Hashem

Doublegee competes against crops and reduces yield.

Eight to nine doublegee plants/m^2 can reduce wheat yield by up to 50%.

Doublegee produces a large number of seeds.

One doublegee plant growing under ideal conditions in the absence of competition may spread up to 1 m in diameter and produce as many as 1,100 seeds. Doublegee produces seed above and below ground, with below ground seed forming from as early as the 4-leaf stage.

Doublegee can contaminate grain, leading to a rejection of grain deliveries.

It is very difficult to separate doublegee achenes from the seeds of pulses. Although it is relatively easy to separate the achenes from cereal and canola seeds, additional cleaning post-harvest may be required. In pedigree and bulk seed production programs of any crop, nil contamination is necessary, which is extremely difficult to achieve.

Doublegee seed dispersal in agriculture is diverse.

Mechanisms for the easy dispersal of seeds include movement in rubber tyres on farm vehicles or on shoes, transport with crop seed, silage or fodder, and animal movement.

Doublegee can cause animal health problems.

Doublegee plants contain oxalate at levels that may not be toxic in small quantities but may poison sheep if eaten in large quantities. The spiny fruits of doublegee can injure animals and people walking barefoot, and are robust enough to puncture bicycle tyres.

Doublegee has evolved resistance to herbicides.

One case of metsulfuron-methyl (Group B) resistance has been confirmed in doublegee in the Western Australian wheatbelt.

Both glyphosate and paraquat + diquat are effective on doublegee seedlings. A range of selective herbicides from Groups B, C, F, G, I and L can effectively control this weed in cereal crops. There are few options to control doublegee in pulse crops.

Two weevils (*Perapion antiquum* and *Lixus cribricollis*) and red apion (*Apion miniatum*) were released for biological control in the 1980s and 1990s but failed to establish due to prolonged dry summers in Australia.

Figure W10.3 Close-up of doublegee fruits.
Photo: Andrew Storrie

Environments where doublegee dominates

Doublegee is widespread throughout the agricultural areas of temperate mainland Australia and on Flinders Island off Tasmania.

It is a weed of concern in cereals, lupins, pulses and canola in South Australia, Western Australia, central and northern NSW, south-eastern Queensland, the Murray River irrigation areas of Victoria and roadsides in the Northern Territory.

It is a weed in agricultural, horticultural, pastoral, industrial, wasteland, grassland and conservation areas but is not usually found in natural ecosystems.

Doublegee prefers soil types from sand to clay loam where pH is neutral to slightly alkaline.

Seasonal conditions that favour doublegee

Doublegee seeds mainly germinate in autumn and winter although germination may occur any time during the year.

In Western Australia and northern NSW where summer rainfall is likely, and in seasons where summer rainfall occurs in temperate climates, germination may occur in late February and seedlings are likely to persist into winter crops.

Conditions that favour doublegee germination and establishment

Doublegee seed germinates over a wide range of temperatures (day and night temperatures from 5 °C to 35 °C) but more quickly at higher temperatures. Germination is staggered, with seedlings usually starting to emerge in autumn after sufficient rain. Summer rains can germinate some doublegee seeds and these plants can successfully complete development.

Seedling emergence is higher in heavier soil types than in sandy soils. Unburied seed has low germinability and very few seeds germinate from deeper than 50 mm.

Seed survival in the soil

Doublegee achenes may remain viable in soil for more than seven years.

An autumn cultivation will stimulate seedling emergence, and if these seedlings are killed the level of viable seeds in the soil will decrease rapidly.

After two growing seasons about 15% of seed remains viable in the soil, and less than 2% remains viable after eight growing seasons.

Table W10.1 Tactics to consider when developing an integrated plan to manage doublegee (*Emex australis*).

Doublegee (*Emex australis*)		Most likely % control (range)	Comments on use
Tactic 1.3	Inversion ploughing	90 (80–99)	Use once on intractable infestations only, and then don't deep cultivate for at least ten years.
Tactic 2.2d	Selective post-emergent herbicides	90 (70–95)	Spray small and actively growing weeds. Repeat if required.
Agronomy 3	Herbicide tolerant crops	90 (50–95)	Very useful for non-cereal phase of rotations
Agronomy 1	Crop choice and sequence	80 (0-95)	Cheaper and easier to control in cereals. Avoid crops that don't have good herbicidal control options.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	75 (50–80)	Use robust rates.
Tactic 2.2c	Pre-emergent herbicides	75 (50–80)	Can be variable depending on season. Subsequent crop choice may be limited after treatment.
Tactic 3.5	Grazing – actively managing weeds in pastures	50 (30–70)	Doublegee is palatable to stock until formation of the spiny achenes. Useful for supressing and reducing seed production, enabling favourable pasture species to actively compete.
Tactic 1.4	Autumn tickle	40 (20–60)	Depends on seasonal break. Use in conjunction with a follow-up herbicide treatment or cultivation.

Contributors

Abul Hashem and John Moore

Weed 11 **Feathertop Rhodes grass (*Chloris virgata*)**

Common names

Feather finger grass, feather windmill grass, feathertop chloris, hairy Rhodes grass, windmill grass, woolly-top Rhodes grass.

Figure W11.1 Inflorescence of feathertop Rhodes grass showing shedding of seed.
Photo: Andrew Storrie

Distinguishing characteristics

Feathertop Rhodes grass (*Chloris virgata*) is a tufted annual grass up to 1 m tall with erect and semi-prostrate branched stems capable of rooting at the joints. Leaf blades are bluish–green, 5–25 cm long and 3–6 mm wide. The seed-heads or panicles have seven to 19 feathery, white-silver spikes that are 3–9 mm long. The feathery appearance comes from the stiff white hairs and awns arising from the seeds.

Unlike common Rhodes grass (*Chloris gayana*), feathertop Rhodes grass panicles tend to remain unsplayed and pointing upwards. Seedlings are erect but with flattened stem bases, and this flattening becomes more obvious in older tillers. Leaf blades have tufts of hairs along the margins and where the blade joins the sheath. The stem joints are hairless and sometimes very dark.

Other weeds that can be confused with feathertop Rhodes grass

In the early growth stages, feathertop Rhodes grass can be easily confused with awnless barnyard grass (*Echinochloa colona*).

Factors that make feathertop Rhodes grass a major weed

Feathertop Rhodes grass has resistance to glyphosate.

When using glyphosate alone to control feathertop Rhodes grass it is often difficult to achieve high levels of control, particularly after the early tillering stage. The prolonged use and reliance on glyphosate in the fallows of northern NSW and Queensland cropping systems has resulted in this species becoming very common. For the same reason, feathertop Rhodes grass has also recently become an issue in glyphosate-tolerant cotton systems. Resistance to glyphosate has been confirmed in populations from Queensland, South Australia and NSW.

Figure W11.2 Feathertop Rhodes grass infesting sorghum crop.
Photo: Andrew Storrie

Feathertop Rhodes grass seed readily germinates unless buried.

With minimal disturbance the seeds remain near the soil surface, which is ideal for emergence and perpetuation of the weed.

Figure W11.3 Feathertop Rhodes grass dominating the road shoulder near Conargo, NSW.
Photo: Andrew Storrie

Environments where feathertop Rhodes grass dominates

Previously a weed of roadsides, fencelines and wasteland areas, feathertop Rhodes grass has now become an issue in cropping country, particularly where minimum or zero tillage has been practised for several years.

Feathertop Rhodes grass is a major weed in broadacre cropping systems in central Queensland, the Darling Downs and Western Downs regions of southern Queensland, the coastal and northern Queensland cropping areas and northern NSW. It is also a problem in the vineyards, orchards and roadsides of South Australia and in parts of the Western Australian grain region.

Seasonal conditions that favour feathertop Rhodes grass

A number of below average rainfall years have made management difficult, allowing seedbank build-up. Very wet seasons have been associated with substantial increases in field populations.

Conditions that favour feathertop Rhodes grass germination and establishment

Seeds germinate between temperatures of 20 °C and 30 °C but a preference is shown for 25 °C and above with exposure to light.

The seeds have innate dormancy, requiring an after-ripening period of approximately six to 10 weeks. While pre-chilling assists in breaking dormancy, it is not essential.

The majority of seedlings emerge from seed at 0–2 cm depth. In a central Queensland experiment 47% of seed buried near the surface germinated, compared with 5% buried 5 cm deep and nil buried 10 cm deep over 12 months. The majority of plants emerged within the first seven months.

While feathertop Rhodes grass prefers lighter textured soils, it will also survive on heavier clay soils.

Seed survival in the soil

Seed appears to be short-lived (about seven to 12 months) irrespective of burial depth, suggesting short field persistence in central Queensland. Seed taken from depth after being buried for 12 months did not germinate even after several dormancy breaking mechanisms were applied. Similar results were found in South Australian experiments, where seed on the soil surface became unviable within 12 months.

Table W 11.1 Tactics to consider when developing an integrated plan to manage feathertop Rhodes grass (*Chloris virgata*).

Feathertop Rhodes grass (*Chloris virgata*)		Most likely % control (range)	Comments on use
Agronomy 1	Crop choice and sequence	95 (75–99)	Choose a rotation with a summer legume crop such as mung beans to allow use of grass selective herbicides combined with crop competition.
Tactic 1.3	Inversion plough	75 (70–80)	Deep burial of seed will prevent emergence.
Tactic 2.1	Fallow and pre-sowing cultivation	90 (50–100)	This is an effective option under dry conditions.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	70 (55–95)	Glyphosate is only effective on pre-tillering weeds.
Tactic 2.2b	Double knockdown or 'double-knock'	90 (80–100)	Best applied to early tillering weeds. Interval between first and second knock should be around 7 days when using glyphosate as the first knock. Double-knock using a grass selective herbicide followed by a bipyridyl herbicide is very effective.
Tactic 2.2d	Selective post-emergent herbicides	90 (75–99)	Target pre-tillering weeds in mung beans, cotton or sunflowers.

Contributors

Vikki Osten and Steve Walker

Weed 12 **Fleabane (*Conyza* spp.)**

There are three main species of fleabane in Australia: flaxleaf fleabane (*Conyza bonariensis*), tall fleabane (*Conyza sumatrensis*) and Canadian fleabane which comprises two varieties (*Conyza canadensis* var. *canadensis* and *Conyza canadensis* var. *pusilla*). Of the three species, flaxleaf fleabane is the most common across Australia particularly in cropping and fallow paddocks.

Common names

Flaxleaf fleabane, Canadian fleabane, tall fleabane, fleabane, hairy fleabane, cobbler's peg (NSW coast only).

Distinguishing characteristics

Flaxleaf fleabane can grow up to 1 m tall and has deeply indented leaves. It has the narrowest leaves at rosette stage when compared with other *Conyza* species. Its branches often grow taller than the main plant axis.

Tall fleabane can grow up to 2 m tall. Its leaves are less indented than flaxleaf fleabane and its branches do not grow taller than the main plant axis.

Both flaxleaf and tall fleabane have flower-heads of approximately 10 mm when pressed. By comparison, Canadian fleabane has smaller flower-heads of 5 mm when pressed.

The two varieties of Canadian fleabane also differ, with var. *canadensis* having very hairy leaves and var. *pusilla* having virtually hairless leaves.

Flaxleaf fleabane has a smoothly pitted receptacle while tall fleabane has a roughly pitted receptacle.

Each of the fleabane species is characterised by the production of fluffy cream seed-heads that possess a pappus. They also produce a very long taproot that can grow up to 350 mm long.

Figure W12.1 Comparison of mature plants of the three fleabane species: (left to right) tall fleabane, flaxleaf fleabane, Canadian fleabane.
Photo: Andrew Storrie

Figure W12.2 Comparison of flowers of (left to right) tall fleabane, flaxleaf fleabane, Canadian fleabane.
Photo: Andrew Storrie

Figure W12.3 Fleabane seedling.
Photo: Andrew Storrie

Other weeds that can be confused with fleabane

Fleabane can be confused with bushy starwort (*Aster subulatus*). See *Figure W12.4* for visual differences.

The main confusion, however, arises from the use of common names, because cobbler's peg is the common name generally used for *Bidens pilosa* and other *Bidens* species, whereas in NSW 'cobbler's peg' is the common name for fleabane in particular.

Figure W12.4 Bushy starwort is a much finer plant than fleabane and usually grows in wetter areas.
Photo: Andrew Storrie

Factors that make fleabane a major weed

Fleabane is a prolific seed producer, each plant producing up to 110,000 seeds.

Of these seeds, up to 80% can be viable. The seeds do not possess dormancy so they can germinate whenever temperature and moisture requirements are met. Prevention of seed set is vital for control.

Figure W12.5 Fleabane seed production.
Photo: Andrew Storrie

Fleabane is a major weed of fallows, summer and winter crops and pastures.

Fleabane competes for soil water in crop and fallow phases. It severely affects fallow efficiency in northern NSW and Queensland and pasture production, particularly in degraded pastures, in southern NSW and southern Western Australia.

Fleabane is very difficult to control with herbicides.

Inconsistent control is often obtained with herbicide treatments, especially once plants exceed a diameter of 50 mm, have dense infestations and high stubble levels. Where fleabane becomes a problem in fallows, weed control costs can increase by up to 80% due to the difficult nature of control (such as double-knock: e.g. glyphosate + 2,4-D followed seven to 10 days later by paraquat).

Fleabane is capable of developing herbicide resistance.

It has already evolved resistance to herbicide Groups C, L and M overseas. Repeated glyphosate applications are often used in an attempt to control the weed in fallow. In 2010, eight fleabane populations resistant to glyphosate were confirmed in northern NSW and southern Queensland. At the time of writing there were 74 populations of fleabane confirmed resistant to glyphosate across Australia. (Refer to the Australian Glyphosate Sustainability Working Group website https://www.glyphosateresistance.org.au/ for the latest information).

Paraquat (Group L) resistance has also been confirmed in fleabane (*C. bonariensis*), as well as 'double-knock' resistance, resistance to both glyphosate and paraquat.

Flaxleaf fleabane emerges throughout most of the year.

The pappus on the seed enables it to be dispersed long distances by high intensity summer storms, through a combination of strong winds and surface run-off, and through the water movement in irrigation channels and waterways. This suggests that the spread of fleabane across an agricultural landscape could be very rapid. The majority of the seed, however, falls within 3 to 5 m of the parent plant. Fleabane invades and flourishes in areas lacking competition.

Environments where fleabane dominates

Flaxleaf fleabane occurs in all Australian states. It was first identified as a major crop weed problem in northern NSW and southern Queensland, but has now spread widely into southern and western states. It is a serious problem in lucerne stands in NSW and fallows and pastures in northern NSW, Queensland, Victoria, South Australia and southern Western Australia.

As the most common fleabane species in South Australia, flaxleaf fleabane is a frequent pasture weed and is relatively unpalatable to stock.

Canadian fleabane and tall fleabane are also weeds in every state.

Each of these three fleabane species is common on roadsides and disturbed wetlands and wastelands in Western Australia from Perth to Kununurra. Flaxleaf fleabane and tall fleabane have rapidly increased their distribution in southern Western Australia between 2008 and 2013.

Fleabane is more common on lighter soils but can also flourish in heavy textured soils. It is poorly competitive in-crop but grows very well in bare fallows, cropping gaps, wide rows and weakly competitive crops.

It is also largely a weed in zero and reduced tillage systems. Increased fleabane presence has forced some growers to use cultivation.

Seasonal conditions that favour fleabane

In the northern grain region of Australia fleabane appears to be an all year-round weed with peak growth periods in autumn, spring and summer. It survives winter with slow vegetative growth while developing a strong taproot.

Significant rain that keeps the soil surface moist for three to four days is required for a major flush of seedlings to germinate.

Often fleabane germinates under a winter crop after the normal application time for post-emergent herbicides. The plants develop unobserved until harvest, when they begin to elongate for flowering. The harvest machinery cuts the tops off the plants but they survive in the summer fallow as woody, deep-rooted plants with little leaf area to absorb herbicides. These established plants are difficult to control in the following summer fallow. However, if left unchecked, they continue to produce seed through the summer.

Conditions that favour fleabane germination and establishment

Fleabane prefers cool and moist conditions for germination. Fleabane emerges in northern NSW and Queensland predominantly in late autumn to early and late winter. However, in southern NSW, fleabane has its major emergence over winter, continuing into spring. Hot summers discourage fleabane emergence.

Fleabane is a small-seeded weed species. Seedlings only emerge from (or near) the soil surface. For this reason fleabane is more commonly found in zero and reduced tillage systems, where the majority of seed remains in the soil surface and increased stubble cover keeps the soil surface wet for longer.

Although very limited emergence occurs in mid-winter in northern NSW and Queensland, young autumn or early winter seedlings actively grow during winter despite cold and dry conditions. Surprisingly, even where there does not seem to be much growth above ground, root growth progresses. The building of such a strong root system during winter provides sufficient food reserves for rapid growth during the following spring. Over-wintering fleabanes are very difficult to control.

Seed survival in the soil

Fleabane emergence is very sensitive to soil burial. Seedlings emerge only from the soil surface or in the top 5 mm. Emergence does not occur below 20 mm of burial depth. Burial depth also affects seed survival. Seed viability declines rapidly to less than 15% after 12 months of burial, followed by a steady but slow decline over an extended period. When sown on the surface, less than 2% of the seed remains viable after three years. After burial at 50 mm and 100 mm for three years about 9% of buried seed remains viable.

Table W12.1 Tactics to consider when developing an integrated plan to manage fleabane (*Conyza* spp.).

Fleabane (*Conyza* spp.)		Most likely % control (range)	Comments on use
Tactic 2.5	Detect sprayers	99 (90-100)	Properly calibrated detect sprayers can give extremely high levels of control of large fleabane plants in fallows.
Tactic 2.2b	Double knockdown or 'double-knock'	95 (60-100)	Glyphosate + Group I herbicide followed seven to 10 days later by robust application of a bipyridyl herbicide (Group L) gives very high levels of control in fallow on heat- and moisture-stressed weeds.
Tactic 2.2c	Pre-emergent herbicides	90 (85–99)	Long-term control applied pre- or post-planting. Use higher recommended rates for better control.
Tactic 2.2d	Selective post-emergent herbicides	90 (85–99)	Target small weeds; timing is critical. Rely on mixtures at sufficiently high rates, especially in fallow. Target in-crop germinations with late post-emergent herbicides in cereal crops.
Tactic 2.4	Spot spraying, chipping, hand roguing, wiper technologies	90 (80–99)	Very effective to reduce potential populations where there are small numbers of survivors. Plants must be cut off below ground.
Agronomy 2	Improve crop competition	50 (30–70)	Avoid wide row cropping in weedy paddocks.
Tactic 2.1	Fallow and pre-sowing cultivation		Small actively growing fleabane can be controlled with robust glyphosate rates. Pre-sowing cultivation or full disturbance sowing will reduce the likelihood of fleabane establishing in-crop.

Contributors

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Weed 13 **Fumitory (*Fumaria* spp.)**

Common names

Fumitory, also known as carrot weed, is the widely used name for several species of *Fumaria*. Worldwide there are about 50 species of which eight are recorded in Australia. *Table W13.1* shows their distribution in Australia.

Figure W13.1 A *Fumaria* species seedling.
Photo: Andrew Storrie

A comprehensive survey in 1997 found that most species were associated with winter cropping practices. Only *F. capreolata* was not associated with disturbed soils and was found mainly in gardens. *F. densiflora* and *F. bastardii* are the most widespread and abundant species while *F. officinalis* is the rarest.

Table W13.1 Distribution of eight *Fumaria* species in Australia.

Species	Distribution in Australia
F. bastardii	All states and the Australian Capital Territory
F. capreolata	All states and the Australian Capital Territory
F. densiflora	All states, but rarely the Northern Territory
F. indica	All states (except Tasmania) and the Northern Territory
F. muralis	All states and the Australian Capital Territory
F. officinalis	Queensland, New South Wales, South Australia and Tasmania
F. parviflora	All states (except Tasmania) and the Northern Territory
F. vaillantii	South Australia

Distinguishing characteristics

Fumitory is an autumn and winter growing annual, glabrous (hairless) herb with a semi-erect climbing habit. Leaves are alternate, divided, deeply lobed and light green to bluish-green. Stems are irregularly five-angled, are brittle, may be reddish and contain a watery, greenish latex. The flowers are arranged in racemes and colour ranges from white to mauve depending on species. The plants vary greatly in their morphology depending on the growing conditions but also within species, particularly for *F. bastardii*. This variability leads to difficulty in correctly identifying the species.

Table W13.2 Distinguishing characteristics of the seven more widespread Fumaria species naturalised in Australia.

Species	Flower colour	Leaves
F. parviflora	Light to mid pink	<1 mm wide
F. indica	Light to mid pink	1– 2 mm wide, 10 mm long
F. densiflora	Dark pink	1– 2 mm wide, 5 mm long
F. officinalis	Dark pink	>2 mm wide
F. muralis	Mauve	>2 mm wide
F. bastardii	Mauve	>2 mm wide
F. capreolata	White	>2 mm wide

Factors that make fumitory a major weed

Fumitory is not considered a serious weed globally and so these species have not been intensively studied from a weeds perspective. However, recent experience in Australia has identified increased incidence of fumitory in winter crops. In the 1960s fumitory was found in less than 4% of crops in southern NSW and Victoria, albeit with occasional serious infestations, but by the early 1990s these proportions had risen to more than a third of cereal crops and over 40% of canola crops. It is likely that this substantial increase is due in part to the increasing importance of canola in winter cropping areas.

Two main factors help explain the change:

1. There are limited herbicide options registered for selective removal of fumitory from canola.
2. Where fumitory seed is harvested together with canola, its similar size precludes the complete decontamination of the canola seed-lot. This scenario indicates that canola seed-lots are a likely means of spreading fumitory further across the cropping zone.

Fumitory has a long-lived seed bank.

Seeds have been known to remain viable for up to 20 years, with a seedbank half-life of 10 years. Extended pasture phases might not have any effect on fumitory populations. Soil disturbance can stimulate seedling emergence. A seedbank persistence study at Mount Barker, Western

Australia, found that cultivation after a pasture phase stimulated *F. muralis* seedling emergence every year and increased the seedbank decline rate from negligible levels to over 65%. The stimulatory effect of tillage occurred every year for five years.

Fumitory has the ability to germinate over a range of temperatures.

Fumitory will continue to germinate after sowing and late-emerging weeds will miss post-emergent herbicide applications.

Fumitory is genetically variable allowing adaption to different conditions.

Fumitory species are able to grow in a wide range of conditions varying from season to season.

Fumitory species have varying susceptibility to herbicides.

Some tolerance of trifluralin is found in all species. Two *F. densiflora* populations have evolved resistance to trifluralin following 15 years of continuous use.

There is no residual control from triasulfuron and chlorsulfuron at recommended rates.
Bromoxynil gives good control of *F. bastardii* only.
Fumitory species are not controlled by
2,4-D, 2,4-DB and MCPA herbicides.

Figure W13.2 Flowering *Fumaria muralis*.
Photo: Andrew Storrie

Conditions that favour fumitory germination and establishment

A survey in the late 1990s showed that most of these *Fumaria* species, like true agricultural weeds, occurred almost exclusively in regularly disturbed sites. The exception was *F. capreolata* which was found in non-disturbed sites. *F. bastardii* and *F. densiflora* were found over a range of soil textures and rainfall zones, giving them widespread and overlapping occurrence. *F. densiflora* presence was influenced more by soil texture, either sandy loams or heavy alkaline clays, and was largely unaffected by the amount of autumn rainfall. *F. bastardii* was present equally on all soil types, although it occurred more frequently in areas with higher April rainfall.

F. muralis was significantly affected by both soil texture and rainfall during autumn, most notably during May when it was often flowering. In agricultural sites it was more prevalent on medium to heavier textured soils with higher rainfall, while in non-agricultural environments it also occurred on lighter soils, provided they were high in organic matter and in higher rainfall areas. *F. muralis* was commonly found with *F. bastardii* but less commonly with *F. densiflora*.

F. parviflora was commonly found in lime-rich environments, particularly in South Australia and north-western Victoria. The scarcity of these soils in NSW explains the rarity of the species in that state. *F. parviflora* is more likely to be found with *F. densiflora*.

Seed survival in the soil

Seedling emergence varies with species, season, soil type, seed burial depth and soil disturbance. It is greater in heavy soils than in light soils and in disturbed soils. There is a high proportion of seedling emergence from shallow seed sources, whereas more deeply buried seeds remain dormant and long-lived with a half life estimated at 10 years.

Seed dormancy is due to an immature embryo, a physiological block commonly removed by high summer temperatures. There are also seed-covering structures, namely a lignified seed wall (pericarp) and a phenol-containing seed coat (testa), that may control germination and emergence.

In Australia ants are the natural dispersal agents with seeds removed to ant nests or 'granaries' where there is a concentration of seedlings at germination time. Such granaries also commonly contain significant quantities of other seeds such as annual ryegrass although strong grass seedling emergence is rarely seen in granaries where fumitory is growing. While clumping of seedlings via this process is likely to reduce seedling survival, the spread of seed from the granaries by cultivation implements is likely to lead to greater populations surviving over larger patches.

Managing fumitory infestations therefore becomes more important. Changing tillage practices to no-till will reduce the spread of the weed by confining populations to ant granaries. Minimising the use of contaminated seed for sowing is common sense, particularly sourcing canola seed from non-fumitory fields. Other appropriate agronomic practices include growing competitive crops and cultivars to reduce fumitory seed production.

Table W13.3 Tactics to consider when developing an integrated plan to manage fumitory (*Fumaria* spp.).

Fumitory (*Fumaria* spp)		Most likely % control (range)	Comments on use
Tactic 1.5	Delayed sowing	95 (90–99)	Combine with autumn tickle. Follow with non-selective herbicides (Tactic 2.2a) targeting small weeds.
Tactic 2.2d	Post-emergent herbicides	90 (80–99)	Wider range for use in wheat and barley.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	90 (50–95)	Use robust rates. Late germinations are not controlled.
Tactic 2.2c	Pre-emergent herbicides	85 (50–95)	Trifluralin can give good control except in *F. bastardii* and *F. muralis*. Look out for resistant populations.
Tactic 1.4	Autumn tickle	85 (10–90)	Use at early break. Cultivation greatly stimulates germination. Combine with delayed sowing.
Agronomy 1	Crop choice and sequence	85 (0–99)	Avoid crops with no post-emergent herbicide options. Minimise canola in the rotation.
Agronomy 3	Herbicide tolerant crops	80 (0–95)	Clearfield™ for *F. densiflora* only and TT canola. Roundup Ready® canola can be effective.
Agronomy 2	Improving crop competition	65 (10–80)	Establish vigorous crops on the narrowest row spacing practical. No-till reduces seed spread from ant granaries.
Tactic 5.1a	Sow weed-free seed	100	Only sow seed grown in fumitory-free areas, especially in canola and small seeded pastures.

Contributors

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Weed 14 **Liverseed grass (*Urochloa panicoides*)**

Common names

Liverseed grass, urochloa, urochloa grass.

Distinguishing characteristics

Liverseed grass (*Urochloa panicoides*) is a stoloniferous (runner-forming), summer-growing annual grass. The leaves are broad (to 15 mm) with wavy margins, loosely to densely hairy on both sides. The leaf blade is rolled in bud, and the ligule is a rim of short hairs. Seedling leaves, 20–100 mm long, are pale green and very broad with numerous hairs on margins and sheaths.

Adult leaves are similar; however, the leaf margins are slightly wavy or crinkled. As plants mature, the stems (tillers) become prostrate on fallow ground or more erect in crops. Prostrate stems can form roots at the nodes. Mature plants can sometimes form a mat-like ground cover in dense populations.

The seed-head is approximately 100 mm long and has two to seven spikes, 10–70 mm long, that branch off the main stem. Seeds are produced in two rows along one side of each spike.

Figure W14.1 Liverseed grass seed-head.
Photo: Andrew Storrie

Other weeds that can be confused with liverseed grass

Young liverseed grass seedlings can be confused with panic grass (*Panicum* spp.) and sweet summer grass (*Moorochloa eruciformis*). Most *Panicum* species have slightly hairy and, once the plant matures, generally much longer leaves (150–500 mm) than those of liverseed grass (100 mm). Adult plants usually have an erect habit in fallows, and their seed-heads are described as open panicle, at least 200 mm long. Sweet summer grass leaves are a much darker green than liverseed grass leaves and have reddish–purple tinges particularly around the leaf margin and sheath. Refer to *Weed 21 Sweet summer grass (Moorochloa eruciformis)* for a more detailed description.

Factors that make liverseed grass a major weed

Liverseed grass emerges in one major flush.

This flush occurs in response to sufficient rain (over 20 mm). It will continue to emerge after this, but this represents a small proportion of the overall seedbank. Controlling the major flush of weeds may result in significant seedbank declines. This cannot be done without considering the seed production potential of the later season plants as substantial seed production per plant may easily refill the seedbank.

Liverseed grass produces a large number of seeds.

A large plant can produce up to 3,000 seeds under favourable conditions.

Liverseed grass can develop resistance to herbicides.

Repeated glyphosate use puts liverseed grass at high risk of developing resistance. Two liverseed grass populations in northern NSW were reported to have moderate levels of glyphosate resistance in 2008. These populations developed resistance due to continuous winter cropping and over reliance on glyphosate as the summer fallow herbicide. As of 2018, four glyphosate-resistant populations have been confirmed in Australia. These infestations have now been managed well with strategic cultivations and the use of pre-emergence herbicides. Alternative post-emergence herbicides have been substituted for glyphosate. Several populations in southern Queensland have been confirmed as resistant to Group C.

Liverseed grass is a host for cereal diseases.

Liverseed grass serves as an alternate host for cereal diseases, including *barley yellow dwarf virus* in south-eastern Queensland.

Environments where liverseed grass dominates

Liverseed grass was introduced as a pasture grass and is naturalised in tropical and subtropical Australia. It is now a problem in NSW and southern and central Queensland. Liverseed grass appears to prefer lighter textured surface soils such as brigalow–belah country (brown to grey vertosols). In its native range in Africa it grows on sandy soil in damp areas.

Seasonal conditions that favour liverseed grass

Wet summers favour liverseed grass. The seedbank often increases dramatically during a forage sorghum–millet phase.

Poor control by herbicide is common when daytime temperatures exceed 35 °C. It is a difficult weed to control in summer crops and fallow. It quickly shows stress under low moisture conditions, often because there are only a few roots supporting a tillered plant. Herbicide efficacy declines as plants mature or are under stressed conditions. It is important to check for good root development accessing good soil moisture levels before applying herbicide.

Conditions that favour liverseed grass germination and establishment

Liverseed grass seed is able to emerge from as deep as 100 mm. However, emergence is maximised when seed is buried at a depth of 50 mm, with warm damp soil favouring emergence. After rain liverseed grass tends to emerge in one flush, compared with the prolonged emergence found with barnyard grass. Most seedlings found in cropping areas germinate from the soil surface or from shallow depths.

Figure W14.2 Liverseed grass seedling.
Photo: Andrew Storrie

Seed survival in the soil

After 12 months' burial in southern Queensland, 24% of the original seeds sown on the surface remained viable, and 10% and 67% remained viable when buried at 50 mm and 100 mm respectively. A very small percentage (less than 0.1%) of liverseed grass seed persisted after four years when positioned in the top soil (0– 2 cm deep) if the soil remained undisturbed. Five per cent remains in undisturbed soil at a depth of 10 cm. Soil disturbance is likely to increase the rate of seedbank decline as no seed persisted after four years between zero and 8 cm deep with regular soil disturbance.

Table W 14.1 Tactics to consider when developing an integrated plan to manage liverseed grass (*Urochloa panicoides*).

Liverseed grass (*Urochloa panicoides*)		Most likely % control (range)	Comments on use
Agronomy 2	Improve crop competition	40 (20–60)	Summer crops only have limited effect on liverseed grass as it grows under low light conditions. Summer crops (e.g. sorghum, maize, sunflowers) grown on wide rows are poorly competitive.
Tactic 1.5	Delayed sowing	95 (30–99)	Followed by knockdown non-selective herbicides (*Tactic 2.2a*). Moisture stress often reduces level of control. Spray when plants are at 3-leaf stage. Adjuvants can improve level of control.
Tactic 2.1	Fallow and pre-sowing cultivation		Combine with delayed sowing (*Tactic 1.5*) to stimulate germination of grass and double-knock (*Tactic 2.2b*).
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	90 (70–99)	Optimum application growth stage is between
Tactic 2.2b	Double knockdown or 'double-knock'	98 (95–100)	Knocks of glyphosate followed by paraquat have resulted in nearly 100%control on early tillering glyphosate-susceptible plants. If treating glyphosate-resistant plants consider using a bipyridyl as first knock followed by cultivation.
Tactic 2.2c	Pre-emergent herbicides	95 (85–100)	Must be applied in November to December. Requires moderate rainfall to become effective. Group B and K herbicides more effective than Group C or D.
Tactic 2.2d	Selective post-emergent herbicides	90 (75–95)	Must be applied to small actively-growing weeds. Poor results generally occur when spraying large or moisture-stressed plants.
Tactic 2.3	Weed control in wide-row cropping	85 (75–95)	Suited to many summer crops such as sorghum, maize and sunflowers. Some survival of liverseed grass is inevitable as plants miss treatment in intra-row area.

Contributors

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Weed 15 **Indian hedge mustard (*Sisymbrium orientale*)**

Common names

Indian hedge mustard, wild mustard, mustard, hedge mustard, oriental hedge mustard, oriental mustard, eastern rocket.

Figure W 15.1 Mature Indian hedge mustard plant. *Photo*: Andrew Storrie

Distinguishing characteristics

Indian hedge mustard (*Sisymbrium orientale*) is an erect annual. It is branched and grows up to 1 m tall. Young plants form a rosette with deeply lobed, pointed leaves up to 110 mm long. Upper leaves are alternate and spear-shaped. Flowers are pale yellow and 6–10 mm long. The pod is 60–100 mm long, two-celled, slender and cylindrical, and opens when ripe.

Other weeds that can be confused with Indian hedge mustard

Indian hedge mustard may be confused with hedge mustard (*Sisymbrium officinale*); however, the latter has pods only 10–20 mm long which are pressed to the stem, and smaller flowers (petals 2–4 mm long).

It can also be confused with wild radish (*Raphanus raphanistrum*), buchan weed (*Hirschfeldia incana*), sand rocket (*Diplotaxis tenuifolia*) and muskweed (*Myagrum perfoliatum*).

Factors that make Indian hedge mustard a major weed

Indian hedge mustard produces very large numbers of seeds.

Indian hedge mustard sheds up to 30,000 seeds/m^2 in early summer.

Indian hedge mustard causes problems at harvest.

Coarse fibrous stems cause problems by wrapping around header parts.

There are populations resistant to Group B, C, F and I herbicides.

The first cases of Group B resistance were confirmed in the early 1990s in North Star, northern NSW, and Wallaroo, South Australia. Subsequent Group B resistant populations were discovered in the district of Goondiwindi in southern Queensland. These collections were growing in continuously cropped wheat paddocks where chlorsulfuron had been applied for between six and 10 years. A further six collections in surrounding districts of Goondiwindi were found to be resistant to chlorsulfuron in later testing.

Random weed surveys across western South Australia, on the Eyre Peninsula in 2009 and western Victoria in 2010 revealed that 52% and 35% of Indian hedge mustard populations were resistant to chlorsulfuron respectively, and that 57% and 38% of the samples were also resistant to metosulam. Screening with 2,4 D revealed no resistant populations from either district.

The first case of 2,4 D resistance in Indian hedge mustard was identified in 2007 from Port Broughton in the South Australian mid-north. Subsequent directed surveys in this region identified 12 Indian hedge mustard populations occurring on seven farms with resistance to both 2,4-D and Group B herbicides. Resistance to Group B and I herbicides is of particular concern as it limits weed control options. The first case of Group C and F herbicide resistance was observed in 2011 from canola and a pea field in Victoria.

The small seeds of Indian hedge mustard can cause grain contamination.

It is one of the species of weed seed contaminants which make up the ‘small foreign seeds’ fraction of the grain delivery standards. There is a limit in wheat of 0.6% or 1.2% by weight depending on wheat grade.

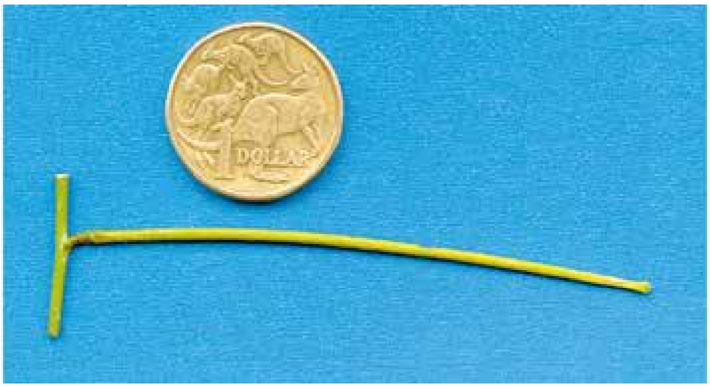

Figure W15.2 Close-up of Indian hedge mustard seed-head and individual pod.
Photo: Andrew Storrie

Environments where Indian hedge mustard dominates

Indian hedge mustard is a widespread introduced weed of the cereal growing regions of Western Australia, western and northern NSW and southern Queensland. It is a weed of crops, pastures, rangelands, open woodlands, roadsides, disturbed sites and waste areas. It is sometimes found in grazed woodlands and is spreading along roadsides and disturbed areas in the arid zone.

Soil type does not greatly influence the presence or absence of Indian hedge mustard.

Seasonal conditions that favour Indian hedge mustard

Because its seeds have a relatively short innate dormancy and germinate more readily in seasons with good rainfall, Indian hedge mustard germinates during autumn to winter. In these seasons effective control can be achieved by pre-sowing knockdown herbicides. However, in seasons when opening rains are late, serious infestations of Indian hedge mustard can develop in sown crops as it continues to emerge after post-emergent herbicides have been applied.

Conditions that favour Indian hedge mustard germination and establishment

An initial germination flush follows cultivation at the start of the winter growing season. Subsequent germinations of Indian hedge mustard occur sporadically after rain at any time over a period of several years. Germination in autumn is stimulated by high summer temperatures.

Figure W15.3 Indian hedge mustard seedling.
Photo: Wilson et al., 1995

Seed survival in the soil

A two-year study (Chauhan et al. 2016) showed that surface germination resulted in the highest emergence (70%), with emergence decreasing with increasing burial depth. No seedlings emerged from 10 mm. Little is known about the long term survival of Indian hedge mustard seed however, persistence in soil is usually from one to several years.

Table W15.1 Tactics to consider when developing an integrated plan to manage Indian hedge mustard (*Sisymbrium orientale*).

Indian hedge mustard (*Sisymbrium orientale*)		Most likely % control (range)	Comments on use
Tactic 1.5	Delayed sowing	95 (90–99)	Follow by knockdown with non-selective herbicides (*Tactic 2.2a*) targeting small weeds.
Tactic 3.1a	Spray-topping with selective herbicides	95 (85–99)	Be aware of resistance status. The control range assumes no Group B resistance.
Agronomy 1	Crop choice and sequence	85 (0-99)	Avoid crops with no post-emergent herbicide options.
Tactic 3.1c	Wiper technology	80 (60–95)	Useful tactic in lentils.
Tactic 2.2d	Selective post-emergent herbicides	80 (60–90)	Spray young actively growing plants and repeat if necessary. Be aware of resistance status.
Agronomy 3	Herbicide tolerant crops	80 (0-95)	Very useful for non-cereal portions of the rotation.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	75 (50–80)	Use high rates to control biennial plants. Tank-mixing with phenoxy herbicides improves control in absence of Group I resistance. Late germinations are not controlled.
Tactic 2.2c	Pre-emergent herbicides	75 (50–80)	Dry conditions post-sowing reduces herbicide efficacy.
Tactic 3.5	Grazing – actively managing weeds in pastures	70 (50–80)	Rotationally graze. Use spray-grazing with herbicide suited to pasture species present.
Tactic 4.1	Weed seed control at harvest	50 (10–70)	Useful on early harvested crops.
Tactic 1.4	Autumn tickle	25 (10–50)	Use with early breaks to the season and combine with delayed sowing.

Contributors

Di Holding, John Moore and Peter Boutsalis

Weed 16 **Muskweed (*Myagrum perfoliatum*)**

Common names

Muskweed, 'Round Island' spinach (localised to the southern Liverpool plains, NSW), mitre cress (in the United Kingdom).

Distinguishing characteristics

Muskweed (*Myagrum perfoliatum*) cotyledons are broad and club-shaped, making them different from any other brassica species. Leaves are a waxy blue-green, hairless and without petioles. They also have distinctive white veins. Rosettes grow to 450 mm in diameter and are very flat to the ground, somewhat like capeweed and unlike other brassica weeds such as wild radish. The flowers are small and pale yellow. The pods are hard, wedge-shaped, 5– 7 mm long and 4– 5 mm wide, and they stick out from the stem.

Figure W16.1 Mature muskweed plant.
Photo: Andrew Storrie

Other weeds that can be confused with muskweed

Muskweed can be confused with turnip weed (*Rapistrum rugosum*) when in pod and at the end of flowering, and common sowthistle (*Sonchus oleraceus*) when at the seedling stage.

It can also be confused with prickly lettuce (*Lactuca serriola*) and willow lettuce (*Lactuca saligna*) when at the seedling stage and when elongating.

Factors that make muskweed a major weed

Muskweed has staggered germination.

It can emerge from April to October, which makes timing of control difficult.

Muskweed produces a large number of seeds.

An average plant is thought to produce about 1,000 seeds, with seedbanks of up to 3,000 seeds/m^2.

Seed is thought to survive at least five to 10 years.

Muskweed is competitive.

It is particularly damaging to pulse yields, with reports of up to 50% yield loss in chickpeas and lentils. It can also completely smother patches of cereal and canola.

Muskweed creates a problem at harvest.

It slows harvest due to the bulk of material and it will 'ball' in front of the comb. Although it rarely reduces canola yield most of the pods will exit with the chaff and straw in a properly adjusted harvester.

Herbicide control options are limited.

Only a few herbicides are registered for the selective control of muskweed in cereals and none are registered for pulses. The poor competitive ability of pulses compounds the problem. There are no herbicide control options in conventional canola.

Muskweed is a serious grain contaminant.

Muskweed pods are the same size as wheat and barley grains. When muskweed is present in canola and pulse grain, additional seed cleaning is often required before delivery. Infestation can reduce grain quality by more than 20%.

Figure W16.2 Close-up of muskweed flowers and pods.
Photo: Andrew Storrie

Muskweed is dispersed by harvesting equipment and in grain and hay.

Plants also tumble across paddocks, dispersing seed.

Environments where muskweed dominates

Muskweed is a major weed of chickpeas, lentils, lupins, field peas, faba beans and canola in western Victoria and South Australia. It is also a weed of winter cereals and lucerne.

Reduced use of long fallow and the trend toward continuous cropping with the inclusion of broadleaf crops have led to an increase in muskweed levels. The high intensity of pulse cropping in the Wimmera district of Victoria and parts of South Australia has been the major reason for its proliferation.

Muskweed prefers alkaline clay-loam and clay soils.

Seasonal conditions that favour muskweed

Muskweed will germinate and establish from April to October with soil temperatures between 4 °C and 29 °C. Most plants emerge from the top 50 mm of soil.

It can start flowering from late July through to mid-October, with seed production from mid-August to early December.

Conditions that favour muskweed germination and establishment

Muskweed germination occurs as the seed pod deteriorates. Warm wet summers will speed deterioration of the pod increasing the germination percentage of the seedbank the following autumn.

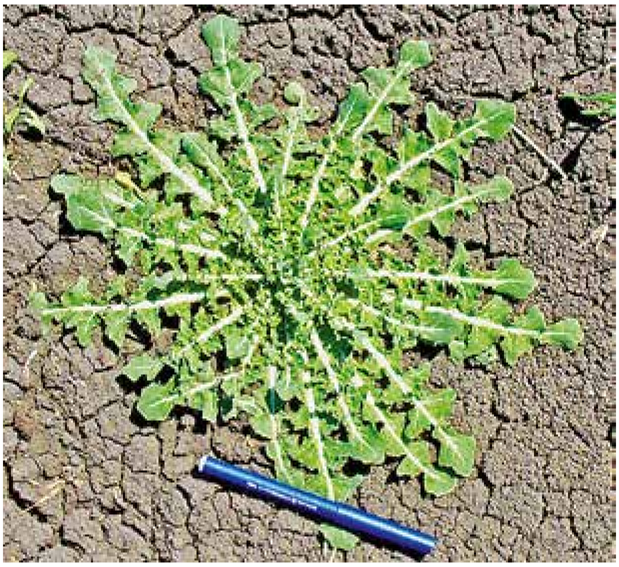

Figure W16.3 Muskweed seedling.
Photo: Andrew Storrie

Seed survival in the soil

Little is known about muskweed seed survival in the soil but it is thought to survive at least five to 10 years. A study by Honarmand et al. (2016) of muskweed in Iran found that although not influenced by light, germination is limited by burial depth, with greatest germination on the surface (91.3%) declining at increasing depth with no emergence at 6 cm burial. It is likely that muskweed would show similar seedbank longevity to that of wild radish.

Table W16.1 Tactics to consider when developing an integrated plan to manage muskweed (*Myagrum perfoliatum*).

Muskweed (*Myagrum perfoliatum*)		Most likely % control (range)	Comments on use
Tactic 5.1a	Sow weed-free seed	100	Muskweed range is still expanding rapidly and transport of weeds in crop seed is the likely source of introduction in clean areas.
Tactic 5.1c	Clean farm machinery and vehicles	99	Contaminated machinery is a likely source of weed seed introduction in clean areas.
Agronomy 3	Herbicide-tolerant crops	90 (80–95)	Imidazolinones, glyphosate and triazines provide good control in imidazolinone-, glyphosate- and triazine-resistant crops respectively.
Tactic 2.2d	Selective post-emergent herbicides	90 (75–95)	Hormone and sulfonylurea herbicides provide good control in cereals. Few options for other pulses or conventional canola.
Tactic 2.2c	Pre-emergent herbicides	90 (50–99)	Chlorsulfuron is effective in competitive wheat crops. Few options in other cereals, pulses and canola.
Agronomy 1	Crop choice and sequence	90 (0–95)	Easier to control in competitive cereal crops. Controlled effectively in winter fallow and in long pasture phases.
Tactic 3.1c	Wiper technology	65 (20–99)	Effective in short pulse crops, e.g. lentils. Time treatment according to weed growth stage.
Tactic 3.1b	Crop-topping with non-selective herbicide	60 (40–90)	Must use a short-season crop. Picks up later germinations and reduces viability of partly filled weed seeds.

Contributors

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Weed 17 **Noogoora burr (*Xanthium* spp.)**

Common names

Noogoora burr is a widely used name for the Noogoora burr complex (*Xanthium strumarium*), encompassing a number of species and hybrids within the *Xanthium* genus. The Noogoora burr complex includes: Noogoora burr (*Xanthuim occidentale*), Californian burr (*Xanthium californicum*), Hunter burr / Italian burr (*Xanthium italicum*) and South American burr (*Xanthium cavanillesii*).

Other common names include: Beach cockleburr, Burrweed, Clotburr, Cockleburr, European cockleburr, Large cockleburr, Italian cockleburr, Rough cockleburr, Sheep's burr.

Figure W 17.1 Noogoora burr plant.
Photo: Bruce Wilson

Distinguishing characteristics

Noogoora burr is an erect annual species up to 4 m high, but usually to a height of 2 m, with triangular alternate leaves with three to five lobes between 5 cm and 15 cm long and wide. Leaves are rough to touch with prominent veins, similar to a grapevine leaf.

Flowers are greenish-yellow and inconspicuous, occurring on lower parts (female) and the ends of branches (male). Female flowers develop into green burrs that turn hard and brown when ripe. Burrs are oval shaped, between 10 mm and 24 mm long, covered in small hooked spines and terminal spines at the tip. Each burr contains two small (4–8 mm) brown seeds, one larger than the other. Noogoora burr has a deep tap root (800 mm) and extensive lateral roots.

Other weeds that can be confused with Noogoora burr

Californian burr (*X. orientale*), Hunter burr / Italian cockleburr (*X. italicum*), and South American burr (*X. cavanillesii*). These species are often, collectively referred to as Noogoora burr or the Noogoora burr complex. Each species can be identified by their burrs (*Table W17.1*)).

Factors that make Noogoora burr a major weed

Noogoora burr is a highly competitive weed.

Noogoora burr is a major weed of irrigated soybean, maize, sunflowers and cotton. By competing for nutrients, moisture and light, Noogoora burr reduces crop and pasture productivity

Noogoora burr has high persistence ability.

Noogoora burr produces large number of seeds, up to 22,000, some of which are highly dormant and can persist up to six years.

Noogoora burr can cause animal health problems.

Noogoora burr seedlings are poisonous to stock, particularly cattle and pigs. Burrs can become entangled in sheep's wool, downgrading value and potentially causing injury.

Table W 17.1 Noogoora burr species burr characteristics for identification.

Species	Burr length (mm)	Hooked spines		Terminal spines	
		Quantity	Length (mm)	Shape	Length (mm)
Noogoora burr	16–22	Numerous	1–2	Straight, not hooked at tips	4–5
Californian burr	18–24	Fewer	2–4	Hooked	4–6
Hunter/Italian burr	25–30	Numerous	3–4	Diverging, hooked at tips	5–7
South American burr	25–30	Numerous	4–5	Hooked diverging, not hooked at tips	6–8

Figure W17.2 Burrs of Noogoora burr.
Photo: Bruce Wilson

Noogoora burr are easily spread as contaminants of grain, and machinery.

The hooked spines assist in the movement of seed, spread by livestock and machinery.

Environments where Noogoora burr dominate

Noogoora burr takes its name from Noogoora Station, Queensland, where it was first noticed in Australia in the 1860s. The plant has since spread over much of Queensland and NSW and occurs in patches in South Australia, Western Australia, Victoria, and the Northern Territory. Within Australia Noogoora burr currently infests over two million hectares.

Seasonal conditions that favour Noogoora burr

Rain or irrigation can trigger several Noogoora burr germination flushes from late winter to summer, although germination can occur year round with favourable conditions.

Conditions that favour Noogoora burr germination and establishment

Noogoora burr emergence is reliant on adequate spring or summer rains, with subsequent growth dependent on sufficient soil moisture. Shallow seed burial can assist germination as it prevents the plant drying out after rainfall. Heavy summer rain or flooding can assist in burying seed, resulting in an abundance of Noogoora burr after these events.

Seed survival in the soil

The two seeds from each burr have different dormancy patterns. The larger seed has a short dormancy period, germinating within the same year it is produced. The other smaller seed usually germinates in the following year or later. Seed can remain viable for up to ten years but is unlikely to survive for more than a couple of years with deep burial.

Table W17.2 Tactics to consider when developing an integrated plan to manage Noogoora burr (*Xanthium* spp.).

Noogoora burr (*Xanthium* spp.)		Most likely % control (range)	Comments on use
Agronomy 2	Herbicide tolerant crops	90 (80–99)	Good to excellent control achieved with glyphosate-resistant and triazine-tolerant crops.
Agronomy 3	Rotation with herbicides	90 (80–99)	Winter and summer cereal: 2,4-D Amine 500. Cotton: Fluometuron 500. Fields/fallow: Good to excellent control achieved with glyphosate. Fallow crop lands, headlands and drains: Ametryn. Pastures (grass): MCPA 500 (Amine). Spraying with 2,4-D or MCPA before flowering will give favourable results. As plants mature, higher rates are necessary.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (70–90)	Good control can be achieved.
Tactic 2.2c	Pre-emergent herbicides	80 (70–90)	Works best when applied at early stage.
Tactic 2.5	Slashing and pulling	80 (80-95)	Cultivation or mechanical pulling is effective if performed before flowering or burr formation. Continuous mechanical slashing is effective to reduced seeds banks.
Tactic 4.1	Weed seed control at harvest	70 (20–80)	Works well on early harvested crops before weed drop its' seeds.
Tactic 5.1c	Prevention and biosecurity	90 (80-90)	Practice good biosecurity, special care should be taken when purchasing fodder; reduce spread to clean properties by monitoring movement of stock.
Agronomy 1	Improve crop competition	Variable	Noogoora burr is a very competitive weed however, competitive crops at optimum sowing rates are very effective.
Tactic 2.6	Biological control	Variable	Some level of control has been achieved with biological control agents including stem-boring and stem-galling insects, and a rust fungus (*Puccinia xanthii*). This form of control has been more effective in tropical areas where temperatures and moisture conditions are favourable.

Contributors

Md Asaduzzaman and Aaron Preston

Weed 18 **Paradoxa grass (*Phalaris paradoxa*)**

Common names

Paradoxa grass, annual canary grass, bristle-spiked canary grass, paradoxical canary grass, awned canary grass.

Distinguishing characteristics

Paradoxa grass (*Phalaris paradoxa*) is an invasive, tufted, annual grass capable of producing a large number of tillers and it generally thrives in moist conditions growing to a height of 1.2 m. Paradoxa grass has distinct reddish-purple colouring at the base of the stems and also around the nodes.

The leaf blade is flat, hairless and approximately 200 mm long. As with many grass species, identification during the vegetative stage relies upon correct recognition of the ligule and auricle characters. The ligule is translucent and thinly membranous, and there are no auricles. The seed-head is readily distinguishable (*Figure W18.2*) although there is variation in the spikelet cluster.

Figure W18.1 Mature paradoxa grass plant.
Photo: Wilson et al., 1995

Other weeds that can be confused with paradoxa grass

Paradoxa grass can be confused with lesser canary grass (*Phalaris minor*), which has a seed-head that is more bristly and a unique spikelet arrangement. The seedlings are distinguishable from wild oats (*Avena* spp.), wheat and barley as they are more slender and have a red base.

Figure W18.2 Inflorescence of paradoxa grass.
Photo: Andrew Storrie

Factors that make paradoxa grass a major weed

Originating in the Mediterranean area, paradoxa grass has spread throughout 26 countries worldwide. It is present across the wheat growing regions of Australia.

The success of paradoxa grass is attributable to its competitiveness and ability to produce large numbers of seeds.

Seed production ranges from 3,500 to 21,500 seeds per plant. In severe infestations in favourable years up to 120,000 seeds/m^2 have been recorded. While paradoxa grass thrives in moist conditions, seedlings will still establish with marginal moisture and plants will set seed. Yield losses due to paradoxa grass infestations in winter cereals have been known to exceed 40%.

Paradoxa grass can cause staggers in sheep.

Paradoxa grass is palatable to livestock and is often grazed by sheep as part of wheat–sheep rotations. As with other *Phalaris* species there have been reports of staggers in sheep that have grazed heavily on paradoxa grass.

Paradoxa seed is a contaminant of winter cereals and may lead to reduced returns.

It may also be a contaminant in seed of Toowoomba canary grass (*Phalaris aquatica*), also known as 'grazing phalaris', which is a major pasture species in Australia.

Seed heads of paradoxa grass tend to shatter when disturbed and drop seed in windy conditions.

The spikelets at the top of the panicle are quite feathery but are not usually carried by wind. They will float and may be transported by water should they fall into creeks or streams. Because it can shatter when disturbed, paradoxa grass seed is easily caught in harvesting equipment, and thorough decontamination is required to prevent seed dispersal to neighbouring fields or farms.

Herbicide resistance is known in paradoxa grass.

Some paradoxa grass populations are known to be resistant to the Group A herbicides (ACCase inhibitors) and the Group B herbicides (ALS inhibitors) in Australia. Paradoxa grass is also resistant to atrazine (Group C) along roadsides and rail lines in Israel. Hence, these herbicides should be used as part of an integrated weed management strategy.

Paradoxa grass thrives in a poorly competitive crop.

In contrast, seed production can be greatly reduced by increasing the sowing densities of wheat and barley.

Environments where paradoxa grass dominate

Paradoxa grass is a minor to moderate weed in Victoria, South Australia and Western Australia but has become particularly troublesome in northern NSW and southern Queensland.

It is a problem weed of winter cereals such as wheat and barley, and is also often seen in winter rotation crops such as faba beans and chickpeas. A common weed in fallows, it is easily controlled with non-selective herbicides and cultivation.

Although found on a variety of soil types, paradoxa grass favours the heavier black or grey clays that have greater water holding capacity.

Paradoxa grass is a weed in no-till, minimum till and conventional cultivation systems. Seed germination is stimulated by cultivation as it becomes sensitive to light after a period of burial in moist conditions. Control can therefore be enhanced by using an autumn tickle to stimulate emergence of paradoxa grass seedlings, allowing the use of knockdown herbicides before planting winter cereals.

Figure W18.3 Paradoxa grass seedlings.
Photo: Andrew Storrie

Seasonal conditions that favour paradoxa grass

Paradoxa seedlings first emerge with winter cereals beginning in May, while the majority of seedlings emerge in June and July. Emergence timing can be altered through a light cultivation (autumn tickle) in March and April so that the majority of seedlings emerge in May and June, thus allowing control with a broad spectrum knockdown herbicide before planting. Seed set generally occurs from late October through November. Paradoxa grass is sensitive to photoperiod with floral initiation occurring with increasing day length. As the day length increases, late emerging seedlings will become reproductive shortly after emergence. If these seedlings are not controlled, late emerging plants will contribute to the soil seedbank and create further problems in the following season.

Seed survival in the soil

Paradoxa grass seed is generally short-lived, with 95–99% either emerging or becoming non-viable within two years. Seed is initially dormant when shed from the parent plant, preventing germination in the warmer months; however, these mechanisms break down rapidly with the majority of seeds germinating within 12 months. Typically, emergence is from seed buried 2.5–5 cm below the soil surface; however, seedlings can emerge from seed buried as deep as 10 cm. Seed buried from 5 cm to 15 cm generally remains viable for longer periods, so growers using inversion tillage techniques may inadvertently prolong the life of paradoxa seed in the seedbank.

Table W18.1 Tactics to consider when developing an integrated plan to manage paradoxa grass (*Phalaris paradoxa*).

Paradoxa grass (*Phalaris paradoxa*)		Most likely % control (range)	Comments on use
Agronomy 2	Improve crop competition	50 (25–95)	Barley is much more competitive than wheat in suppressing seed production.
Tactic 1.4	Autumn tickle	40 (10–60)	Use with an early break. Combine with delayed sowing. Follow with non-selective knockdown herbicide.
Tactic 1.5	Delayed sowing	85 (50–95)	Follow by knockdown non-selective herbicide (*Tactic 2.2a*). Effectiveness depends on seasonal conditions. Late germinations often occur. Use in conjunction with an autumn tickle (*Tactic 1.4*) to promote seed germination.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	Up to 90%	Young seedlings offer a small target area. Sufficient number of droplets/cm^2 is required for high levels of control especially with dense infestations.
Tactic 2.2c	Pre-emergent herbicides	70 (60–90)	Dry conditions post-sowing will reduce herbicide efficacy.
Tactic 2.2d	Selective post-emergent herbicides	80 (70–95)	Spray young actively growing plants and repeat if necessary. Target small weeds.
Tactic 3.1a	Spray-topping with selective herbicides	80 (70–95)	Good potential in broadleaf crops.
Tactic 3.1b	Crop-topping with non-selective herbicides	75 (60–90)	Useful in early-sown short season pulse crops.
Tactic 3.1c	Wiper technology	50 (40–70)	Good in short broadleaf crops such as lentils.
Tactic 3.3	Silage and hay – crops and pastures	50 (40–70)	Spray with a knockdown herbicide or graze regrowth.
Tactic 3.5	Grazing – actively managing weeds in pastures	50 (40–80)	Graze heavily and continuously from winter until senescence.

Contributor

Ian Taylor

Weed 19 **Paterson's curse (*Echium plantagineum*)**

Common names

Paterson's curse, Riverina bluebell, Salvation Jane, Blue echium, Blueweed, Lady Campbell weed, Plantain-leaf viper's bugloss, Purple bugloss, Purple echium, Purple vipers bugloss.

Distinguishing characteristics

Occurring in all Australian states and territories, Paterson's curse is an erect annual or biannual herb growing between 60 cm to 150 cm tall. Leaves are green and covered in short hairs (1.5 mm). Leaves are egg-shaped, alternate, up to 30 cm long and 8 cm wide, forming a basal rosette with distinctive branched veins. Stems are branched and with smaller alternate leaves (30–90 mm). Flowers are trumpet like shape, 15–30 mm long and bright purple, though sometimes blue, white or pink, with two protruding stamens. Paterson's curse forms up to four brown seeds (2–3 mm long) from each flower.

Other weeds that can be confused with Paterson's curse

Paterson's curse (*Echium plantagineum*) is very similar to viper's bugloss (*Echium vulgare*) and relatively similar to Italian bugloss (*Echium italicum*). These species have the following differences:

1. Viper's bugloss (*E. vulgare*)
- Leaves have a warty appearance and are narrower than Paterson's cures with non-prominent leaf veins.
- Is biennial or perennial, Paterson's curse is usually annual.
- Rosette leaves are stalkless and spear-shaped.
- Has a later and longer flowering period than Paterson's Curse.
- Has four protruding stamens

2. Italian bugloss (*E. italicum*)
- Flowers are pinkish white.
- Hairier than Paterson's curse or Vipers bugloss.
- Has five protruding stamens.

Figure W 19.1 Paterson's curse seedling.
Photo: Tony Cook

Factors that make Paterson's curse a major weed

Paterson's curse is highly competitive to crops.

Paterson's curse is a significant pasture weed and is competitive in crops. Depending on the intensity of infestation, yield losses can range from 30% to 80% for a clover crop.

Figure W 19.2 Paterson's curse plants.
Photo: Aaron Preston

Paterson's curse is a prolific seeder.

Seed production ranges from 5,000 to 10,000 seeds per plant per year. Seed dormancy may persist for up to five years and with seeds accumulating in the soil, creating large seedbanks. Cases of seedbanks with 30,000 seed/m^2 have been reported.

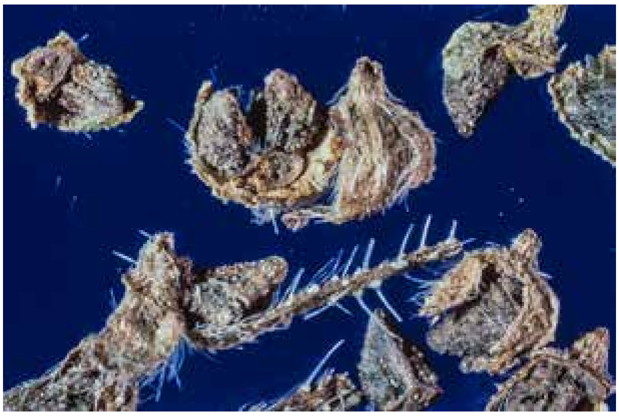

Figure W19.3 Paterson's curse seed pods.
Photo: Peter Abell and Geoff Sainty

Paterson's curse has high persistence ability.

Paterson's curse is tolerant to a range of climates, drought and soil condition. It is usually a winter annual or biennial herb, but can be found at all growth stages all year round. Even under grazing conditions, plants can still produce 15–250 seeds per plant.

Paterson's curse is a major damaging weed to the Australian meat and wool industries.

Paterson's curse contains toxins (pyrrolizidine alkaloids) that that can cause chronic cumulative liver damage. Prolonged grazing can lead to deaths of animals, especially when substantial amounts are consumed. Horses and pigs are highly susceptible to poisoning by Paterson's curse, cattle are moderately susceptible. Sheep are also susceptible and fleece contamination is an additional concern.

Paterson's curse is a noxious weed.

It can contaminate hay and grain and can also affect human health and can result in allergies from pollen and skin irritation from the rough hairy texture of the leaves and stems.

Paterson's curse can easily develop resistance to Group B herbicide.

Group B herbicide resistance has been detected in Australian populations of Paterson's curse.

Figure W19.4 The hairy stem and flower of Paterson's curse.
Photo: Geoff Sainty

Environments where Paterson's curse dominate

Paterson's curse can be found in all Australian states and territories but thrives in the pastoral winter rainfall regions of NSW, Victoria, South Australia and in the south-west region of Western Australia.

Conditions that favour Paterson's curse germination and establishment

Paterson's curse generally germinates in autumn and winter and flowers mainly in spring and early summer. In cooler conditions it may persist through the summer and regrow in the following season.

Seed survival in the soil

Seed usually germinates within two years from the soil surface but can persist longer if buried, up to 11 years in soil buried at 15 cm. Shallow cultivation can encourage germination. A study by Grigulis et al. (2001) of Paterson's Curse from the Australian Capital Territory found that 60–70% of seed remained viable after one year buried at 5 cm, however if buried deeply (7 cm) it is unable to germinate.

Table W19.1 Tactics to consider when developing an integrated plan to manage Paterson's curse (*Echium plantagineum*).

Paterson's curse (*Echium plantagineum*)		Most likely % control (range)	Comments on use
Agronomy 3	Herbicide tolerant crops	90 (80–99)	Good to excellent control achieved with glyphosate-resistant and triazine-tolerant crops.
Tactic 5.1b	Manage weeds in non-crop areas	90 (80–90)	Glyphosate is used where killing surrounding plants is not a concern, e.g. in-fallows or small areas. Continual use of the sulfonylurea type herbicides such as chlorsulfuron and metsulfuron has resulted in Paterson's curse developing resistance in several areas around the metropolitan area. Rotation of herbicide groups will help to avoid this problem.
Tactic 3.1a	Spray topping with selective herbicides	80 (70–95)	This technique involves using a sub lethal dose of one of the phenoxy herbicides such as 2,4-D or MCPA amine. Paterson's curse is treated 6–8 weeks after germination. Clover should have at least eight leaves if the highest rate of 2,4-D amine is used.
Agronomy 4	Early sowing	80 (70–90)	Early completive crop variety (e.g. canola) sowing is an effective tool.
Tactic 1.3	Inversion ploughing	70	Cultivation can successfully remove Paterson's curse. Cultivate in spring before summer cropping, followed by an autumn weed control cultivation before sowing crops or pastures.
Agronomy 1	Crop choice and sequence	Variable	Cropping for two or three years followed by pasture reestablishment, which includes spray-grazing and spot spraying, can contribute to successful control of Paterson's curse. Maintaining a clean summer fallow is the key to success.
Tactic 2.6	Biological control	Variable	The leaf-mining moth (*Dialectica scalariella*), crown weevil (*Mogulones larvatus*), the root weevil (*Mogulones geographicus*), the stem boring weevil (*Phytoecia coerulescens*) the flea beetle (*Longitarsus echii*) and the pollen beetle (*Meligethes planiusculus*). The larvae of these agents feed leaf stalk, tap and secondary root of Paterson's curse.

Contributors

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Weed 20 **Silver grass (*Vulpia* spp.)**

Silver grass is an annual grass occurring in cropping and grazing regions across Australia. There are several species, the most common being *Vulpia bromoides* and *Vulpia myuros*. These species commonly occur together.

Common names

Silver grass, vulpia, hairgrass, silkygrass.
V. bromoides is known as squirrel-tail fescue and *V. myuros* as rat's tail fescue.

Distinguishing characteristics

Silver grass is a slender annual grass with fine (0.5–3.0 mm wide) hairless leaves. It has a membranous ligule, no auricles and slender hairless stems. The seed-head is a narrow, one-sided panicle containing numerous seeds that have a straight terminal awn up to 14 mm long.

Figure W 20.1 Mature *Vulpia bromoides* plant

Other weeds that can be confused with silver grass

In the early seedling growth stages silver grass can be confused with annual ryegrass (*Lolium rigidum*) and toad rush (*Juncus bufonius*). Toad rush can be distinguished from silver grass by the absence of a ligule and by fleshy leaves that arise from the base of the plant. Annual ryegrass can be distinguished from silver grass because of the shiny lower surface of its leaf blade, larger wider leaves (especially when there are more than three leaves) and the presence of auricles.

The early growth of the perennial bulbous meadow grass (*Poa bulbosa*) is also often mistaken for silver grass, particularly in the tableland areas of Australia. However, the leaf stems of bulbous meadow grass have a distinctive pear-shaped swollen base.

Factors that make silver grass a major weed

Silver grass competes with sown crops and pastures.

Although less competitive than other annual grasses such as wild oats (*Avena* spp.), silver grass can severely reduce crop yields when present in high densities. This is most likely to occur in direct-drilled early-sown crops. During perennial pasture establishment on the slopes and tablelands, silver grass can present a major problem by competing with the sown species. Silver grass with resistance to paraquat has been found in Victoria whilst a population with resistance to simazine has been detected in Western Australia.

Silver grass residues can reduce crop establishment and growth.

In paddocks where silver grass has been a heavy pasture contaminant, the degraded residues have been found to have an adverse effect on biomass and germination of a number of crops (including wheat, lucerne and 'grazing' phalaris, but not canola). This effect is most apparent after a dry summer and autumn period, where minimal soil disturbance maintains the residue on the soil surface. Heavy residues can be burnt in autumn to reduce the effect.

Silver grass is an alternate host for cereal diseases.

It acts as a host for a wide range of cereal root diseases including take-all, crown rot, rhizoctonia, bare patch and common root rot. Like other annual grasses, silver grass can be a host for the crop pest webworm *Hednota* species. It is also a host for the nematode that causes annual ryegrass toxicity.

It is an undesirable component in pastures.

Silver grass has low herbage production during autumn and winter, and low palatability and nutritive value in late spring and summer. Livestock avoid grazing silver grass after seed-heads emerge. In pastures on low fertility soils with low intensity set stocking, silver grass will quickly dominate.

Silver grass causes animal health problems.

The awned seeds of silver grass can seriously injure livestock by penetrating the skin and lodging in feet, eyes, ears and mouths. Seed present in hay can also cause livestock injury. The seeds and awns are a significant source of wool contamination.

Environments where silver grass dominates

Silver grass occurs over a wide range of climatic conditions in Australia, from coastal to inland regions receiving between 200 mm and 1200 mm annual rainfall. It mainly grows in areas with Mediterranean climates (cool winters and warm summers, absence of severe drought, dominant winter–spring rainfall). Silver grass plants have shallow roots which makes them sensitive to drought and are therefore found mostly in the higher rainfall areas of southern Australia, including the major cereal and livestock regions.

Silver grass grows on a wide range of soil types from highly fertile loams to low fertility acid sands, but it is a bigger weed problem on low fertility soils (low in nitrogen and phosphorus). On higher fertility soils increased competition from other species reduces its impact.

Silver grass prefers low pH soils. It is not tolerant of cultivation and so is favoured by direct drilling. It is often a problem in pastures, particularly during establishment.

Seasonal conditions that favour silver grass

Silver grass seed can germinate and emerge at any time during the year, providing that the after-ripening dormancy has been broken and sufficient moisture is available. Silver grass is most likely to be present in paddocks that are cultivated before the autumn break. It is a minor species when cultivation occurs after the autumn break, as seedlings are destroyed by cultivation and any remaining viable seeds are buried.

Conditions that favour silver grass germination and establishment

Silver grass seed has an after-ripening period of two to three months, after which germination can occur (given adequate moisture) over a wide range of temperatures. The seeds are intolerant of burial and germinate from the soil surface or to a depth of approximately 10 mm. Seeds buried at depths greater than 50 mm are unlikely to germinate.

Silver grass emerges rapidly from cultivated soils. Field studies by Dillon and Forcella (1984) in northern NSW tableland pastures found that 21% of the *V. myuros* and 46% of the *V. bromoides* seedbank emerged in the first seven months. Total emergence was staggered over a 16 month period. At two sites in southern Western Australia, however, over 97% of *V. myuros* and *V. fasiculata* emerged in the first few months of the first season after seed set, and the seedbank did not persist after that.

V. bromoides and *V. myuros* can germinate under light and dark conditions over a range of temperatures (approximately 10 °C to 30 °C). However, light increases the germination rate.

Seed survival in the soil

Large seedbanks of silver grass can develop and seed can persist for at least three years. However, given the right conditions most seed will germinate in the first year, with only a small percentage remaining dormant to germinate in following seasons.

Table W 20.1 Tactics to consider when developing an integrated plan to manage silver grass (*Vulpia* spp.).

Silver grass (*Vulpia* spp.)		Most likely % control (range)	Comments on use
Agronomy 1	Crop choice and sequence	80 (70–95)	Rotate to a triazine-tolerant or glyphosate-resistant canola in heavily infested areas.
Agronomy 3	Herbicide tolerant crops	95 (90–99)	Using pre- and post-emergent applications of triazine herbicide in triazine-tolerant crops will almost eradicate most species of *Vulpia*.
Tactic 1.1	Burning residues	50 (30–70)	Use a hot fire back-burning into the wind.
Tactic 1.3	Inversion ploughing	90 (80–99)	Use a plough with skimmers to bury seed more than 75 mm deep.
Tactic 1.4	Autumn tickle	60 (50–80)	Requires an early break to the season. Combine with delayed sowing.
Tactic 1.5	Delayed sowing	75 (50–90)	Works well in most seasons. Tends to fail on non-wetting soils.
Tactic 2.1	Fallow and pre-sowing cultivation	70 (50–90)	Generally works well. Crop using full soil disturbance with late sowing to allow use of knockdown herbicides plus cultivation.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	Up to 95%	Ensure good herbicide coverage.
Tactic 2.2b	Double knockdown or 'double- knock'	80 (70–95)	If this is required, pasture cleaning or spray-topping should have occurred two years before cropping.
Tactic 2.2c	Pre-emergent herbicides	80 (70–95)	Triazines are very good on most species of *Vulpia*.
Tactic 2.2d	Selective post-emergent herbicides	Up to 95%	If silver grass is the main component of the pasture there will be a loss of winter fodder. The treated pasture should be resown in the following season or renovated to increase the component of desirable species.
Tactic 3.2	Pasture spray-topping	Up to 85%	Timing is critical. Heavy grazing leading up to topping will induce uniform head emergence. Gives the ability to keep desirable pasture species while reducing the incidence of silver grass. Conduct two seasons before cropping.
Tactic 3.3	Silage and hay – crops and pastures	Up to 90%	Cut for silage at start of flowering. Control regrowth.
Tactic 5.1	On-farm hygiene	Variable	Contaminated hay should not be moved to clean areas.
Agronomy 4	Improve pasture competition	Variable	Reduces seed production, helping to maintain a low incidence of silver grass in a pasture. Winter clean with simazine.

Contributors

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Weed 21 **Sweet summer grass (*Moorochloa eruciformis*)**

Common names

Sweet summer grass, sweet signal-grass. Sweet summer grass is the preferred common name in the subtropics and tropics of Queensland.

Figure W 21.1 Mature plant and seed-head of sweet summer grass.
Photo: Vikki Osten

Distinguishing characteristics

Sweet summer grass (*Moorochloa eruciformis* formerly *Brachiaria eruciformis*) is delicate and fine in appearance compared with the major subtropical summer cropping grasses such as *Urochloa* and *Echinochloa* species.

It is distinguished by its colouring. The culms, leaf margins and leaf sheaths are strongly reddish–purple, while the leaf blades are dark green. Leaves are 15–100 mm long by 2–6 mm wide.

Sweet summer grass tends to be a tufted annual grass that may root at the lower joints, giving a sprawling stoloniferous (stem-forming) appearance. The upright growth habit parts of the plant reach 300–600 mm in height.

The flowering section of the stem is 10–80 mm long with three to 14 spikes of short (10–30 mm long) florets. Seed-heads do not have the typical 'signal' appearance of the other *Brachiaria* species as they do not droop, instead remaining upright and parallel with the stem. Seeds are purplish, elliptical and about 2 mm long.

Other weeds that can be confused with sweet summer grass

Sweet summer grass is not easily confused with other summer growing grasses of cultivation. *M. eruciformis* is unique in appearance, although confusion does arise when growers refer to it as just 'summer grass', which reflects an incorrect use of common name terminology (summer grass is *Digitaria ciliaris*).

Some confusion could arise where it grows together with native members of its former genus such as velvet-leafed summer grass (*Brachiaria windersii*) and green summer grass (*Brachiaria subquadripara*). However, M. *eruciformis* can be easily distinguished from these other *Brachiaria* species by the architecture of the seed-heads and the higher degree of reddish–purple colouring.

Factors that make sweet summer grass a major weed

Sweet summer grass has been shown to predominantly emerge from the soil surface (39% seed emerging at 0–2 cm), although it can also emerge from 5 cm (6–22%). Few seeds can emerge from deeper in the soil (10 cm, 1–2%). Seed persistence is lost at 2 cm after two years, however seed persistence increased with depth (7% and 20% at 5 cm and 10 cm respectively). Sweet summer grass emerges in flushes in December and February.

Sweet summer grass can be competitive when it forms dense mats or carpets across areas of cultivation.

The impact on crop yield is greatest when it emerges before or with the crop. Studies in central Queensland showed that sweet summer grass which emerged two to three weeks after the crop reduced sorghum yields by 10–20%.

Figure W 21.2 Sweet summer grass infesting grain sorghum.
Photo: Vikki Osten

Sweet summer grass creates a problem when the remnant plant material impedes winter crop emergence.

During cultivation the green and/or dead plant material tends to wrap around tynes, causing blockages and dragging across the paddock.

The plant is a short-lived summer weed dispersed by seed. Seeds fall very close to the parent plant and it is unknown whether further dispersal occurs by insects or birds.

Sweet summer grass can develop resistance to herbicides

Glyphosate-resistant (Group M) sweet summer grass has been confirmed in the Fitzroy region of Queensland.

Anecdotal observations indicate that sweet summer grass is a prolific seeder.

Under good growing conditions, a single plant is likely to produce around 4,000 seeds/m^2.

Sweet summer grass is not known to host insects or diseases. It was identified as a moderate to high risk for glyphosate resistance in central Queensland farming systems, and herbicide resistance to glyphosate was recently confirmed for this weed within Australia.

Environments where sweet summer grass dominates

Sweet summer grass is native to northern Africa, the Mediterranean and India, and was most probably introduced into Australia as a pasture species.

It is mainly a cropping weed, and is a major problem in central Queensland, particularly on the Central Highlands. It has been identified as a moderately important weed of coastal and sub-coastal southern Queensland, extending through to the Darling and Western Downs regions.

Sweet summer grass prefers heavy soil types, and does not grow well in saline conditions.

It is predominant in summer crops and summer fallows in environments that have warm to hot temperatures with summer dominant rainfall. In central Queensland it is a major weed in sorghum and sunflower cropping enterprises, and less so in dryland and irrigated cotton.

Being a summer annual, sweet summer grass emerges from mid-spring to early autumn. When autumn and winter are mild, emergence can occur later into the season if moisture is available, and it can then become a weed in winter crops. Since central Queensland has no winter grass issues per se, grass herbicides are not used in winter crops and late emerging sweet summer grass can create problems. However, as temperatures begin to drop the weed becomes far less competitive.

Anecdotal evidence over the past 20 years indicates that sweet summer grass favours zero or minimum tillage systems, since its occurrence and importance has dramatically increased with the wider adoption of reduced tillage practices.

Seasonal conditions that favour sweet summer grass

Central Queensland research showed that sweet summer grass often becomes a problem after the first spring to summer rains. If these rains occur late when temperatures are greater than 30 °C, it is very quick to complete its life cycle (within four to six weeks).

Several cohorts of sweet summer grass can emerge between October and March if sufficient moisture is available. These emergences can be both in-crop and in-fallow, depending on paddock use at the time and whether residual grass-active herbicides have been used.

More often than not the weed will emerge on the same planting rains used for crop emergence, but other cohorts will emerge later with in-crop rains. The uncontrolled plants emerging with or before the crop create the biggest problems for the cropping phase. Uncontrolled sweet summer grass during the fallow, while using 'stored' water, has the greatest impact on soil nitrogen and the weed seedbank.

Conditions that favour sweet summer grass germination and establishment

Sweet summer grass germination is favoured by good soil water conditions, particularly in the surface and upper 50 mm, as well as warm to hot temperatures (greater than 30 °C). Low stubble cover and smooth soil surfaces provide an excellent environment for seedlings to flourish.

Figure W 21.3 Sweet summer grass seedling.
Photo: Wilson et al 1995

Seed survival in the soil

Seeds produced in summer are highly viable in the following summer. It is not known whether two generations can be produced per season, but it is likely as the weed is short-lived and ideal conditions (wet and hot) are often prolonged for several months. In a seed burial study by Werth and Osten (2008) found 39% of seed emerged from 2 cm depth, 6–22% from 5 cm, and 1–2% from 10 cm over two years. After two years however, no seed was viable at 2 cm, but 7% and 20% of seed persisted at 5 cm and 10 cm depth respectively. This helps explain why minimum or zero tillage systems are the preferred environments for sweet summer grass, as minimal soil disturbance keeps the weed seed in the upper surface layer.

Table W 21.1 Tactics that should be considered when developing an integrated plan to manage sweet summer grass (*Moorochloa eruciformis*).

Sweet summer grass (Moorochloa eruciformis)		Most likely % control (range)	Comments on use
Tactic 2.2b	Double knockdown or 'double-knock'	99 (95–100)	Target small weeds and apply the second knock within five days of the first.
Tactic 2.1	Fallow and pre-sowing cultivation	95 (90–100)	During the fallow before the grass forms dense mats.
Agronomy 1	Crop choice and sequence	95 (75–99)	Use when weed burden is moderate to high and select crops that allow use of Group A 'fop' and 'dim' chemistry. See *Tactic 2.2d*.
Agronomy 2	Improve crop competition	95 (75–99)	Increased competition results in lower weed pressure and reduces reliance on herbicides.
Agronomy 6	Controlled traffic or tram-lining for optimal herbicide application	95 (75–99)	See Tactic 2.3.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	95 (75–99)	Best control when targeting small weeds.
Tactic 2.2c	Pre-emergent herbicides	95 (75–99)	Best control when applied before germinating rains.
Tactic 2.2d	Selective post-emergent herbicides	95 (75–99)	Target small weeds. Best used in conjunction with *Agronomy 1 Crop choice and sequence*, particularly if potential weed burden is going to be high. Group A selective grass herbicides can be used in sunflower, mung bean and cotton.
Tactic 2.3	Weed control in wide row cropping	95 (75–99)	Target small weeds. Best used in conjunction with *Agronomy 6 Controlled traffic or tramlining* for optimal herbicide application. Also presents opportunity to band pre-emergent herbicide over the crop row.
Tactic 1.5	Delayed sowing	90 (75–99)	Best when used in conjunction with *Tactic 2.2a Knockdown non-selective herbicides*. Hold off as long as practically possible after sowing rains to allow weeds to emerge and use herbicide or full disturbance sowing.

Contributor

Vikki Osten

Weed 22 **Turnip weed (*Rapistrum rugosum*)**

Common names

Turnip weed, rapistrum, turnip, wild turnip, giant mustard, bastard cabbage.

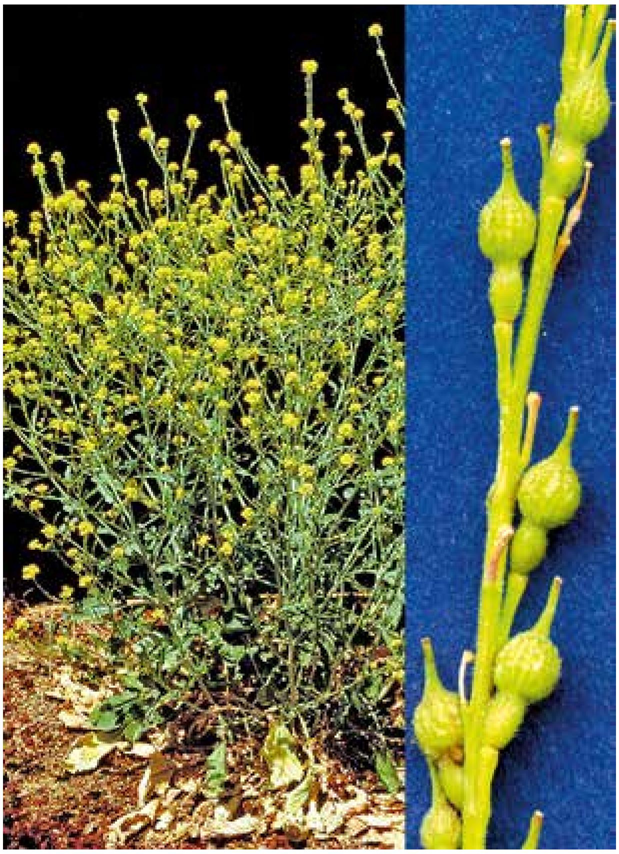

Figure W 22.1 Mature turnip weed plant and close-up of pods.
Photo: Wilson et al (left), Andrew Storrie (right)

Distinguishing characteristics

As an erect annual or biennial, turnip weed (*Rapistrum rugosum*) grows to a height of 1 m and is covered in short, stiff hairs. The upper leaves have a petiole, and the flower petals are yellow with dark veins.

Turnip weed is difficult to distinguish from other brassica species until pods form. Pods are 5–10 mm long and consist of two segments. The lower segment is 2–5 mm long, often with no seeds, while the upper segment is globular, wrinkled and ribbed with a conical beak, usually containing a single seed. The pods do not split upon ripening.

Other weeds that can be confused with turnip weed

Turnip weed is easily confused with other brassica weeds until pods form. It is similar to the following three species.

Wild mustard (*Sinapis arvensis*) is often found in the same environment. The leaves on the upper stem are attached directly to the stem (i.e. no petiole) and the pod is elongated, 20–60 mm long, with a flattened beak.

Wild turnip (*Brassica tournefortii*) tends to prefer red, lighter textured soils. It has erect pods 30–70 mm long that are constricted between the seeds.

Buchan weed (*Hirschfeldia incana*) is usually found along roadsides and in wastelands, as well as in declining pasture and lucerne stands. It has pods up to 20 mm long that are held close to the stem and have a swollen beak containing one seed.

Figure W 22.2 Turnip weed and wild mustard are often confused. Note that wild mustard stemleaf (right) has no petiole (leaf stalk).
Photo: Andrew Storrie

Factors that make turnip weed a major weed

Turnip weed is very competitive.

Turnip weed reduced barley yields in southern Queensland by an average of 8% and wheat yields by an average of 17% over 10 experiments in the 1980s. In chickpeas, with average crop plant populations, no herbicide and turnip weed populations of 10 plants/m^2 or 40 plants/m^2, yield reductions were 17% and 50% respectively.

Turnip weed produces a large number of seeds.

Plants can produce up to 77,000 seeds per plant.

Turnip weed causes problems at harvest.

Large plants slow harvest operations and can lead to drum chokes. There is a limit of 50 seeds/half-litre in Australian milling grade wheats.

Turnip weed is readily dispersed in agriculture.

It is spread in crop seed, fodder and machinery.

Turnip weed can develop herbicide resistance.

Like other brassica weeds, there are numerous turnip weed populations across eastern Australia that have evolved resistance to several Group B herbicides. Group B resistance has also been found in turnip weed in Iran.

Turnip weed can have an impact on other farm enterprises.

Infestations have been implicated in the failure of curly Mitchell grass to re-establish in north-western NSW, while turnip weed seeds in the feed have been found to reduce pig growth rates in Queensland by 1.5%. Turnip weed is also known to taint the meat of animals grazing the pastures it dominates and this can cause the rejection of carcasses at the abattoir.

Environments where turnip weed dominates

Turnip weed is found across a range of environments but is better adapted to hotter and drier environments compared with most brassica weeds (except wild mustard, with which it is often found in mixed infestations in northern NSW). It favours clay soils but will grow on sandy loams.

Although widespread in NSW and southern Queensland, turnip weed is only of minor concern in Victoria and South Australia. It has the potential to extend its range in all Australian states, including Western Australia.

It is a significant weed of pulses, and a lesser weed in cereals due to its susceptibility to phenoxy and sulfonylurea herbicides.

Tillage systems do not affect the abundance of turnip weed. Although it tends to be a winter weed, it will continue into the summer if sufficient soil moisture is available.

Seasonal conditions that favour turnip weed

The optimum temperature range for germination is 15–30 °C, so turnip weed will germinate during autumn to early summer, with the main period in autumn. Dormancy is broken by high temperatures (approximately 35 °C).

In northern NSW and southern Queensland flowering can commence in early August, with viable seed being produced by early September. Frost will limit the timing of seed set in cooler areas.

Turnip weed is most competitive when chickpeas are flowering, possibly due to shading of the crop by the bolting weed plants. In most other crops competition will begin earlier in the crop's development.

Conditions that favour turnip weed germination and establishment

A wet autumn following a dry summer favours turnip weed establishment, particularly in poorly competitive crops and pastures.

Figure W22.3 Turnip weed seedling.
Photo: Andrew Storrie

Seed survival in the soil

A seed burial study by Manalil et al. (2018) of Queensland turnip weed populations showed that emergence was greatest at 1 cm burial depth (48–56% emergence), compared to 28–33% emergence on soil surface. Emergence decreased at depths greater than 1 cm, with no germination at 6 cm. Seed removed from pods appears to have a short half-life, whereas it is thought that the presence of entire pods will prolong the life of the turnip weed seedbank. A no-till seedbank study in southern Queensland found 36% of turnip weed seed persisted after two years, and 7% remained after four years in the top 10 cm of soil.

Table W 22.1 Tactics to consider when developing an integrated plan to manage turnip weed (*Rapistrum rugosum*).

Turnip weed (*Rapistrum rugosum*)		Most likely % control (range)	Comments on use
Agronomy 3	Herbicide tolerant crops	90 (75–99)	Very useful for broadleaf crop phase of the rotation.
Tactic 4.1	Weed seed control at harvest	Variable	Very good potential for control as most seed is retained at harvest. Best results when crop can be harvested at optimum height for weed capture. 95-100% of seed above harvest height for chickpeas, only 20% above harvest height for sorghum
Tactic 2.2d	Selective post-emergent herbicides	90 (20–99)	Very good in cereals, but limited range in pulses and canola.
Agronomy 2	Improve crop competition	80 (50–99)	Competitive crops at optimum densities, row spacing and nutrition greatly reduces crop yield loss and reduces weed seed set.
Agronomy 1	Crop choice and sequence	80 (40–99)	Pulses are poor competitors; winter fallow–summer crop is a good choice.
Tactic 2.2c	Pre-emergent herbicides	70 (60–90)	Control varies depending on seasonal conditions, with poorer results in dry starts.
Tactic 1.5	Delayed sowing	60 (30–80)	Provides reasonable control in most seasons.
Tactic 2.1	Fallow and pre-sowing cultivation	50 (25–75)	Encourages germinations which can be controlled pre-planting.
Tactic 1.4	Autumn tickle	40 (20–60)	Effectiveness depends on seasonal conditions. Combine with delayed sowing (*Tactic 1.5*).

Contributor

Andrew Storrie

Weed 23 **Wild oats (*Avena* spp.)**

Common names

Wild oat, black oat.

Most of the information in the following text applies to both species of wild oat (*Avena fatua* and *Avena sterilis* ssp. *ludoviciana)* so the common name 'wild oats' will be used. The scientific names are only used in the two instances where information applies to one species or the other.

Figure W 23.1 Mature *Avena sterilis* ssp. *ludoviciana* plants.
Photo: Andrew Storrie

Distinguishing characteristics

Wild oats tend to grow in discrete patches at low to moderate densities (up to 100 plants/m^2).

The seedling leaves are twisted anticlockwise, the opposite direction to wheat and barley. Wild oats have a large ligule with no auricles, and the leaves tend to be hairy with a slight bluish hue. The emerging leaf is rolled.

Wild oat seeds are usually dark but can vary through to cream. Hairiness of seeds also varies.

Other weeds that can be confused with wild oats

In the seedling phase wild oats can be confused with all *Bromus* species which have tubular leaf sheaths and hairy leaves and sheaths. Wild oats have a rolled sheath and few hairs on the leaves.

Figure W 23.2 Wild oat ligule. Note the absence of auricles. Easily confused with brome grasses.
Photo: Andrew Storrie

Factors that make wild oats a major weed

Wild oats are highly competitive.

They have evolved closely with modern winter crop production. Plant for plant, wheat and wild oats are very close competitors. Competition for nutrients and water starts soon after emergence, leading to a reduction in wheat tillers. Left uncontrolled, wild oats have been shown to cause wheat yield losses as high as 80%. Greatest yield loss occurs when the plants emerge before or at the same time as the crop.

Figure W 23.3 *Avena fatua* seeds (left) and *Avena sterilis* ssp. *ludoviciana* seeds in floret (right). Note that *A. sterilis* ssp. *ludoviciana* spikelets tend to hold together at maturity while *A. fatua* readily break into individual seeds.
Photo: Andrew Storrie

Wild oats produce a large number of seeds.

The number of wild oat seeds produced depends on crop competitiveness, crop rotation and management techniques. In northern NSW the maximum seed set is estimated to be approximately 225 seeds per plant for low densities and less than 50 seeds per plant for densities above 50 plants/m^2. Up to 20,000 seeds/m^2 can be produced by uncontrolled infestations.

Wild oats can easily develop resistance to herbicides.

Group A herbicide resistance has been present in Australian wild oat populations since the mid 1980s. However, since 2003 Group A resistance has exploded in frequency and area, particularly in northern NSW.

The incidence of Group A 'dim' (e.g. Achieve®) resistance in wild oats continues to increase. In 2003 the first commercial case of Group Z (flamprop methyl) resistance was recorded in Australia. This population was also resistant to the Group A 'dim' herbicides. Much of the resistance to flamprop methyl appears to be cross-resistance from Group A resistance with one in three 'fop' resistant wild oat populations also having Group Z resistance.

The first case of Group B resistance in wild oats in Australia was identified in South Australia in 2005.

Internationally, wild oats have developed resistance to Group A herbicides in seven countries, and resistance to multiple MOA herbicides in Canada, Iran, Great Britain, South Africa and the USA (see *International Survey of Resistant Weeds* – http://www.weedscience.org/).

Wild oats avoid early herbicide applications through later germinations.

Staggered germination is a wild oat persistence mechanism, with the main cohort emerging in autumn to early winter and small numbers emerging through until spring. Later cohorts produce enough seed for the following season because they avoid the pre-emergent or early post-emergent herbicide applications relied on for control.

Wild oats represent a large cost to cropping.

Wild oats are a high impact weed, covering more than 2 million hectares, and reduce revenue by over $28 million per year via lost yield.

The level of grain contamination varies from year to year and depends on ripening and shedding of wild oats in relation to harvest. *Table W23.1)* outlines Australian grain receival tolerance levels.

Table W 23.1 Australian grain receival tolerance levels for wild oats contamination.

Varietal grade option	Allowable number grains/half-litre
APH2	50
H2	50
APW1	50
ASW1	50
AGP1	50
AUW1	150
FEED	400

Wild oats are easily spread as contaminants of grain, hay and machinery.

Up to 75% of wild oat seed may be collected at harvest, with seeds being transported up to 250 m from the parent plant. Delaying harvest can reduce seed movement in the paddock and grain sample, as the delay means a greater proportion of the wild oat seeds will have shattered.

Wild oats act as a host for a number of important cereal diseases and pests.

They are one of the main hosts for cereal cyst nematode (*Heterodera avenae*), stem nematode (*Ditylenchus dipsaci*), root lesion nematode (*Pratylenchus neglectus*) and the root diseases rhizoctonia (*Rhizoctonia solani*) and crown rot (*Fusarium graminearum*).

Environments where wild oats dominate

Both wild oat species are significant weeds wherever winter crops are grown. *A. sterilis* ssp. *Ludoviciana* tends to be more prevalent in warmer areas of northern NSW and southern Queensland, while *A. fatua* dominates in southern areas. Most infestations are a mix of the two species.

Soil type doesn't greatly influence the weed's distribution although wild oats can emerge from a greater depth in lighter textured soils.

Seasonal conditions that favour wild oats

Wild oats that emerge before or at the same time as the crop are more competitive than those emerging later. Most competition with the crop occurs in the first six weeks following cereal crop emergence. Competition with slower growing pulses (e.g. chickpeas) occurs during the period of rapid growth in spring.

Conditions that favour wild oat germination and establishment

Opening autumn rains germinate about 40% of wild oat seeds, with a further 10–30% germinating later in the season. This means that early planted crops are most likely to have wild oat competition unless control methods are implemented. Dry sowing of crops without an effective pre-emergent herbicide is likely to result in significant yield loss from wild oats.

Direct drilling retains most wild oat seed near the soil surface, resulting in a quicker seedbank turnover rate. Most of the seeds will emerge from the top 50–75 mm of soil.

Figure W 23.4 *Avena sterilis* ssp. *ludoviciana* seedling.
Photo: Wilson et al 1995

Seed survival in the soil

Despite common belief, the half-life of wild oat seed is about six months, equating to 75% depletion in 12 months. Research in northern NSW in the 1990s has shown that once seed production has ceased, the seedbank can be depleted to extremely low numbers within three to five years. Deep burial of wild oat seed will increase survival times, but is highly variable, with viability extending to 14 years in favourable conditions.

Table W 23.2 Tactics to consider when developing an integrated plan to manage wild oats (*Avena* spp.).

Wild oats (*Avena* spp.)		Most likely % control (range)	Comments on use
Tactic 3.3	Silage and hay – crops and pastures	97 (95–99)	Harvest when wild oats are flowering. Control regrowth.
Agronomy 1	Crop choice and sequence	95 (30–99)	Summer crop–winter fallow rotation is very effective; numbers build up in winter pulse crops. Maintaining a clean winter fallow is the key to success.
Tactic 5.1a	Sow weed-free seed	95 (0–100)	Only sow seed produced in paddocks free of wild oat.
Agronomy 3	Herbicide tolerant crops	90 (80–99)	Good to excellent control achieved with glyphosate-resistant and triazine-tolerant crops.
Tactic 3.1a	Spray-topping with selective herbicides	90 (60–99)	Flamprop methyl is very effective on flamprop-susceptible wild oats. Best results are achieved with competitive crops, warmer conditions and at the very early jointing stage of wild oats. Group Z resistance is common in many areas.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (70–90)	Wait until the youngest plants have two leaves if possible. Late germinations will not be controlled.
Tactic 2.2c	Pre-emergent herbicides	80 (70–90)	Works best when combined with competitive crops.
Tactic 2.2d	Selective post-emergent herbicides	80 (70–90)	Test for resistance before spraying. Use in combination with competitive crops.
Tactic 3.2	Pasture spray-topping	80 (70–90)	Graze or spray survivors. Hay freezing works well.
Tactic 5.1c	Clean farm machinery and vehicles	80 (0–100)	Ensure harvesters are well cleaned before moving to a clean property or paddock.
Tactic 3.5	Grazing – actively managing weeds in pastures	75 (60–80)	Graze heavily and continuously in spring.
Agronomy 2	Improve crop competition	70 (20–99)	Competitive crops at optimum sowing rates are very effective. High levels of control are achieved with barley, much lower with wheat.
Tactic 4.1	Weed seed control at harvest	70 (20–80)	Works well on early harvested crops before wild oats drop their seeds.
Tactic 1.4	Autumn tickle	40 (30–60)	Needs an early break to season. Combine with delayed sowing (*Tactic 1.5*).
Tactic 1.5	Delayed sowing	40 (30–60)	Must be used with *Tactic 1.4* Autumn tickle.

Contributor

Andrew Storrie

Weed 24 **Wild radish (*Raphanus raphanistrum*)**

Common names

Wild radish, white weed, white charlock, wild charlock, cadlock, wild kale, wild turnip, jointed radish.

Figure W 24.1 Wild radish flowering.
Photo: Andrew Storrie

Distinguishing characteristics

Wild radish (*Raphanus raphanistrum*) is generally a winter and spring growing annual which may grow up to 1.5 m high. The cotyledons are heart-shaped and hairless with long stems. The first true leaves are irregularly lobed around the edges with one or more completely separated lobes at the base of the leaf blade.

The seedling develops into a flat rosette, the leaves of which do not have a distinct stalk. Erect branches covered with prickly hairs arise from near the base as the plant matures. The rosette of lobed leaves does not persist.

Lower stem leaves are covered with prickly hairs and deeply lobed, with a rounded terminal lobe. When crushed these leaves have a strong turnip-like odour. Upper stem leaves become narrower, shorter and often undivided.

Flowers are in clusters on the ends of stem branches. They have four petals which alternate with four sepals. The petals may vary in colour; yellow or white petals are more common than purple, pink or brown. Petals often have light or dark distinct veins.

The seed pod is constricted between the seeds and does not split lengthwise. It breaks up into distinct segments when ripe, and during threshing it is often broken up into single-seeded segments. Each pod usually has three to nine seeds, ovoid to almost globular, yellowish to reddish–brown, and covered with white bran-like scales. There is no seed in the beak of the pod.

Other weeds that can be confused with wild radish

Wild radish may be confused with wild turnip (*Brassica tournefortii*), wild mustard (*Sinapis arvensis*), turnip weed (*Rapistrum rugosum*) or garden radish (*Raphanus sativus*). In the seedling stage it can also be confused with capeweed (*Arctotheca calendula*).

Figure W 24.2 Wild radish can have a range of flower colours.
Photo: Andrew Storrie

Despite both species having heart-shaped cotyledons and similarly shaped rosette leaves, wild radish can be distinguished from wild turnip at the seedling stage. Both have deeply-lobed leaves except that in wild radish the margins of individual lobes are uniformly serrated, whereas those of wild turnip are irregularly serrated. The leaves of wild turnip carry 'warts' on the upper surface and are broader in relation to their length. The basal rosette of leaves in wild turnip persists until late in the growing season, unlike that of wild radish. Wild turnip has very few stem leaves.

The flowers of wild turnip are similar to wild mustard (rather than wild radish) in colour, shape and size. Wild turnip seed pods split lengthwise to release the seeds when ripe. Wild radish pods do not split lengthwise; instead, the seed remains in the pod, which breaks into segments.

Wild radish that displays yellow flowers can sometimes be confused with wild mustard in the absence of fruit. Wild radish has larger flowers, with longer and narrower petals that do not touch or overlap and are a paler yellow. The sepals of wild radish are pressed against the back of the petal, while in wild mustard the sepals are widely spreading.

Separating wild radish and wild mustard at seedling stage is extremely difficult; however, wild mustard has smoother and rather shiny leaves, with less deeply impressed veins.

Wild radish and capeweed look similar when young but the underside of the capeweed leaf is white with fine fur. There is similarity in colour on both sides of the wild radish leaf (see *Weed 7 Capeweed (Arctotheca calendula)*).

At the seedling stage wild radish may be confused with turnip weed because the cotyledons are very similar. However, the mature plants are quite different, with turnip weed having only yellow flowers. The one- to three-seeded turnip weed pod is often pressed to the stem, and when mature usually breaks into upper and lower segments. The lower segment is cylindrical and contains up to two seeds, whereas the upper segment is globular with one seed and a beak (see *Weed 22 Turnip weed (Rapistrum rugosum)*).

Garden radish is similar to wild radish in the above-ground parts but the flowers are purplish, pink or white, never yellow. Garden radish seed pods are spongy, lack distinct joints and split in various ways at maturity (not into segments containing single seeds).

Figure W24.3 Garden radish pods.
Photo: Andrew Storrie

Factors that make wild radish a major weed

The ease of dissemination of wild radish has resulted in its widespread occurrence.

It is easily distributed as an impurity in hay, chaff and grain. Wild radish pods often break into segments similar in size to wheat seed, and removal of the contamination can be quite difficult. It is important to ensure that all crop seeds for sowing, and all hay purchased, are not contaminated with wild radish seed. Livestock, wind, water and machinery also spread wild radish seed.

Figure W24.4 Mature wild radish pods showing how they break into cereal grain-size segments.
Photo: Andrew Storrie

Wild radish is very competitive because its seedlings rapidly establish and have a relatively fast growth rate.

Competition is further increased due to the introduction of modern crop cultivars that are shorter in habit. Yield response following spraying is often four to five times higher for wild radish killed early at the 3-leaf stage than for control after tillering (*Table W24.1*).

The trend to wider row spacings with direct sowing also reduces the ability of cereal crops to compete with weeds such as wild radish.

Yield losses are even more significant in alternate crops (*Table W24.2*). The impact on yield depends on the density of wild radish plants and emergence time compared to the crop plants.

Table W 24.1 Effect on wheat yields of early and late spraying of wild radish in central west of NSW (Dellow and Milne 1987).

Treatment	Wheat yield (t/ha)
Unsprayed	0.14
Sprayed late (wheat tillered)	0.36
Sprayed early (3-leaf wheat)	1.66

Figure W 24.5 Wild radish dominating a crop of canola.
Photo: Andrew Storrie

Table W 24.2 Effect of wild radish population on crop yield reduction (Blackshaw et al 2002; Cheam unpublished; Hashem and Wilkins 2002; Moore 1979).

Crop	Wild radish plant density (plants/m^2)							
	2–4	10	25	50	64	75	100	200
	Crop yield loss (%)							
Wheat	–	–	11	20	–	26	33	50
Canola	11	–	–	–	91	–	–	–
Lupin	15	28	56	81	–	92	–	–
Faba bean	–	36	–	–	–	–	–	–
Field pea	–	36	–	–	–	–	–	–
Lentil	–	42	–	–	–	–	–	–
Chickpea	–	49	–	–	–	–	–	–

Lupin, wheat, field pea and barley grains rapidly lose their viability during storage when contaminated with green wild radish pods.

This is due to the toxic substances released by the wild radish pods and seeds. Research in Western Australia showed the degree of sensitivity to the wild radish toxins depends on storage temperature, level of pod contamination, exposure time and crop type. Damage to lupin seed began at 5% by weight contamination and a storage period of three days. All lupin seed was killed after five days exposure to 8% contamination.

The fibrous stems of wild radish can make harvesting difficult by choking the header comb.

It is now uncommon to see crops left unharvested due to the smothering effect of wild radish and the difficulty of harvesting heavily infested crops. Improvements in harvester design have overcome these problems.

Moisture levels of harvested grain can be affected.

In years with late rains, when wild radish continues to grow and remains green after crop maturity, the moisture squeezed from the wild radish stems during harvest often raises the grain moisture content above acceptable storage levels.

Wild radish can cause animal health problems.

When eaten by dairy cows wild radish has caused milk taint. In some cases poisoning occurs if the seeds (the most toxic part of the plant) are consumed in considerable quantities. Generally, mortality due to wild radish poisoning is rare.

Wild radish has allelopathic activity.

Its extracts and residues can suppress germination, emergence and seedling growth of some crops and weeds.

Wild radish is an alternate host for a number of pests and diseases.

The more common plant pests and diseases found on wild radish are thrips, flea beetles, club root of *Brassica* species, *tobacco streak virus* and *cucumber mosaic virus*.

Wild radish produces abundant seeds.

In Western Australia wild radish is a more prolific seeder than wild turnip, doublegee, annual ryegrass and brome grass. Early emerging plants produce more seeds than the later emerging cohorts. In a Western Australian lupin crop, cohorts emerging later than 21 days after crop emergence failed to reproduce altogether.

Failure of later cohorts to reproduce has also been confirmed in other crops such as wheat and canola in Western Australia. However, wild radish plants that emerged 10 weeks after canola (in NSW) and wheat (in Victoria) managed to produce some seeds.

As wild radish density increases, seed production per plant decreases. Victorian research by Cheam and Code (1998) has shown that seed production ranged from 292 seeds/m^2 at a density of 1 plant/m^2 to 17,275 seeds/m^2 at 52 plants/m^2 in a wheat crop.

Seed production must be prevented or at least minimised, to achieve long-term control of wild radish.

Complex seed dormancy is one of the most important characteristics that enables wild radish to persist as a cropping weed.

Wild radish seeds are dormant at maturity and as many as 70% of the seeds are still dormant at the start of the next cropping season. Many seeds will not germinate until the second season after their formation (about 18 months later). Research conducted on field populations of wild radish at Mount Barker, Western Australia, showed the highest emergence of radish seedlings occurred two seasons after seed-rain (*Figure W24.6)*). This emergence pattern fits perfectly with the wheat–lupin rotation that was favoured in the northern Western Australian wheatbelt. Seeds enclosed by pods have much slower emergence than naked seeds. In addition to the role of the seed-coat in controlling dormancy, there is also embryo dormancy in wild radish. As a result there is a cycling of dormancy in the field which in turn determines the ability of the seed to germinate at various times during the season.

Dormancy breakdown is enhanced by shallow burial of the seed in early summer, which can be achieved through trampling by livestock.

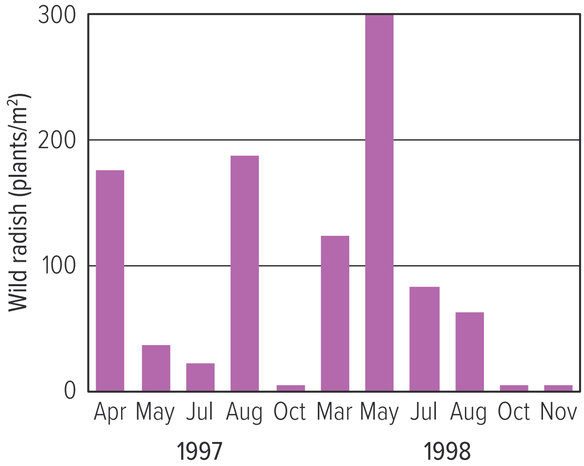

Figure W 24.6 Emergence patterns of wild radish following seed rain in late 1996.
Source: after Pelzer 2004

Geographic location and temperature also influence wild radish dormancy. For example, seeds from Western Australia's warmer northern agricultural region have lower dormancy levels than seeds from the cooler southern region.

Dormancy is further complicated by flower colour. Seeds of purple-flowered forms are more dormant than those of the white and yellow forms. It follows that purple-flowered forms of wild radish have a greater likelihood of avoiding control by early herbicides because they tend to germinate after the time of application.

The dormancy factor is also influenced by seedling emergence time. Early emerging plants produce more seeds with greater dormancy as they start flowering and forming seed in winter when conditions are favourable to producing a thicker pod. Pods produced on the same plant in spring when it is hotter and dryer will have lower levels of dormancy than those produced earlier.

The overall dormancy behaviour of wild radish is therefore complex and has played a significant role in the persistence of this weed.

Wild radish can germinate at any time of the year given sufficient soil moisture.

Germination is possible under widely fluctuating temperatures from 5 °C to over 35 °C, with optimal diurnal fluctuation of 25 °C to 10 °C.

The flexible flowering patterns of wild radish, requiring less than 600 degree-days to flower, indicate that wild radish has the capacity to grow and set seeds in most areas of southern Australia.

Temperature is the major factor controlling development up to flowering, while day length as well as temperature influence the duration of flowering.

Wild radish seed persistence is greatest when seed is buried at depths greater than 40 mm.

Although the decline in the number of viable seeds is greatest in the top 10 mm of soil, any measures taken to completely exhaust the seeds in the top 100 mm of soil (with the prevention of input of fresh seeds) would need to be applied for at least a minimum of six years (*Table W24.3)*).

Tillage, besides stimulating emergence, also affects wild radish seed longevity through the placement of seed at different depths.

Wild radish sheds pods before crop harvest, enabling it to persist in cropping systems.

In a Victorian study, between 50% and 60% of wild radish pods had shed prior to harvest, while the remainder fell during the harvest process. Environmental conditions (e.g. hot dry spells, severe wind, rain) close to crop harvest can cause the seed pods to shed. Nevertheless, early windrowing of crops such as canola and pulses may capture the green wild radish pods and prevent the seeds being returned to the soil.

Through its genetic and phenotypic variability, wild radish has managed to adapt well to varied crops, environments and control tactics.

This variability in wild radish is also evident in its flower colour variations; more than 12 different forms have been differentiated based on colour and venation pattern on the petal.

Being an outcrossing species, wild radish has sufficient genetic variability and biochemical adaptability to evolve resistance to the commonly used herbicides in cropping systems.

Populations (mostly in Western Australia) have developed resistance to herbicides in MOA Groups B, C, F, I and M. Group B resistance is the most common, followed by Group F.

A major concern is the increasing frequency of wild radish populations that are developing resistance to atrazine (Group C) and 2,4-D amine (Group I). It is common to find populations that have developed multiple resistance across several MOA groups. Resistance to herbicides in up to three MOA groups has been documented in individual populations. Resistance to Group C herbicides (e.g. atrazine) is maternally inherited. This means that these genes do not move with the pollen, so containment of these Group C resistant populations is feasible.

Environments where wild radish dominates

Wild radish is a cosmopolitan weed. Regarded as being native to Europe and through the Mediterranean region to central Asia, it is now naturalised in most temperate countries of the world. In southern Australia it is one of the most widespread and troublesome cereal and pulse crop weeds. It occurs in pastures and is a common roadside and wasteland weed.

The worst wild radish problem is in Western Australia, especially on the sand plain soils of the northern wheatbelt.

Although wild radish has a preference for slightly acidic soils, it grows well over a range of soil types in southern Australia, and flourishes in fertile nitrogenous soil. In NSW and southern Queensland it is found on lighter textured acidic soils.

Planting pulse crops (other than lupins) has the potential to worsen the wild radish problem due to limited in-crop herbicide choices against wild radish in these crops, and the poor competitive ability of pulses.

While the introduction of triazine-tolerant canola cultivars initially resulted in improved wild radish management, the dependence on triazine herbicides is selecting for resistance to this MOA. Several atrazine failures were observed in 2011 and atrazine resistance was confirmed in at least four wild radish populations. The long term 1:1 rotation of lupin–wheat practised in the northern wheatbelt of Western Australia for many years has encouraged the build-up of the wild radish seedbank and increased the risk of the weed developing herbicide resistance.

Seasonal conditions that favour wild radish

Wild radish can emerge at any time of the year providing there is sufficient soil moisture although the majority of seed germinates in autumn and winter. It can produce seed in a very short time from germinations late in spring or during summer.

Conditions that favour wild radish germination and establishment

Greatest emergence occurs from wild radish seeds at depths of 10–20 mm following autumn shallow cultivation; seedlings rarely emerge from depths greater than 50 mm. Autumn stimulation with cultivation is achievable only when the temperature of the surface soil is below 20 °C and there is sufficient soil moisture.

The fact that buried wild radish seeds need exposure to light and surface seeds prefer darkness for germination partially explains the stimulation by cultivation. Cultivation changes the position of seeds in the soil and therefore access (or not) to light. Seeds left on the soil surface without soil disturbance have poorer emergence, as do seeds buried at greater than 40 mm.

The presence or absence of trash may also determine wild radish germination in the field. Organic trash increases the moisture level of the soil as well as lowering soil temperatures. Consequently, the germination window for the surface and buried seeds is increased. If trash must be removed to allow the crop to be sown, it should be done only after allowing maximum wild radish germination followed by appropriate control measures.

Figure W 24.7 Wild radish seedling showing distinctive heart-shaped cotyledons.
Photo: Andrew Storrie

Figure W 24.8 Wild radish rosette showing deeply lobed leaves.
Photo: Andrew Storrie

Seed survival in the soil

Deep burial extends wild radish seed viability, and subsequent cultivation must be shallow to avoid relocating buried seed close to the surface where it could germinate.

Seed longevity is also affected by tillage at different depths by different implements, with longer survival of seed placed at greater depths (*Table W24.3*).

Other factors such as soil microbes, frequency of soil disturbance, soil temperature and soil moisture can vary seed survival from six to over 10 years.

Table W 24.3 Percentages of wild radish seed remaining viable after burial at various depths (Code et al 1987).

Depth of burial (mm)	Duration of burial (years)					
	0.5	1	2	3	4	6
	Viable wild radish seed after burial (%)					
0	43	19	5	4	5[a]	0
10	10	12	16[a]	5	3	1
50	55	47	52[a]	27	21	7
100	75	57	53	44	43	0

[a] Apparent increases in viability with time due to variation between samples

Table W 24.4 Tactics to consider when developing an integrated plan to manage wild radish (*Raphanus raphanistrum*).

Wild radish (*Raphanis raphanistrum*)		Most likely % control (range)	Comments on use
Tactic 1.3	Inversion ploughing	98 (20–100)	Plough must be correctly 'set up' and used under the right conditions. Must use skimmers.
Tactic 3.4	Manuring, mulching and hay freezing	95 (90–100)	Brown manuring is more efficient than green manuring and more profitable. Grazing before spraying to open the sward will improve results. Hay freezing works well and is the most profitable manuring option in most cases.
Tactic 5.1a	Sow weed-free seed	95 (90–100)	Very important as resistance in wild radish is increasing and introduction via crop seed is increasingly likely.
Agronomy 3	Herbicide tolerant crops	90 (80–99)	If growing canola in a wild radish infested area it is essential to use a herbicide-resistant cultivar and associated herbicide package.
Tactic 2.2d	Selective post-emergent herbicides	90 (70–99)	Apply to young and actively growing weeds. Repeat if necessary to control late emerging weeds or survivors.
Tactic 3.1a	Spray-topping with selective herbicides	80 (70–95)	Wild radish may regrow if there are late rains. Good for seed set control. Spray before embryo development for best results.
Tactic 3.3	Silage and hay – crops and pastures	80 (70–95)	Cut before embryo formation in developing wild radish seed (21 days after first flower). Graze or spray regrowth.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	80 (70–90)	Add a reliable herbicide spike for more reliable control. Late germinations will not be controlled.
Tactic 4.1	Weed seed control at harvest	75 (65–85)	Most reliable in early harvested paddocks.
Tactic 3.1c	Wiper technology	70 (50–80)	Has potential in low growing pulses such as lentils.
Tactic 3.5	Grazing – actively managing weeds in pastures	70 (50–80)	Rotationally graze and use spray-grazing. Can also use slashing to improve palatability and reduce pasture growth rate in spring.
Tactic 1.1	Burning residues	70 (20–90)	In concentrated windrows. Burn when conditions are conducive to a hot burn.
Tactic 1.4	Autumn tickle	45 (15–65)	Follow-up rain is needed for better response.

Contributors

Aik Cheam and Andrew Storrie

Weed 25 **Windmill grass (*Chloris truncata*)**

Common names

Windmill grass, umbrella grass, black windmill grass, creeping windmill grass, early chloris, star grass, blow-away grass.

Figure W 25.1 Mature windmill grass plants and seed-heads.
Photo: Andrew Storrie

Distinguishing characteristics

Windmill grass (*Chloris truncata*) is an erect, hairless, warm season biennial or short-lived perennial to 0.5 m high, usually forming a dense low crown, sometimes with short, branched stolons. The leaf blade is 2–5 mm wide with a blunt (obtuse) and boat-shaped tip and has a ligule consisting of short hairs.

Flower spikes are usually six to nine in number, resembling fingers radiating horizontally and 4–20 cm long. Spikelets are arranged alternately in two rows on the underside of the spikes. Florets are black when mature and the seed is ovoid.

Other weeds that can be confused with windmill grass

Tall windmill grass (*Chloris ventricosa*) and Rhodes grass (*Chloris gayana*) can be confused with windmill grass when young. Tall windmill grass however grows to at least 1 m high and has a drooping inflorescence (*Figure W25.3*)). Rhodes grass has a compact and upright flowerhead.

Factors that make windmill grass a major weed

Windmill grass is difficult to control in no-till fallows and can reduce winter crop yield.

Windmill grass can reduce winter crop yield by using stored soil moisture and nutrients over summer. Yield losses of up to 50% have been recorded.

Field experiments in central and northern NSW have shown that windmill grass is tolerant of glyphosate and a range of other herbicide MOA groups. Field experiments in Western Australia have achieved higher levels of control with glyphosate and other herbicides compared with NSW. There are also limited herbicide registrations for windmill grass in fallow and in-crop.

Windmill grass populations have evolved resistance to glyphosate.

In a 2011 risk assessment undertaken in the northern grain region, windmill grass was identified as a moderate to high risk for glyphosate resistance in northern NSW farming systems. At the time of writing, 13 populations with glyphosate resistance had been found.

Windmill grass is a prolific seeder.

Windmill grass can produce up to 20,000 seeds per plant. Its ability to quickly respond to rain and flower and produce viable seed at almost any time of year means seedbanks can be continually replenished.

Windmill grass is a host to cereal diseases.

Anecdotal evidence suggests that something other than competition for moisture and nitrogen is reducing winter cereal yield. Windmill grass is a common host for *barley yellow dwarf virus* and has also been found to be a host for crown rot (*Fusarium graminearum*).

Windmill grass seed-heads blow in the wind, enhancing its spread.

An abscission layer forms at the base of each flowering stem on maturity. This allows the seed-head to break off and blow in the wind. Seed shatters easily as the heads tumble. Seed-heads often accumulate along fencelines and buildings.

Figure W 25.2 Windmill grass in fallow.
Photo: Andrew Storrie

Environments where windmill grass dominates

Windmill grass is an Australian native found in temperate mainland Australia extending to central Australia, but it is absent from the Northern Territory. It is associated with dryland grasslands and woodlands on most soil types, ranging from grey cracking clays to light sandy soils. Windmill grass will grow on a range of soil types but prefers lighter textured soils. In Australia it has been recognised as a useful pasture species and was introduced into California and South Carolina in the USA as a turf species.

Windmill grass is becoming a no-till cropping weed and is a major problem in central-northern NSW. Removal of sheep from many farming systems since 2005 has seen an increase in the incidence of windmill grass in summer fallows.

Anecdotal evidence over the past 20 years indicates that windmill grass favours zero or minimum tillage systems, since its occurrence and importance has dramatically increased with the wider adoption of reduced tillage practices.

Figure W 25.3 Windmill grass showing its stoloniferous habit.
Photo: Andrew Storrie

Seasonal conditions that favour windmill grass

Windmill grass will flower at most times of the year, thereby ensuring the seedbank is topped up with fresh seed. Seed drops about one month after flowering. Fresh seed has some dormancy; however, this is variable. Research on the north-west slopes of NSW shows that windmill grass will establish following significant rains (greater than 20 mm) from early summer until autumn.

Conditions that favour windmill grass germination and establishment

Windmill grass germination is favoured by good soil water conditions, particularly in the surface and upper 50 mm; however, the number of days until germination is not affected by lower soil moisture compared with many other native perennials. Windmill grass will germinate over a wide range of temperatures (15–35 °C).

Windmill grass seeds will germinate in light. This fact combined with its tolerance of a wide temperature range and ability to germinate in a drying soil allow it to germinate on the soil surface. Research has found little successful recruitment (greater than 96% mortality) in established native grass pastures over a two-year period, despite large numbers of seeds germinating. Any seedlings that did establish were in bare spaces between other plants and no new recruits flowered during this time.

Seed survival in the soil

Seed persistence is short, with viability typically lost within 12 months; however, this weed's ability to flower and set seed at most times of year ensures a constant supply of new seed. When buried, seed health is marginally higher (2 cm and 10 cm), although few seeds persist past 12 months. Dry conditions have been found to increase seedbank persistence.

Table W 25.1 Tactics to consider when developing an integrated plan to manage windmill grass (*Chloris truncata*).

Windmill grass (*Chloris truncata*)		Most likely % control (range)	Comments on use
Agronomy 1	Crop choice and sequence	95 (75–99)	Use when weed burden is moderate to high and select broadleaf crops (summer) that allow use of 'fop' and 'dim' chemistry. See *Tactic 2.2d*. Alternatively, summer fallows will allow the use of full-disturbance cultivation. See *Tactic 2.1*.
Tactic 2.1	Fallow and pre-sowing cultivation	95 (70–100)	Several cultivations may be necessary. Grazing (*Tactics 3.5* and *4.2*) before cultivation often improves control. Also glyphosate before cultivation dramatically improves control.
Tactic 2.2b	Double knockdown or 'double-knock'	90 (80–100)	Target small weeds and apply the second knock (paraquat) at a robust rate within seven to 14 days of the first.
Tactic 2.2d	Selective post-emergent herbicides	90 (75–99)	Target small weeds in mung beans, cowpeas, cotton or sunflowers. Best used in conjunction with *Agronomy 1 Crop choice and sequence*, particularly if potential weed burden is going to be high.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	70 (55–85)	Best control when targeting weeds up to 4-leaf stage. High temperatures and moisture stress significantly reduce levels of control.
Agronomy 2	Improve crop competition	50 (30–80)	Increased competition results in lower weed pressure and reduces reliance on herbicides.

Contributors

Andrew Storrie and Tony Cook

Weed 26 **Wild mustard (*Sinapis arvensis*)**

Common names

Charlock, crunch-weed, field mustard, field kale, mustard, kedlock.

Distinguishing characteristics

Wild mustard is an annual herb found in all states and territories except the Northern Territory. The plant grows erect between 30–80 cm tall, occasionally branching with white hairs along the stem. Lower leaves petiolate, are lobed and coarsely toothed and are up to 20 cm long. They are usually broader at the tip than at the base. Upper leaves have short petioles (or clasp the stem) are alternate, up to 30 cm long and are also coarsely toothed. Flowers are yellow and share the appearance of most flowers within the mustard family. They have a sweet smell and have four petals 9–12 mm long. Pods are 20–60 mm long and contain six to 24 seeds. Wild mustard seed is spherical, 1–2 mm in diameter and can range from red–brown to black in colour.

Figure W 26.1 Wild mustard at vegetative stage. *Photo*: Tony Cook

Other weeds that can be confused with wild mustard

There are a number of similar brassica weeds to wild mustard, making identification difficult. The name wild mustard is also sometimes used for other brassica weeds for example *Sisymbrium orientale* in Western Australia, known as Indian Hedge mustard in other states. Wild mustard (*Sinapis arvensis*) can be identified by its long white hairs on its stems, as other brassica weeds hairless stems. Its yellow flowers are usually shorter and brighter than other brassica weeds such as wild radish. Its leaves are smoother and shiner than wild radish, and do not have the 'warts' appearance of wild turnip. Identification between these weeds at the seedling stage is extremely difficult however.

Factors that make wild mustard a major weed

Wild mustard is highly competitive.

Wild mustard is well adapted to dry conditions and grow aggressively even when soil moisture is limiting to the crop. Control of wild mustard is difficult as it emerges with winter crops and sets seed before the crop matures. Wild mustard strongly competes with crops, internationally, 20 wild mustard plants/m^2 has been shown to reduce canola seed yield by greater than 35% and chickpea yield by 50% at 40 plants/m^2.

Wild mustard produces a large number of seeds.

Wild mustard plants can produce large amounts of seed (up to 30,000 found in NSW). Even under crop competition, wild mustard can produce 3,500 seeds per plant. The species is readily dispersed in soil during harvest and contaminates crop seed.

Figure W 26.2 Hairy stem of wild mustard. *Photo*: Tony Cook

Figure W 26.3 Wild mustard is highly competitive.
Photo: Tony Cook

Wild mustard represents a large cost to cropping.

A recent study by Llewellyn et al. (2016) found that wild mustard losses equated to $4.9 million in lost yield, and covering over 970,000 ha. It has been ranked as the sixth and fourth most problematic residual weed in northern and southern cropping regions respectively.

Wild mustard seed causes problems during crop harvest.

Wild mustard seeds contaminate canola seed readily, as they are of similar size and appearance. Wild mustard is high in glucosinolates and erucic acid, contaminating canola products. The small seeds can also cause grain contamination in other cereals.

Wild mustard can easily develop resistance to herbicides.

Group B herbicide resistance has been detected in Australian wild mustard populations. Internationally, wild mustard has developed resistance to Group B, I and C herbicides (see *International Survey of Resistant Weeds* - http://www.weedscience.org/).

Wild mustard shows high levels of genetic variability.

Wild mustard has a high degree of genetic variation which makes it prone to developing herbicide resistance. As it is self-incompatible, wild mustard outcrosses readily so resistance has the potential to spread long distances via pollen movement.

Environments where wild mustard dominates

Wild mustard is well adapted to most of the cropping and grazing zones and can be a major weed problem in fallows and winter crops. A widespread weed, it is found throughout the cropping belts and higher rainfall areas in most states.

Figure W 26.4 Wild mustard flowers.
Photo: Tony Cook

Seasonal conditions that favour wild mustard

Seedlings emerge in late autumn and winter, growing over winter and early spring and flowering in spring and early summer. The lifecycle can closely match that of a cereal crop, with seeds maturing before or with the crop. Plants can persist over summer under mild conditions and will flower through autumn and winter.

Conditions that favour wild mustard germination and establishment

Wild mustard prefers seed bare soil or shallow burial, with germination occurring mainly in autumn and winter, and appears to favour heavy soils. Emergence patterns and dormancy are not well understood in Australia, although Northern Hemisphere research indicates that wild mustard has variable emergence and seed dormancy. Emergence from below 6 cm is unlikely, however as seed can persist as long as 60 years, deep cultivation bares the risk of re-emergence from subsequent cultivation.

Seed survival in the soil

Wild mustard seed survival in Australia is unknown. However research in Canada showed that 70% of freshly harvested wild mustard seeds are dormant. Burial of wild mustard seed to a depth of 8 inches took 14 years to obtain 95% seed loss. Wild mustard seed can persist for a very long time, up to 60 years in soil and over 100 years in long term grain storage.

Figure W 26.5 Wild mustard pods.
Photo: Tony Cook

Table W 26.1 Tactics to consider when developing an integrated plan to manage wild mustard (*Sinapis arvensis*).

Wild mustard (*Sinapis arvensis*)		Most likely % control (range)	Comments on use
Tactic 1.5	Delayed sowing	95 (90–99)	Follow by knockdown with non-selective herbicides targeting small weeds.
Tactic 3.1a	Spray-topping with selective herbicides	95 (85–99)	Be aware of resistance status. The control range assumes no Group B resistance.
Agronomy 1	Crop choice and sequence	85 (0–90)	Avoid crops with no post-emergent herbicide options.
Tactic 3.1c	Wiper technology	80 (60–95)	Useful tactic in lentil.
Tactic 2.2d	Selective post-emergent herbicides	80 (60–90)	Spray young actively growing plants and repeat if necessary. Be aware of resistance status.
Agronomy 2	Herbicide tolerant crops	80 (0–95)	Very useful for non-cereal portions of the rotation.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	75 (50–80)	Use high rates to control biennial plants. Tank-mixing with phenoxy herbicides improves control in absence of Group I resistance. Late germinations are not controlled.
Tactic 2.2c	Pre-emergent herbicides	75 (50–80)	Dry conditions post-sowing reduces herbicide efficacy.
Tactic 3.5	Grazing – actively managing weeds in pastures	70 (50–80)	Rotationally graze. Use spray-grazing with herbicide suited to pasture species present.
Tactic 4.1	Weed seed control at harvest	50 (10–70)	Useful on early harvested crops
Tactic 1.4	Autumn tickle	25 (10–50)	Use with early breaks to the season and combine with delayed sowing.

Contributors

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Weed 27 Wild turnip (*Brassica tournefortii*)

Common names

African mustard, Asian mustard, long-fruited wild turnip, Mediterranean mustard, Mediterranean turnip, Moroccan mustard, prickly turnip, Sahara mustard, turnip weed, wild turnip, wild turnip-rape.

Distinguishing characteristics

Wild turnip in an erect annual found in all Australian states and territories. It is an annual herb that usually grows 60–90 cm tall (although can grow as tall as 1.8 m), with stiff white hairs mainly on the lower stems and the undersides of mid-veins and leaf stalks.

Figure W 27.1 Mature wild turnip plants
Photo: Bruce Wilson

First leaves form a rosette and are oval, round apex, and lobed margin. Lower leaves form six to 10 pairs of backward pointing, irregular, bluntly toothed lobes. Upper leaves are smaller, spear shaped, with few hairs, and have a 'wartish' appearance. Flowers are pale yellow to white in colour, with small petals (5–8 mm). Seed pods are 30–70 mm long, on stalks, cylindrical without prominent midrib, containing 12–20 seeds. Pods also have a beak up to one third its length containing one to two seeds.

Figure W 27.2 Wild turnip seedling.
Photo: Bruce Wilson

Other weeds that can be confused with wild turnip

Wild turnip is easily confused with other brassica weeds but can be distinguished by its pods or leaves.

Wild turnip pods: 30–70 mm long and are constricted between the seeds, splits lengthwise to release seeds. Leaves have wartish appearance.

Wild mustard: leaves are smoother and shiner, and do not have wartish appearance.

Wild radish: 30–80 mm long, pod splits into segments, no seed in beak of pod.

Figure W 27.3 Wild turnip seed pods.
Photo: Geoff Sainty

Factors that make wild turnip a major weed

Wild turnip is competitor for resources.

Wild turnip is a significant weed that reduces the yield and quality of canola and other winter crops through competition for resources. Densities as low as 1 plant/m^2 can cause 0.35% yield-loss in wheat. This weed ranks sixth nationally in terms of revenue loss (AU$10.6 million) due to crop yield losses in Australia.

Wild turnip reduces crop quality.

Wild turnip is a source of contamination, with its glucosinolate concentration of wild turnip is greater than 100 µmol/g of oil-free meal, and erucic acid more than 2%, well above the threshold for meeting oilseed quality. Hence contamination of wild turnip seeds in canola can significantly reduce the oil quality and commercial value of canola.

Wild turnip can easily develop resistance to herbicides.

Like other brassica weeds, there are numerous (greater than 100) wild turnip populations that have evolved resistance to Group B herbicides. Resistance to Group B herbicides was first confirmed in South Australia and West Australia in 1996. Herbicide usage records show that resistance has developed after three to 10 years of selection with chlorsulfuron.

Wild turnip is easily dispersed in agriculture.

It is spread in crop seed, fodder and machinery.

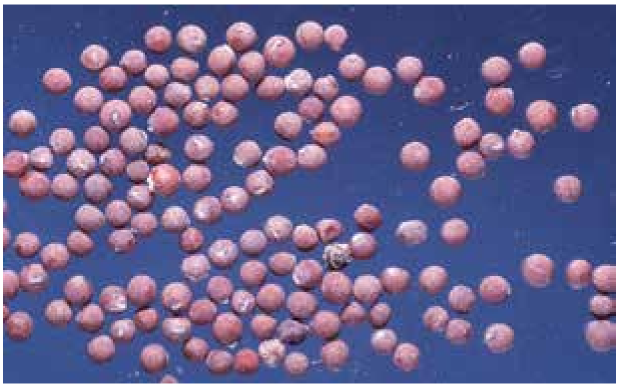

Figure W 27.4 Wild turnip seeds.
Photo: Peter Abell and Geoff Sainty

Environments where wild turnip dominates

Wild turnip is a weed common in southern and central Queensland, many parts of NSW, Victoria, Tasmania and South Australia, and in southern and central Western Australia. This weed can germinate at any time of the year, though most germination occurs either in autumn or spring.

Seasonal conditions that favour wild turnip

Seedlings emerge in late autumn and winter, growing over winter and early spring and flowering in spring and early summer. The lifecycle can closely match that of a cereal crop, with seeds maturing before or with the crop.

Conditions that favour wild turnip germination and establishment

Wild turnip germination is not influenced by light at the optimum temperature of 20 °C to 12 °C. However, seed germination can be controlled by light at lower temperatures (15 °C to 9 °C). Light increases the sensitivity of seeds to low temperature, as well as salt and osmotic stress. Seed germination is unaffected at high levels of water stress and seeds can germinate across a broad range of pH from 4 to 10.

Seed survival in the soil

A study by Chauhan et al. (2006) of a South Australian wild turnip population found that seed removed from pods appears to have a short half-life, with 77–87% of non germinated seed being non-viable after a single growing season, the other 12–18% remaining dormant. A study by Mahajan et al. (2018) using Queensland populations, has shown that seed dormancy can be quite variable between different populations, ranging from 90% to 100%. Burial studies have shown that wild turnip seedling emergence is generally greatest at surface level (0–1 cm deep) with no seedlings emerging from seeds placed 5cm deep.

Table W 27.1 Tactics to consider when developing an integrated plan to manage wild turnip (*Brassica tournefortii*).

Wild turnip (*Brassica tournefortii*)		Most likely % control (range)	Comments on use
Agronomy 3	Herbicide tolerant crops	90 (75–99)	Very useful for broadleaf crop phase of the rotation.
Tactic 2.2d	Selective post-emergent herbicides	90 (20–99)	Very good in cereals, but limited range in pulses and canola.
Tactic 2.5	Spray-topping with selective herbicides	80 (60–90)	Logran® good for cereals and Eclipse® in some pulses for Group B susceptible populations.
Agronomy 2	Improve crop competition	80 (50–99)	Competitive crops at optimum densities, row spacing and nutrition greatly reduces crop yield loss and reduces weed seed set.
Agronomy 1	Crop choice and sequence	80 (40–99)	Pulses are poor competitors; winter fallow–summer crop is a good choice.
Tactic 3.5	Grazing – actively managing weeds in pastures	75 (0–95)	Unmanaged pastures are a major source of crop weed problems. Rotational heavy grazing in combination with spray-grazing gives good control.
Tactic 2.2c	Pre-emergent herbicides	70 (60–90)	Control varies depending on seasonal conditions, with poorer results in dry starts.
Tactic 3.1b	Crop topping with non-selection herbicides	70 (60–80)	Good for early-planted short-season pulses.
Tactic 4.1	Weed seed control at harvest	60 (50–70)	Use on early harvested crops.
Tactic 1.5	Delayed sowing	60 (30–80)	Provides reasonable control in most seasons.
Tactic 2.1	Fallow and pre-sowing cultivation	50 (25–75)	Encourages germinations which can be controlled pre-planting.
Tactic 3.2	Pasture spray topping	50 (30–70)	Graze heavily over winter to induce a more uniform flowering. Graze or respray survivors.
Tactic 1.4	Autumn tickle	40 (20–60)	Effectiveness depends on seasonal conditions. Combine with delayed sowing (*Tactic 1.5*).
Tactic 3.1c	Wiper technology	Variable	Potentially useful in short pulse crops such as lentils where all the weeds are the same development stage and height.

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Weed 28 **Wireweed (*Polygonum* spp.)**

Common names

Wireweed, hogweed, knotweed, prostrate knotweed, sand wireweed (*Polygonum arenastrum*).

Distinguishing characteristics

There are two similar species of wireweed: *Polygonum aviculare*, which has branch leaves about half the size of stem leaves, and *Polygonum arenastrum* in which all leaves are of similar size.

Figure W 28.1 Mature *Polygonum arenastrum* plant
Photo: Andrew Storrie

Wireweed is an autumn to early summer germinating annual or biennial. Cotyledons are spear-shaped with a pointed apex, hairless, 7–15 mm long and blue–green.

Mature plants have a prostrate habit with branches up to 1.2 m long and a long fibrous taproot. Leaves are blue–green and occur alternately on the stems. Leaves have a short petiole and up to five flowers can be present in the leaf axils. Stems can root at the nodes.

The flowers are small and pinkish white. There is evidence to suggest that considerable variation exists within this species, with fruit dimension and shape the best characters to determine the different taxa.

Wireweed seeds are 1–2 mm in length and rusty brown.

Figure W 28.2 Flowering *Polygonum aviculare*
Photo: Andrew Storrie

Other weeds that can be confused with wireweed

Wireweed can be confused with tree hogweed (*Polygonum bellardii)*, which also has spear-shaped leaves. However, tree hogweed has a red stem and is an erect weed, growing up to 100 cm tall.

At the seedling stage wireweed is similar to ribwort (*Plantago lanceolate*) and bucks-horn plantain (*Plantago coronopus*) neither of which have a sheathing membrane at the base of the true leaves.

Factors that make wireweed a major weed

Delayed germination makes wireweed hard to control.

Wireweed often germinates and emerges during or after crop or pasture establishment. This is due to its physiological requirement for low soil temperatures to break the innate dormancy of fresh seed. It has a long tap-root that allows growth through the drier months of the year in southern Australia.

Wireweed competes for moisture and nutrients.

It can reduce crop and pasture yields by extracting nutrients, but generally has minimal impact on winter cereal crop yields due to its delayed emergence. Infestation of 1–3 seedlings/m^2 can reduce wheat dry mass by 10–19% whereas lucerne biomass can be reduced by 52% and 81%.

Wireweed often causes problems with machinery.

The long, tough branches of wireweed become tangled in cultivation equipment, causing blockages and spreading the weed. It can also interfere with harvesting operations because of lengthy branching.

Wireweed has phytotoxic properties.

These phytotoxic chemicals inhibit the establishment of other plant species, especially medic and lucerne. It also affects rhizobium bacteria required for legume nodulation.

Wireweed is not readily managed through grazing because of its low forage quality and relative unpalatability. It can be toxic to horses, with deaths having been recorded in NSW.

Figure W28.3 Wireweed choking crop of durum wheat.
Photo: Andrew Storrie

Environments where wireweed dominates

Both species of wireweed are natives of Europe and Asia and distribution is listed as cosmopolitan. Both are widespread cultivation weeds in Australia, particularly in cereal crops, canola and field peas, and are also serious weeds of lucerne and establishing pastures.

Wireweed is tolerant of atrazine and is often a weed of triazine-tolerant canola. Wireweed tolerates a wide range of environmental conditions and soil pH (5.6–8.5), although increasing salinity can reduce germination.

Seasonal conditions that favour wireweed

Wireweed is a problem when its germination coincides with that of crop or pasture seed. As wireweed requires a period of low soil temperature to germinate, there is an opportunity to establish crop and pasture before its germination peak, given appropriate moisture conditions.

With a long taproot wireweed often survives throughout the dry summer months in south-eastern Australia and occasionally in south-western Australia. This may present problems for perennial pasture systems such as lucerne because of additional competition for water and nutrients and contamination of the feed supply.

Conditions that favour wireweed germination and establishment

Current knowledge suggests that wireweed germination is favoured by low soil temperature in late autumn and early winter, and by cultivated seedbeds. Soil disturbance until June in South Australia favoured the emergence of wireweed.

A wireweed infestation depends on more than the simple cultural system used by the grower. Direct drilling is reported to discourage germination of the weed compared with full cultivation. Under a semi-arid agro-ecosystem in central Spain there was more wireweed in plots with conventional tillage than those with no tillage. However, studies in the United Kingdom showed increased levels of wireweed in minimum tillage paddocks and reduced levels in continuous winter wheat after shallow cultivation.

Figure W28.4 Wireweed seedlings.
Photo: Andrew Storrie

Seed survival in the soil

Wireweed seed is hard-coated and adapted for medium-term survival in the soil environment, with persistence likely to be greater than 5 years. The seeds produce a large dormant seed pool. Seed dormancy can be broken if seeds are exposed to low temperatures (2–4 °C) and light.

Under specific management the annual decline of the seedbank is estimated to be about 30%per year, with many seeds germinating but not surviving through to reproduction.

Research from the United Kingdom estimated a period of four to seven years is required to exhaust the wireweed seedbank.

Table W 28.1 Tactics to consider when developing an integrated plan to manage wireweed (*Polygonum* spp.).

Wireweed (*Polygonum* spp.)		Most likely % control (range)	Comments on use
Tactic 1.3	Inversion ploughing	90 (80–95)	Use once to bury resistant seed deeply then avoid bringing that seed back to the surface for at least 10 years.
Tactic 2.2a	Knockdown (non-selective) herbicides for fallow and pre-sowing control	90 (75–90)	Glyphosate, dicamba and some sulfonylurea herbicides are the most effective.
Tactic 2.2d	Selective post-emergent herbicides	90 (75–90)	Metsulfuron and dicamba provide good control. Target small weeds for better control. Few options exist in broadleaf crops.
Agronomy 3	Herbicide tolerant crops	90 (50–95)	Some imidazoline herbicides provide useful control in legume and imidazoline-tolerant crops. Glyphosate will provide good control in glyphosate-tolerant crops.
Tactic 2.2c	Pre-emergent herbicides	90 (50–80)	Trifluralin, pendimethalin, chlorsulfuron and triasulfuron provide good control, but are dependent on rain after application.
Tactic 3.4	Manuring, mulching and hay freezing	90 (50–80)	Good for controlling late germinations and reducing problems in summer fallow.
Agronomy 5	Fallow phase	80 (0–80)	Control early in the fallow to reduce vining (i.e. kill small plants).
Agronomy 1	Crop choice and sequence	80 (0–50)	Avoid continuous cereals or broadleaf crops where control is difficult. Avoid growing pulses in heavily infested paddocks. Wireweed increases in triazine-tolerant canola.

Contributors

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Weed 29 **Yellow burrweed (*Amsinckia* spp.)**

Common names

Amsinckia, Common fiddleneck (*Amsinckia intermedia*), Fiddleneck, Hairy fiddleneck (*Amsinckia calycina*), Iron weed, Tar weed, Yellow burrweed, Yellow forget-me-not.

Distinguishing characteristics

Yellow burrweed is a collective name for three plants of the *Amsinckia* species, *A. calycina*, *A. intermedia* and *A. lycopsoides*. It is an erect winter annual herb, found in all Australian states and territories although mainly in the south-eastern states of NSW, Victoria, South Australia. It between 30–120 cm tall with a branched stem and covered with long and short stiff hairs. The leaves are up to 20 cm long also with tiny hairs and leaves at ground level form a rosette, smaller leaves are arranged alternately along the stem. The flowers are bright yellow, trumpet shaped, with five petals approximately 5 mm long, grouped on a one-sided curling spike 10–25 cm long and curled over on itself at the tip. The fruit is a group of one to four seeds surrounded by a bristly green husk, ripe seeds are brown to black. Yellow burrweed has a stout taproot with many laterals.

Factors that make Yellow burrweed a weed.

Yellow burrweed is a competitive weed.

Yellow burrweed can germinate early, grows rapidly, competes for light, and is a strong competitor for nitrogen. This vigorous competition can reduce yields by 20–50% in cereals when heavy infestations occur and can reduce tiller number in wheat.

Yellow burrweed produces a large number of seeds and possesses high persistence.

Each yellow burrweed plant can produce up to 1,600 seeds per plant. The hard seed may remain viable in soil for at least five years although most seed is not likely to persist after two years. Germination can occur over a long period (March–July), making control difficult.

Yellow burrweed is a damaging weed to the Australian meat and wool industries.

Yellow burrweed competes in pastures and can cause liver damage and skin photosensitization. As yellow burrweed is from the same plant family of Paterson's Curse, and contains similar damaging chemicals, pyrrolizidine alkaloids. These chemicals can be toxic to pigs, cattle and horses, however, sheep and poultry are relatively resistant. The bristly calyx is also a wool contaminant.

Figure W 29.1 Mature *Amsinckia* spp. plants.
Photo: Michael Moerkerk

Yellow burrweed can tolerate herbicides.

Yellow burrweed is tolerant to phenoxy-acid (hormone) herbicides such as 2,4-D.

Yellow burrweed reduces the quality of crops.

The presence of yellow burrweed seed in wheat is claimed to impart a peculiar taint to flour and fragments of the black seed coat discolour flour.

Figure W 29.2 *Amsinckia* spp. seedling.
Photo: Geoff Sainty

Environments where yellow burrweed dominates

Yellow burrweed is a significant weed of cereals in the Wimmera and Mallee districts of Victoria and in NSW. Isolated infestations have been found occasionally in the cereal growing areas of Western Australia. Yellow burrweed grows vigorously on a wide range of soil types, including sandy surfaced mallee soils, black clays and red loams.

Figure W 29.3 *Amsinckia* spp. flowers.
Photo: Geoff Sainty

Seasonal conditions that favour yellow burrweed

Seeds germinate after the first autumn break, although small germination events can occur through autumn and winter. Plants die with the onset of high temperatures in late spring or early summer.

Conditions that favour yellow burrweed germination and establishment

Yellow burrweed prefers areas with an annual rainfall over 275 mm and is found on a wide range of soils, but grows particularly well in light sandy soils.

Seed survival in the soil

Studies have indicated that stored seed will survive at least two years. Seed germination is consistently high under both light and dark conditions (66% and 62% germination respectively). Seed can thus germinate whether buried or exposed. However, observations of seed in the field suggest a greatly reduced survival rate.

Table W 29.1 Tactics to consider when developing an integrated plan to manage yellow burrweed (*Amsinckia* spp.).

Yellow burrweed (*Amsinckia* spp.)		Most likely % control (range)	Comments on use
Agronomy 3	Herbicide tolerant crops	95 (40–99)	Glyphosate products can be used for control in pasture cropping situations.
Tactic 2.2d	Selective post-emergent herbicides	95 (40–99)	Use in combination with competitive crops.
Tactic 5.1a	Sow weed-free seed	95 (0–100)	Only sow seed produced in Yellow burrweed free paddocks, or have seed cleaned.
Tactic 3.1a	Spray-topping with selective herbicides	90 (80–99)	Good, while actively growing.
Tactic 2.5	Chipping, hand roguing	90 (80–90)	Small infestations can be removed by hand pulling.
Tactic 3.2	Pasture spray-topping	80 (70–90)	At 60 mm diameter head in clover based pastures.
Tactic 5.1c	Clean farm machinery and vehicles	80 (0–100)	Ensure harvesters are well cleaned before moving to clean property or paddock. Avoid using fodder and seed grain sourced from areas infested.
Tactic 3.5	Grazing – actively managing weeds in pastures	75 (60–80)	Grazing of goats can be used.
Agronomy 1	Crop choice and sequence	Variable	Pasture legumes can be used to suppress yellow burrweed during the fallow phase on lands used for cereal growing. In cereal fallows, repeated cultivations will destroy yellow burrweed seedlings from early germinations, but follow up herbicide treatment is needed after crops are sown.
Agronomy 2	Improve crop competition	Variable	Some degree of control can be obtained with competition from pasture species, particularly subterranean clover, supplemented by grazing and mowing to prevent flowering and seed formation.
Tactic 2.2c	Pre-emergent herbicides	Variable	Works best when combined with competitive crops. Metsulfuron-methyl applied before crop is sown will give control from several germinations before and after crop.

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References

Weed 1. Annual ryegrass

Aitken Y 1966. Flowering responses of crop and pasture species in Australia. I. Factors affecting development in the field of *Lolium* species (*Lolium rigidum* Gaud., *L. perenne* L., *L. multiflorum* Lam.). *Australian Journal of Agricultural Research*, vol. 17, pp. 821–839.

Chauhan BS, Gill GS, and Preston C 2006. Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. *Weed Science*, vol. 54, pp. 669–676.

Code GR 1990. Cost of selective ryegrass control and losses due to competition in Victorian winter field crops. *Proceedings of the Annual Ryegrass Workshop*, Adelaide, pp. 137–143.

Cousens R and Mortimer M 1995. *Dynamics of weed populations*. Cambridge University Press, Great Britain.

Davidson RM 1990. Management of herbicide resistant annual ryegrass, *Lolium rigidum*, in crops and pastures. *Proceedings of the 9th Australian Weeds Conference*, Adelaide, pp. 230–233.

Dodd J Martin RJ and Howes MK 1993. Management of agricultural weeds in Western Australia. Bulletin 4243, Department of Agriculture, Western Australia.

Douglas A and Peltzer SC 2004. Managing herbicide resistant annual ryegrass (*Lolium rigidum* Gaud.) in no-till systems in Western Australia using occasional inversion ploughing. *Proceedings of the 14th Australian Weeds Conference*, Wagga Wagga, pp. 300–303.

Gill GS 1993. Development of herbicide resistance in annual ryegrass in the cropping belt of Western Australia. *Proceedings of the 10th Australian and 14th Asian-Pacific Weed Conference*, pp. 282–285.

Gill GS 1996a. Why annual ryegrass is a problem in Australian agriculture. *Plant Protection Quarterly*, vol. 11, pp. 193–194.

Gill GS 1996b. Ecology of annual ryegrass. *Plant Protection Quarterly*, vol. 11, pp. 195–198.

Hussey BMJ, Keighery GJ, Cousens RD, Dodd J and Lloyd SG 1997. *Western Weeds: A Guide to the Weeds of Western Australia*. Plant Protection Society of Western Australia.

Kloot PM 1983. The genus *Lolium* in Australia. *Australian Journal of Botany*, vol. 31, pp. 421–435.

Matthews JM 1996a. Cultural management of annual ryegrass. *Plant Protection Quarterly*, vol. 11, pp. 198–200.

Matthews JM 1996b. Chemical management of annual ryegrass. *Plant Protection Quarterly*, vol. 11, pp. 200–202.

Moerkerk MR and Barnett AG 1998. *More Crop Weeds*. R.G. & F. J. Richardson, Meredith, Victoria, Australia.

Mullett HA 1919. *Lolium subulatum*, vis., 'Wimmera' rye-grass. *Journal Department of Agriculture, Victoria*, vol. 17, pp. 266–278.

Peltzer SC and Matson PT 2002. How fast do the seedbanks of five annual cropping weeds deplete in the absence of weed seed input? *Proceedings of the 13th Australian Weeds Conference*, Perth, pp. 553–555.

Peltzer SC, Minkey D and Walsh M 2005. Ingest, incinerate or invert? The pros and cons of three weed seed removal tactics. *Proceedings of Crop Updates, Technical Information for Agribusiness Conference*, Perth 2005. Weed Updates, Department of Agriculture, Western Australia and Grains Research and Development Corporation, pp. 6–8.

Reeves TG 1976. Effect of annual ryegrass (*Lolium rigidum*) on the yield of wheat. *Weed Research*, vol. 16, pp. 57–63.

Sindel BM 2000. *Australian Weed Management Systems*. R.G. & F.J. Richardson, Meredith, Victoria, Australia.

Steadman K and Owen M 2005. When is annual ryegrass emergence optimised? *Proceedings of Crop Updates, Technical Information for Agribusiness Conference*, Perth, 2005. Weed Updates, Department of Agriculture, Western Australia and Grains Research and Development Corporation, pp. 54–56.

Wilding JL, Barnett AG and Amor RL 1998. *Crop Weeds*. R.G. & F.J. Richardson, Meredith, Victoria, Australia.

Weed 2. Barley grass

Ali SM 1981. Barley grass as a source of pathogenic variation in *Rhynchosporium secalis*. *Australian Journal of Agricultural Research*, vol. 32, pp. 21–25.

Booth TA and Richards AJ 1976. Studies in the *Hordeum murinum* aggregate. I. Morphology. *Botanical Journal of the Linnean Society*, vol. 72, pp. 149–159.

Borchert MI 1977. The effect of rodent seed predation on four species of California annual grasses. *Dissertation Abstracts International B*, vol. 38, pp. 2507.

Borchert MI and Jain SK 1978. The effect of rodent seed predation on four species of California annual grasses. *Oecologia*, vol. 33, pp. 101–113.

Campbell RJ and Beale JA 1973. Evaluation of natural annual pastures of Trangie in central western New South Wales. 2. Botanical composition changes with particular reference to *Hordeum leporinum*. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 662–668.

Campbell RJ, Robards GE and Saville DG 1972. The effect of grass seed on sheep production. *Proceedings of the Australian Society of Animal Production*, vol. 9, pp. 225–229.

Campbell RJ, Saville DG and Robards GE 1973. Evaluation of natural annual pastures at Trangie in central western New South Wales. 1. Sheep production. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 238–244.

Chapin FS III and Bieleski RL (1982). Mild phosphorus stress in barley and a related low-phosphorus-adapted barley grass: Phosphorus fractions and phosphate absorption in relation to growth. *Physiologia Plantarum*, vol. 32, pp. 309–317.

Cocks PS 1974a. Response to nitrogen of three annual grasses. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 14, pp. 167–172.

Cocks PS 1974b. The influence of density and nitrogen on the outcome of competition between two annual pasture grasses (*Hordeum leporinum* Link and *Lolium rigidum* Gaud.). *Australian Journal of Agricultural Research*, vol. 25, pp. 247–258.

Cocks PS, Boyce KG and Kloot PM 1976. The *Hordeum marinum* complex in Australia. *Australian Journal of Botany*, vol. 24, pp. 651–662.

Cocks PS and Donald CM 1973a. The early vegetative growth of two annual pasture grasses (*Hordeum leporinum* Link and *Lolium rigidum* Gaud.). *Australian Journal of Agricultural Research*, vol. 24, pp. 11–19.

Cocks PS and Donald CM 1973b. The germination and establishment of two annual pasture grasses (*Hordeum leporinum* Link and *Lolium rigidum* Gaud.). *Australian Journal of Agricultural Research*, vol. 24, pp. 1–10.

Cornish PS and Beale JA 1974. Vegetable fault and grass seed infestation of sheep in New South Wales. *Journal of the Australian Institute of Agricultural Science*, vol. 40, pp. 261–267.

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1992. *Plants of Western New South Wales*. Inkata Press, Melbourne, Australia, pp. 110–111.

Fleet BJ and Gill GS 2010. Barley grass, an emerging weed threat in southern Australian cropping systems. *Proceedings of the 15th Australian Society of Agronomy Conference*, p. 47.

Fleet BJ and Gill GS 2011. Barley grass, an Emerging Weed Threat. Eyre Peninsula. *Farming Systems Summary 2010*, Minnipa, Australia, pp.164–169.

Fleet BJ and Gill GS 2012. Seed dormancy and seedling recruitment in smooth barley (*Hordeum murinum* ssp. *glaucum*) populations in southern Australia. *Weed Science*, vol. 60, pp. 394–400.

George JM 1972. Effects of grazing by sheep on barley grass (*Hordeum leporinum* Link) infestation of pastures. *Proceedings of the Australian Society of Animal Production*, vol. 9, pp. 221–224.

Gibson PR 1977. Persistence of perennial ryegrass under grazing in a Mediterranean-type environment of South Australia. *Proceedings of the 13th International Grassland Congress*, Leipzig, Sectional Papers, sections 3–4–5, pp. 295–300.

Gill G, Kleemann S and Fleet B 2018. Latest research on brome grass and susceptibility of emerging weed species to harvest weed seed capture, GRDC Update Papers, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/brome-grass-and-susceptibility-of-emerging-weed-species, Viewed 2 December 2018.

Gudkova GN 1976. On seed dormancy periods of wild species of *Hordeum* and the effect of floral scales on their germination. *Byulleten' Vsesoyuznogo Ordena Lenina i Ordena Druzhby Narodov Instituta Rastenievodstva imeni N.I.Vavilova*, vol. 60, pp. 25–26.

Halloran GM and Pennell AL 1981. Regenerative potential of barley grass (*Hordeum leporinum*). *Journal of Applied Ecology*, vol. 18, pp. 805–813.

Hartley MJ 1976a. Some effects of barley grass seed on young sheep. *Proceedings of the New Zealand Grassland Association*, vol. 37, pp. 59–65.

Hartley MJ 1976b. *The Barley Grass Problem in New Zealand* (vol. 2). British Crop Protection Council, London, pp. 575–581.

Hartley MJ, Atkinson GC, Bimler KH, James TK and Popay AI 1978. *Control of Barley Grass by Grazing Management*. New Zealand Weed and Pest Control Society, Palmerston North, pp. 198–202.

Hashem A and Borger C 2019. Barley grass (*Hordeum leporinum*) has evolved a delayed emergence strategy to escape knockdowns in Western Australia, GRDC Update Papers, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/barley-grass-hordeum-leporinum-has-evolved-a-delayed-emergence-strategy-to-escape-knockdowns-in-western-australia. Viewed 13 March 2019.

Holmes JE 1984. Seed set control – potential of fluazifop-butyl and Dowco 453. *Proceedings of the 7th Australian Weeds Conference*. Weed Society of Western Australia, Perth, vol. 1, pp. 358–362.

Khan TN 1973. Host specialization by Western Australian isolates causing net blotch symptoms on *Hordeum. Transactions of the British Mycological Society*, vol. 61, pp. 215–220.

Kloot PM 1981. A reassessment of the ecology of barley grass in Australia. *Proceedings of the 6th Australian Weeds Conference*, Gold Coast, Queensland, vol. 1, pp. 45–50.

Kohn GD 1974. Superphosphate utilisation in clover ley farming. 1. Effects on pasture and sheep production. *Australian Journal of Agricultural Research*, vol. 25, pp. 525–535.

Mayfield AH and Clare BG 1984. Survival over summer of *Rhynchosporium secalis* in host debris in the field. *Australian Journal of Agricultural Research*, vol. 35, pp. 789–797.

McIvor JG and Smith DF 1973a. Plant factors influencing the nutritive value of some temperate annual pasture species. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 404–410.

McIvor JG and Smith DF 1973b. The effect of management during spring on the growth of a mixed annual pasture containing capeweed (*Arctotheca calendula*). *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 398–403.

McKinney GT 1974. Management of lucerne for sheep grazing on the Southern Tablelands of New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 14, pp. 726–734.

Michalk DL and Beale JA 1976. An evaluation of barrel medic (*Medicago truncatula*) as an introduced pasture legume for marginal cropping areas of south-eastern Australia. *Journal of Range Management*, vol. 29, pp. 328–333.

Michalk DL, Byrnes CC and Robards GE 1976. Effects of grazing management on natural pastures in a marginal area of south-eastern Australia. *Journal of Range Management*, vol. 29, pp. 380–383.

Moore CB and Moore JH 2005. HerbiGuide – the pesticide expert on a disk, Version 19.3. 1–5–2005. Box 44, Albany, Western Australia 6331.

Moore RM and Williams JD 1983. Competition among weedy species: diallel experiments. *Australian Journal of Agricultural Research*, vol. 34, pp. 119–131.

Peltzer SC and Matson PT 2002. How fast do the seedbanks of five annual cropping weeds deplete in the absence of weed seed input? *Proceedings of the 13th Australian Weeds Conference*, Perth, pp. 553–555.

Popay AI 1975. Laboratory germination of barley grass. New Zealand Weed and Pest Control Society, Hamilton, pp. 7–11.

Popay AI 1981. Germination of seeds of five annual species of barley grass. *Journal of Applied Ecology*, vol. 18, pp. 547–558.

Preston C 2003. Latest developments in herbicide resistance. *GRDC Research Update*, Grains Research and Development Corporation, Wagga Wagga, New South Wales.

Rodin LE, Bazilevich NI and Miroshnichenko Y 1972. Productivity and biogeochemistry of Artemisia in the Mediterranean area. *Eco physiological foundation of ecosystems productivity in arid zone*. Nauka, Leningrad, pp. 193–198.

Shearer BL 1973. *Septoria halophila*, a pathogen of *Hordeum leporinum* in the wheat-growing area of Western Australia. *Plant Disease Reporter*, vol. 57, pp. 367–370.

Southwood OR, Saville DG and Gilmour AR 1976. The value to Merino ewes and lambs of continued superphosphate topdressing on a subterranean clover pasture ley. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 16, pp.197–203.

Thorn CW and Perry MW 1983. Regulating pasture composition with herbicides. *Journal of Agriculture – Western Australia*, vol. 1, pp. 21–26.

Wallwork H 1987. A *Tapesia* teleomorph for *Pseudocercosporella herpotrichoides*, the cause of eyespot of wheat. *Australasian Plant Pathology*, vol. 16, pp. 92–93.

Warner RB 1984. Further studies on a population of barley grass, *Hordeum leporinum* spp. *glaucum* Steud., tolerant to paraquat. *Proceedings of the 7th Australian Weeds Conference*, Weed Society of Western Australia, Perth, pp. 356–357.

Warr GJ and Thompson JM 1976. Liveweight change and intake of lambs as affected by seed infestation. *Proceedings of the Australian Society of Animal Production*, pp.173–176.

Weed 3. Barnyard grass

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1981. *Plants of Western New South Wales*. Soil Conservation Service of New South Wales.

Duke J 1983. Handbook of energy crops. www.hort.purdue.edu/newcrop/duke_energy/Echinochloa_crusgalli.html

Hazelwood S and Johnson SB 2002. Weed Identification and Information Guide. WEEDpak, a guide for integrated management of weeds in cotton. Australian Cotton Cooperative Research Centre, Narrabri, pp. A 2.9–A 2.10.

Holm LG, Plucknett DL, Pancho JV and Herberger JP 1977. *The World's Worst Weeds–Distribution and Biology*. The University Press of Hawaii, Honolulu, pp. 32–45.

Martinkova Z, Honek A and Lukas J 2006. Seed age and storage conditions influence germination of barnyard grass (*Echinochloa crus-galli*). *Weed Science*, vol. 54, pp. 298–304.

Maun MA and Barrett SCH 1986. The biology of Canadian weeds. No 77. *Echinochloa crus-galli* (L.) Beuav. *Canadian Journal of Plant Science*, vol. 66, pp. 739–759.

Mercado BL and Talatala RL 1977. Competitive ability of *Echinochloa colonum* L. against direct-seeded lowland rice. *Proceedings of the 6th Asian-Pacific Weed Science Society Conference*, Indonesia, pp. 161–165.

Michael PW 2001. The taxonomy and distribution of *Echinochloa* species (barnyard grasses) in the Asian–Pacific region, with a review of pertinent biological studies. *Proceedings of the 18th Asian–Pacific Weed Science Society Conference*, Beijing, China, pp. 57–67.

Norris RF, Elmore CL, Rejmanek M and Akey WC 2001. Spatial arrangement, density, and competition between barnyard grass and tomato: II. Barnyard grass growth and seed production. *Weed Science*, vol. 49, pp. 69–76.

Preston C 2013. Australian Glyphosate Sustainability Working Group. Online.

Ramakrishnan ES 1960. Ecology of *Echinochloa colonum* LINK. *Proceedings of the Indian Academy of Science*, Section B2, pp. 73–90.

Wu H, Walker SR, Osten VA, Taylor IN and Sindel B 2004. Biology of barnyard grass and its management options in summer crops. *Proceedings of the 14th Australian Weeds Conference*, Wagga Wagga, pp. 538–541.

Weed 4. Black bindweed

Conn JS and Deck RE 1995. Seed viability and dormancy of 17 weed species after 9.7 years of burial in Alaska. *Weed Science*, vol. 43, pp. 583–587.

Fain DM, Peeper TF and Greer HA 1980. Wild buckwheat in Oklahoma wheat: problems and control. *Proceedings of the 33rd Annual Meeting of the Southern Weed Science Society*, pp. 66.

Forcella F, Wilson RG, Dekker J, Kremer RJ, Cardina J, Anderson RL, Alm D, Renner R, Harvey RG, Clay S and Buhler DD 1997. Weed seed bank emergence across the Corn Belt. *Weed Science*, vol. 45, pp. 67–76.

Hussey BJM, Keighery GJ, Cousens RD, Dodd J and Lloyd SG 1997. *Western Weeds: A Guide to the Weeds of Western Australi*a. Plant Protection Society of Western Australia.

Metzger JD 1992. Physiological basis of achene dormancy in *Polygonum convolvulus* (*Polygonaceae*). *American Journal of Botany*, vol. 79, pp. 882–886.

Thomas AG, Le´Gere A, Leeson JY, Stevenson FC, Holm FA and Gradin BG 2011. Weed community response to contrasting integrated weed management systems for cool dryland annual crops. *Weed Research*, vol. 51, pp. 41–50.

Wills DA, Walker SR and Adkins SW 1996. Herbicide resistant weeds from the north-east grain region of Australia. *Proceedings of the 11th Australian Weeds Conference*, Melbourne, pp. 126–129.

Weed 5. Bladder ketmia

Craven LA, de Lange PJ, Lally TR, Murray BG and Johnson SB 2011. A taxonomic re-evaluation of *Hibiscus trionum* (Malvaceae) in Australasia. *New Zealand Journal of Botany*, vol. 49, pp. 27–40.

Johnson SB 2004. Best management of bladder ketmia. What you can do to make a difference. *Proceedings of the 12th Australian Cotton Conference*, Broadbeach, Queensland, pp. 301–306.

Johnson SB, Charles GW, Roberts GN and Taylor IN 2002. Weed Identification and Information Guide. *WEEDpak, a guide for integrated management of weeds in cotton*. Australian Cotton Cooperative Research Centre, Narrabri, pp. A2.39–A2.41. https://cottoninfo.com.au/publications/weedpak, Viewed 12 December 2018.

Johnson SB, Sindel BM and Charles GW 2003. What bladder ketmia have you got? *The Australian Cottongrower*, vol. 24, pp. 50–54.

Taylor I, Johnson S and MacKinnon L 2002. Best Bet Management Guide. *WEEDpak, a guide for integrated management of weeds in cotton*. Australian Cotton Cooperative Research Centre, Narrabri, pp. G2.7–G2.8. https://cottoninfo.com.au/publications/weedpak, Viewed 12 December 2018.

Walker S, Wu H and Bell K 2010. Emergence and seed persistence of *Echinochloa colona*, *Urochloa panicoides* and *Hibiscus trionum* in the sub-tropical environment of north-eastern Australia. *Plant Protection Quarterly*, vol. 25, pp. 127–132.

Wilson BJ, Hawton D and Duff AA 1995. *Crop Weeds of Northern Australia*. Queensland Department of Primary Industries, Brisbane, pp. 134–135.

Weed 6. Brome grass

Amor RL and de Jong RW 1983. Changing weed problems in cereal cropping in Victoria since 1920. *Journal of the Australian Institute of Agricultural*, vol. 49, pp. 139–147.

Blacklow WM 1983. The ecology and control of weeds in the coupled evolution of man and agronomy. *Symposium of the Biology and Taxonomy of Weeds*. Australian and New Zealand Association for Advancement of Science, Perth.

Cheam AH 1986. Patterns of change in seed dormancy and persistence of *Bromus diandrus* Roth (great brome) in the field. *Australian Journal of Agricultural Research*, vol. 37, pp. 471–481.

Cheam AH 1987. Longevity of *Bromus diandrus* Roth seed in soil at three sites in Western Australia. *Plant Protection Quarterly*, vol. 2, pp. 137–139.

Cheam AH 1988. Brome grass seed banks and regeneration under lupins–wheat rotation cropping in Western Australia. *VIIIème Collogue International sur la Biologie, L'Ecologie et la Systematique des Mauvaises Herbes,* pp. 343–352.

Cheam AH and Zaicou CM 1993. Integrated control of brome grass. Management of Agricultural Weeds in Western Australia. Bulletin 4243, Department of Agriculture, Western Australia, pp. 55–62.

Gill GS and Blacklow WM 1985. Variations in seed dormancy and rates of development of great brome *Bromus diandrus* Roth, as adaptations to the climates of southern Australia and implications for weed control. *Australian Journal of Agricultural Research*, vol. 36, pp. 295–304.

Gill GS and Bowran DG 1990. Tolerance of wheat cultivars to metribuzin and implications for the control of *B. diandrus* and *B. rigidus* in Western Australia. *Australian Journal of Experimental Agriculture*, vol. 30, pp. 373–378.

Gill GS, Poole ML and Holmes JE 1987. Competition between wheat and brome grass in Western Australia. *Australian Journal of Experimental Agriculture*, vol. 27, pp. 291–294.

Harradine AR 1986. Seed longevity and seedling establishment of *Bromus diandrus* Roth. *Weed Research*, vol. 26, pp. 173–180.

Kleemann SGL and Gill GS 2004. Eyre Peninsula Farming Systems, Handbook. Farming Systems Group, Minnipa, South Australia, pp. 145–149.

Kon KF and Blacklow WM 1995. *Bromus diandrus* Roth and *B. rigidus* Roth. The Biology of Australian Weeds. R.G. and F.J. Richardson, Melbourne, pp. 13–28.

Mock IT and Amor RL 1982. Brome grasses (*Bromus* spp.) as contaminants of barley grain in the Victorian Mallee. *Australian Weeds*, vol. 2, pp. 16–17.

Poole ML and Gill GS 1987. Competition between crops and weeds in southern Australia. *Plant Protection Quarterly*, vol. 2, pp. 86–96.

Rossiter RC 1966. Ecology of Mediterranean annual-type pasture. *Advances in Agronomy*, vol. 18, pp. 1–56.

Tiver NS and Crocker RL 1951. The grasslands of south-east South Australia in relation to climate soils and developmental history. *Journal of the British Grassland Society*, vol. 6, pp. 29–80.

Wilding JL, Barnett AG and Amor RL 1998. Crop Weeds. R.G. and F.J. Richardson, Melbourne, Australia.

Weed 7. Capeweed

Allen JM 1977. Weeds in grain-lupins. 1: The effect of weeds on grain–lupin yields. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 17, pp. 112–117.

Arnold GW, Ozanne PG, Galbraith KA and Dandridge F 1985. The capeweed content of pastures in south-west Western Australia. *Australian Journal of Experimental Agriculture*, vol. 25, pp. 117–123.

Auld BA and Medd RW 1992. *Weeds: An illustrated botanical guide to the weeds of Australia*. Inkata Press, Melbourne, Australia.

Bolger TP, Thomson CJ and Turner NC 1993. Nitrogen effects on competition between subterranean clover and capeweed plant nutrition – from genetic engineering to field practice. *Proceedings of the 12th International Plant Nutrition Colloquium*, Perth, Western Australia, pp. 509–512. Kluwer Academic Publishers, Dordrecht.

Chaharsoghi AT and Jacobs B 1998. Manipulating dormancy of capeweed (*Arctotheca calendula* L.) seed. *Seed Science Research*, vol. 8, pp. 139–146.

Dodd J 1993. Biology and ecology of weeds – major agricultural weeds. *Management of Agricultural Weeds in Western Australia*. Department of Agriculture, Western Australia, pp. 9–40.

Dunbabin MT and Cocks PS 1999. Ecotypic variation for seed dormancy contributes to the success of capeweed *Arctotheca calendula* in Western Australia. *Australian Journal of Agricultural Research*, vol. 50, pp. 1451–1458.

Ellery AJ 2002. Embryo dormancy responses to temperature in capeweed (*Arctotheca calendula*) seeds. *Seed Science Research*, vol. 12, pp. 181.

Ellery AJ and Chapman R 2000. Embryo and seed coat factors produce seed dormancy in capeweed (*Arctotheca calendula*). *Australian Journal of Agricultural Research*, vol. 51, pp. 849–854.

Hussey BMJ, Kieghery GJ, Cousens RD, Dodd J and Lloyd SG 1997. *Western Weeds: A Guide to the Weeds of Western Australia*. The Plant Protection Society of Western Australia.

Lazarides M and Hince B 1993. *CSIRO handbook of economic plants of Australia*. CSIRO, Melbourne, Australia.

Manoto MM, Ferreira MI and Agenbag GA 2004. The effect of temperature on the germination of six selected weed species. *South African Journal of Plant and Soil*, vol. 21, pp. 214–219.

McIvor JG and Smith DF 1973a. The effect of defoliation and sward density on the growth of some annual pasture species. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 178–184.

McIvor JG and Smith DF 1973b. The effect of defoliation on seed production by cape weed (*Arctotheca calendula*). *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 13, pp. 676–680.

McIvor JG and Smith DF 1974. The effect of fertilizer application and time of seasonal break on the growth and dominance of capeweed (*Arctotheca calendula*). *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 14, pp. 553–556.

Peirce JR 1979. The use of diuron and MCPA mixtures for broadleaved weed control in cereals. *Proceedings of the 7th Asian-Pacific Weed Science Society Conference*, Sydney, Australia, pp. 427–430.

Peirce JR, Bowran DG, Sawkins DN, Roberts BH and Buckley J 1991. *Control of Capeweed in Oats*. Department of Agriculture, Western Australia, RIS 91NA96.

Peirce JR and Rayner BJ 1992. *Capeweed Control Prior to Cropping*. Department of Agriculture, Western Australia, RIS 92WH61.

Pemberton DH and White WE 1976. Bovine nasal granuloma in Victoria – a search for the causative allergens. *Australian Veterinary Journal*, vol. 52, pp. 155–157.

Pethick DW and Chapman HM 1991. The effects of *Arctotheca calendula* (capeweed) on digestive function of sheep. *Australian Veterinary Journal*, vol. 68, pp. 361–363.

Powles SB, Tucker ES and Morgan TR 1989. A capeweed (*Arctotheca calendula*) biotype in Australia resistant to bipyridyl herbicides. *Weed Science*, vol. 37, pp. 6–62.

Purba E, Preston C and Powles SB 1993. Inheritance of bipyridyl herbicide resistance in *Arctotheca calendula* and *Hordeum leporinum*. *Theoretical and Applied Genetics*, vol. 87, pp. 598–602.

Reeves TG and Lumb JM 1972. Selective chemical control of capeweed in wheat and oats. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 12, pp. 60–64.

Shovelton JB 1979. Survey of weeds of Victorian dryland pastures. *Proceedings of the 7th Asian-Pacific Weed Science Society Conference*, Sydney, Australia, pp. 169–172.

Sousa ME and Caixinhas ML 1998. Seed germination of weeds from grasslands of Portugal. *Comptes-rendus 6ème Symposium Mediterranean EWRS*, Montpellier, France. ENSA, Montpellier, pp. 236–237.

Taylor AJ 1987. Influence of weed competition on autumn-sown lucerne in south-eastern Australia and the field comparison of herbicides and mowing for weed control. *Australian Journal of Experimental Agriculture*, vol. 27, pp. 825–832.

Turner NC, Thomson CJ and Rawson HM 2001. Effect of temperature on germination and early growth of subterranean clover, capeweed and Wimmera ryegrass. *Grass and Forage Science*, vol. 56, pp. 97–104.

Walsh GL and Birrell HA 1987. Seasonal variations in the chemical composition and nutritive value of five pasture species in south-western Victoria. *Australian Journal of Experimental Agriculture*, vol. 27, pp. 807–816.

Wells GS 2008a. Florasulam+isoxaben for management of herbicide resistant wild radish in Western Australia. *Proceedings of the 16th Australian Weeds Conference, Cairns, Australia*, 2008, pp 336–338. Queensland Weed Society, Queensland, Australia.

Wells G.S. 2010b. Pyroxsulam for broad-spectrum weed control in wheat. *Proceedings of the 16th Australian Weeds Conference, Cairns, Australia*, pp 297–299, Queensland Weed Society, Queensland, Australia.

Wilding JL, Barnett AG and Amor RL 1998. *Crop Weeds*. R.G. and F.J. Richardson, Melbourne, Australia.

Wood H 1994. The introduction and spread of capeweed, *Arctotheca calendula* (L.) (Asteraceae) in Australia. *Plant Protection Quarterly*, vol. 9, pp. 94–100.

Weed 8. Common sowthistle

Adkins SW, Wills D, Boersma M, Walker SR, Robinson G, McLeod RJ and Einam JP 1997. Weeds resistant to chlorsulfuron and atrazine from the north-east grain region of Australia. *Weed Research*, vol. 37, pp. 343–349.

Barber HN 1941. Spontaneous hybrids between *Sonchus asper* and *S. oleraceus*. *Annals of Botany*, vol. 18, pp. 375–377.

Chauhan BS, Gill GS and Preston C 2006. Factors affecting seed germination of annual sowthistle (*Sonchus oleraceus*) in southern Australia. *Weed Science*, vol. 54, pp. 854–860.

Frankton C and Mulligan GA 1987. *Weeds of Canada*. New Canada Publication, NC Press Limited, Toronto, Ontario, pp. 202–203.

Widderick M 2002. *Common Sowthistle – Understanding its Ecology is the Key to Better Management*. Crop Link Extension Brochure, Queensland Department of Primary Industries and Fisheries.

Widderick M, Sindel B. and Walker S 1999. Distribution, importance and management of *Sonchus oleraceus* (common sowthistle) in the northern cropping region of Australia. *Proceedings of the 12th Australian Weeds Conference, Hobart, Tasmania*, p. 198. Tasmanian Weed Society.

Widderick M, Sindel B and Walker S 2002. Emergence of *Sonchus oleraceus* is favoured under zero tillage farming systems. *Proceedings of the 13th Australian Weeds Conference*, Perth, Western Australia, pp. 91–92.

Widderick M, Walker S and Sindel B 2004. Better management of *Sonchus oleraceus* L. (common sowthistle) based on the weed's ecology. *Proceedings of the 14th Australian Weeds Conference*, Wagga Wagga, New South Wales, pp. 535–537.

Widderick MJ, Walker SR, Sindel BM, and Bell KL 2010. Germination, emergence, and persistence of *Sonchus oleraceus*, a major crop weed in subtropical Australia. *Weed Biology and Management*, vol. 10, pp. 102–112.

Weed 9. Cutleaf mignonette

Heap JW 1997. Biology and control of *Reseda lutea* L. 1. Seed biology and seedling growth. *Australian Journal of Agricultural Research*, vol. 48, pp. 511–16.

Heap JW 1997. Biology and control of *Reseda lutea* L. 2. Life cycle: Seedling emergence, recruitment, and vegetative reproduction. *Australian Journal of Agricultural Research*, vol. 48, pp. 517–524.

Heap JW, Willcocks MC and Kloot PM 1987. The Biology of Australian Weeds, 17. *Reseda lutea* L. *Plant Protection Quarterly*, vol. 2, pp. 178–85.

Heap JW, Wilcocks MC and Kloot PM 1995. *Reseda lutea* L; Groves RH, Shepherd, RCH and Richardson RG (eds), *The Biology of Australian Weeds*. vol. 1, pp. 203–216. RG and FJ Richardson Publ., Melbourne.

Parsons WT and Cuthbertson EG 2001. *Noxious Weeds of Australia*. 2nd Edition, CSIRO Publishing.

South Australian Murray darling Basin Natural Resource management Board (SA MDB NRMA Board). Cutleaf mignonette (*Reseda lutea*). *Weed sheet*, https://data.environment.sa.gov.au/Content/Publications/pests_cutleaf_mignonette.pdf Viewed 13 November 2018

Weed 10. Doublegee

Auld BA and Medd RW 1992. *Weeds: An illustrated botanical guide to the weeds of Australia*. Inkata Press, Melbourne, Australia.

Borger C and Hashem A 2019. Doublegee's seedy secret, GRDC Update Papers, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/doublegees-seedy-secret, Viewed 15 March 2019.

Cheam A 1987. Emergence and survival of buried doublegee seeds. *Australian Journal of Experimental Agriculture*, vol. 27, pp. 101–106.

Fromm G 1996. *Emex* spp. in South Australia. *Plant Protection Quarterly*, vol. 11, pp. 146–149.

Gilbey DJ 1987. Doublegee (*Emex australis* Steinh) seed longevity in Western Australia. *Proceedings of the Weed Seed Biology Workshops*, Orange, Australia pp. 39–40.

Gilbey DJ and Lightfoot RJ 1979. Doublegee control in pasture – what is it worth? *Journal of Agriculture Western Australia*, vol. 20, pp. 21–23.

Gilbey DJ, Weiss PW and Shepperd RCH 1998. *Emex autralis* Steinh. *The Biology of Australian Weeds*. R.G. and F.J. Richardson, Meredith, Australia.

Hagon M and Simmons D 1978. Seed dormancy of *Emex australis* and *E. spinosa*. *Australian Journal of Agricultural Research*, vol. 29, pp. 565–575.

Hashem A and Pathan S 2007. Doublegee has developed resistance to metsulfuron-methyl within WA wheatbelt. *Proceedings of Crop Updates: weed updates 2007*. pp 39–40. Department of Agriculture and Food, Western Australia, Perth.

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S and Ouzman J 2016. *Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices.* Grains Research and Development Corporation, Canberra, ACT, Australia.

Panetta F and Randall R 1993. Variation between *Emex australis* populations in seed dormancy/non-dormancy cycles. *Australian Journal of Ecology*, vol. 32, pp. 275–280.

Pearce GA 1969. Control of weeds in cereals. *Journal of the Department of Agriculture Western Australia*, vol. 10, pp. 138–147.

Wilding JL, Barnett AG and Amor RL 1998. *Crop Weeds*. R.G. and F.J. Richardson, Melbourne, Australia.

Yeoh PB and Scott JK 2004. *Emex australis–Crop Protection Compendium, 2004 edition*. CAB International, Wallingford, UK.

Weed 11. Feathertop Rhodes grass

Ngo TD, Krishnan M, Boutsalis P, Gill G and Preston C 2018. Target-site mutations conferring resistance to glyphosate in feathertop Rhodes grass (*Chloris virgata*) populations in Australia. *Pest management science*, vol 74., pp.1094–1100

Osten V 2012. Managing feathertop Rhodes grass–A best weed management guide. Northern IWM Factsheet. Grains Research and Development Corporation.

Walker SR 2013. Managing summer grasses in fallows – A review of the latest research findings on chemical control. *Grains Research Updates*. Independent Consultants Australia Network P/L and Grains Research and Development Corporation, Goondiwindi, Australia.

Weed 12. Fleabane

Preston C 2013. Australian Glyphosate Sustainability Working Group: www.glyphosateresistance.org.au/index.html Viewed 15 November 2018

Walker S, Widderick M and Wu H 2004. Fleabane. *Proceedings of the management of fleabane workshop*. Department of Primary Industries and Fisheries, Queensland. www.pandora.nla.gov.au/pan/64168/20080620-0000/www.weeds.crc.org.au/publications/wshop_proceedings.html

Walker S, Werth J and Widderick M 2007. Management of flaxleaf fleabane. *Proceedings of the management of flaxleaf fleabane workshop*. Department of Primary Industries and Fisheries, Queensland. www.pandora.nla.gov.au/pan/64168/20080620-0000/www.weeds.crc.org.au/publications/wshop_proceedings.html

Walker S 2011. *Management of flaxleaf fleabane*. Department of Primary Industries and Fisheries, Queensland.

Walker SR, Bell K, Robinson G and Widderick M 2011. Flaxleaf fleabane (*Conyza bonariensis*) populations have developed glyphosate resistance in north-east Australian cropping fields. *Crop Protection*, vol. 31, pp. 311–317.

Werth J, Walker S, Boucher L and Robinson G 2010. Applying the double knock technique to control *Conyza bonariensis*. *Weed Biology and Management*, vol. 10, pp. 1–8.

Wu H, Walker S, Rollin MJ, Tan DKY and Werth G 2007. Germination, persistence and emergence of flaxleaf fleabane (*Conyza bonariensis* L. Cronq.). *Weed Biology and Management*, vol. 7, pp. 192–199.

Wu H, Walker S and Robinson G 2008. Control of flaxleaf fleabane (*Conyza bonariensis* L. Cronq.) in winter fallows. *Plant Protection Quarterly*, vol. 23, pp. 162–165.

Wu H 2009. Biology of flaxleaf fleabane (*Conyza bonariensis* L. Cronq.). *The biology of Australian Weeds* (*vol. 3*), pp. 85–101. R.G. and F.J. Richardson. Melbourne, Australia.

Wu H, Walker S and Robinson G 2010. Control of flaxleaf fleabane (*Conyza bonariensis* L. Cronq.) in wheat and sorghum. *Weed Technology*, vol. 24, pp. 102–107.

Weed 13. Fumitory

Bowcher A and Condon K 2005. *Fumitory update*. Cooperative Research Centre for Australian Weed Management. www.pandora.nla.gov.au/pan/64168/20080620-0000/www.weeds.crc.org.au/documents/fs12_fumitory_id.pdf

Harden GJ 1990. Fumariaceae. *Flora of New South Wales* (*vol.1*), pp. 172–175. Royal Botanic Gardens, Sydney, Australia.

Lemerle D, Yuan TH, Murray GM and Morris S 1996. Survey of weeds and diseases in cereal crops in the southern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture*, vol. 36, pp. 545–54.

Norton GM 2003. Understanding the success of fumitory as a weed in Australia. PhD Thesis, Charles Sturt University, Wagga Wagga, Australia.

Norton GM, Lemerle D, Pratley JE and Norton MR 2011. Association between environmental factors and the occurrence of six fumitory species (*Fumaria* spp. L.) in southern-eastern Australia. *Plant Protection Quarterly*, vol. 26, pp. 57–66.

Walsh NG 1994. Fumariaceae. *Flora of Victoria* (*vol. 3*): *Dicotyledons – Winteraceae to Myrtaceae*, pp. 73–78. Inkata Press, Melbourne, Australia.

Weed 14. Liverseed grass

Cook AS, Coldham JL and Storrie AM 1992. 1989–92 Results. Crops, Weed Research and Demonstration Unit, Tamworth Centre for Crop Improvement, NSW Agriculture, pp. 49–59.

Harden GJ (ed.) 1993. *Flora of New South Wales* (*vol. 4*), p. 469. University of NSW Press, Sydney, Australia.

Sommervaille A and McLennan B 2003. *The Second Fallow Weed Management Guide*. Conservation Farmers Inc.

Walker SW, Wilson B, Wu H, Widderick M and Taylor I 2007. *Seed persistence of key northern region weeds*. Information brochure available from www.dpi.qld.gov.au/26_4428.htm

Walker SW, Widderick M, Thornby D, Boucher L, McLean A, Osten V, Cook T, Davidson B and Miller B 2011. Technical Report. Risk assessment and preventative strategies for herbicide resistance in NR (DAQ00136). A report submitted to the Grains Research and Development Corporation, pp. 23–8.

Wicks CA, Felton WL and Welsby SM 1993. Effect of rainfall on glyphosate performance on stressed grass weeds following wheat harvest. *Plant Protection Quarterly*, vol. 8, pp. 2–6.

Weed 15. Indian hedge mustard

Boutsalis P and Powles SB 1995. Resistance of dicotyledon weeds to acetolactate synthase (ALS) inhibiting herbicides in Australia. *Weed Research*, vol. 39, pp. 149–155.

Chauhan BS, Gill GS, and Preston, C. 2006. Influence of environmental factors on seed germination and seedling emergence of Oriental mustard (*Sisymbrium orientale*). *Weed Science*, vol. 54, pp. 1025–1031.

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1992. *Plants of Western New South Wales*. Inkata Press, Melbourne, Australia.

Navie S and Adkins SW 2004. *Crop Weeds of Australia: An Identification and Information System* (educational version). CD-ROM identification tool, produced by CBIT. www.cbit.uq.edu.au.

Walker SR 2002. *Resistance sampling – a survey of herbicide resistance in the north*. GRDC Research Update. Grains Research and Development Corporation.

Wilding JL, Barnett AG and Amor RL 1998. *Crop Weeds*. R.G. and F.J. Richardson, Melbourne.

Weed 16. Muskweed

Honarmand SJ, Nosratti I, Nazari K, and Heidari H 2016. Factors affecting the seed germination and seedling emergence of muskweed (*Myagrum perfoliatum*). *Weed Biology and Management*, vol 16, pp. 186–193.

Moerkerk M (1999a). Muskweed management. Workshop proceedings, Volunteering for International Development from Australia (VIDA). February 1999.

Moerkerk M (1999b). Muskweed management. Workshop proceedings, Volunteering for International Development from Australia (VIDA). April 1999.

Storrie AM 2001. *Muskweed*. Weed alert series. New South Wales Agriculture.

Stuchbery J 2002, Integrated management of muskweed (*Myagrum perfoliatum*) in cropping systems in Victoria–Final Report. John Stuchbery & Associates, Donald, Victoria.

Weed 17. Noogoora burr

Anon 2016. Noogoora burr (*Xanthium strumarium*): Invasive plant, Department of Agricultural and Fisheries, Biosecurity Queensland.

Australian Cotton Cooperative Research Centre 2002. *Weedpak a guide for integrated management of weeds in cotton*. Narrabri, NSW: Australian Cotton Cooperative Research Centre.

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1992. *Plants of Western New South Wales*, pp. 726–727.

Laidlaw MJ, Louden MA, Bean AR and Thompson EJ 2017. *Reducing weed risks from fodder*. Queensland Herbarium, Toowong.

Nehl DB and Brown JF 2000. Biological control of the Noogoora burr complex with *Alternnria zinniae*: environmental conditions favouring disease. *Australasian Plant Pathology*, vol. 29, pp. 71–80.

Weed 18. Paradoxa grass

Dellow JJ and Milne BR 1986. Control of Phalaris paradoxa in wheat. *Australian Weeds*, vol. 3, 22–23.

Lamp CA, Forbes SJ and Cade JW 2001. *Grasses of Temperate Australia: A field guide*. Bloomings Books, Melbourne, Australia.

Taylor IN 2001. Aspects of the biology and ecology of *Phalaris paradoxa* L. PhD thesis, University of Queensland, Queensland, Australia.

Taylor IN, Peters NCB, Adkins SW and Walker SR 2004. The germination response of *Phalaris paradoxa* L. (awned canary grass) seed to different light regimes. *Weed Research* vol. 44, pp. 254–264.

Taylor IN, Walker SR and Adkins SW 2005. Burial depth and cultivation influence, emergence and persistence of *Phalaris paradoxa* seed in an Australian sub-tropical environment. *Weed Research,* vol. 45, pp. 33–40.

Walker SR, Medd RW, Robinson GR and Cullis BR 2001. Improved management of *Avena ludoviciana* and *Phalaris paradoxa* with more competitive wheat and less herbicide. *Weed Research* vol. 42, pp. 257–270.

Walker SR, Robinson GR and Medd RW 2001. Management of *Avena ludoviciana* and *Phalaris paradoxa* with barley and less herbicide. *Australian Journal of Experimental Agriculture,* vol. 41, pp. 1179–1185.

Wilson BJ, Hawton D and Duff AA 1995. *Crop Weeds of Northern Australia*. Queensland Department of Primary Industries, Australia.

Weed 19. Paterson's curse

Asaduzzaman M, Luckett DJ, An M, Pratley JE and Lemerle D 2014. Management of Paterson's curse (*Echium plantagineum*) through canola interference. *Science, Community and Food Security: the Weed Challenge: 19th Australasian Weeds Conference*. Hobart, Tasmania, Australia, (eds M Baker), pp.162–165.

Australian Cotton Cooperative Research Centre 2002. *Weedpak a guide for integrated management of weeds in cotton*. Narrabri, NSW: Australian Cotton Cooperative Research Centre.

Australian Capital Territory Government 2009. Paterson's curse (*Echium plantagineum*)'. *ACT Weeds Fact Sheet*, ACT Government, ACT Parks Conservation and Lands, Conservation Council of the South East Region and Canberra, Canberra, Australia.

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1992. *Plants of Western New South Wales*, pp. 561.

Grigulis K, Sheppard AW, Ash J E and Groves R H 2001. The comparative demography of the pasture weed *Echium plantagineum* between its native and invaded ranges. *Journal of Applied Ecology*, vol. 38, pp. 281–290.

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S and Ouzman J 2016. *Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices*. Grains Research and Development Corporation, Canberra, ACT, Australia.

McLarty A, Kruger E, Stubbs P, Peirce J, Hawkins C, Wilson P and Merewethe S 2001. *Paterson's curse management handbook*. Department of agriculture Western Australia.

Morley T and Stapleton P 1999. *The Paterson's Curse Management Handbook*, Department of Natural Resources and Environment.

Naughton M, Kidston J, Sullivan P and Bourke C 2008. Paterson's curse'. *Prime facts*, NSW Department of Primary Industries.

Weed 20. Silver grass

An M, Pratley JE and Haig T 1993. The effect of soil on the phytotoxicity of residues of *Vulpia myuros*. *Proceedings of the 7th Australian Agronomy Conference*, Adelaide, pp. 162–164. Australian Society of Agronomy.

Bowcher AJ 2002. Competition between temperate perennial pasture species and annual weeds: the effect of pasture management on population dynamics and resource use. PhD thesis, Charles Sturt University, New South Wales.

Button JA 1963. The Webworm. Bulletin 3175, Department of Agriculture, Western Australia.

Dillon SP and Forcella F 1984. Germination, emergence, vegetative growth and flowering of two silvergrasses, *Vulpia bromoides* (L.) and *V. myuros* (L.). *Australian Journal of Botany,* vol. 32, pp. 165–175.

Jones CE 1994. Comparative emergence of *Vulpia* spp. Under field and glasshouse conditions. *Proceedings of the 8th Biennial Conference Australian Rangeland Society*, Katherine, pp. 255–256. Australian Rangeland Society.

Jones CE, Whalley RDB, Lovett JV and McIntyre S 1992. Seed bank dynamics of *Vulpia* spp. in pastures. *Proceedings of the 6th Australian Agronomy Conference*, Armidale, p. 532. Australian Society of Agronomy.

MacIntyre S and Whalley RDB 1990. Co-occurrence of *Vulpia* species on the northern tablelands of New South Wales. *Australian Journal of Botany,* vol. 38, pp. 445–450.

McGowan AA 1970. Comparative germination patterns of annual grasses in north-eastern Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 10, pp. 401–404.

Ozanne, PG and Asher CJ 1965. The effect of seed potassium on emergence and root development of seedlings in potassium-deficient sand. *Australian Journal of Agricultural Research*, vol. 16, pp. 773–784.

Pratley JE 1989. Silvergrass residue effects on wheat. *Proceedings of the 5th Australian Agronomy Conference*, Perth, p. 472. Australian Society of Agronomy.

Pratley JE 1990. Silvergrass allelopathy on crop and pastures. *Proceedings of the 9th Australian Weeds Conference*, Adelaide, pp. 436–439. Crop Science Society of South Australia Inc.

Rossiter RC 1966. Ecology of the Mediterranean annual type pasture. *Advances in Agronomy*, vol. 18, pp. 1–56.

Velthius RG and Amor RL 1983. Weed survey of cereal crops in south west Victoria. *Australian Weeds*, vol. 2, pp. 50–52.

Wallace A 1998. *Vulpia bromoides* (L.) and *V. myuros* (L.). *Biology of Australian Weeds* (*vol.2*). R.G. and F.J. Richardson, Melbourne, Australia, pp. 291–308.

Weed 21. Sweet summer grass

Kleinschmidt, HE and Johnson RW 1977. *Weeds of Queensland*. Queensland Department of Primary Industries, AGDEX 642.

Stanley TD and Ross EM 1989. *Flora of South-eastern Queensland* (*vol. III*). Queensland Department of Primary Industries, Miscellaneous Publication QM88001.

Wilson BJ, Hawton D and Duff AA 1995. Crop *Weeds of Northern Australia – identification at seedling and mature stages*. Department of Primary Industries, Queensland.

Werth J and Osten V 2008. Final report improving management of summer weeds in dryland cropping systems with cotton. Cotton Catchment Communities CRC

Weed 22. Turnip weed

Adkins SW, Wills D, Boersma M, Walker SR, Robinson G, McLeod RJ and Einam PJ (1997). Weeds resistant to chlorsulfuron and atrazine from north-east grain region of Australia. *Weed Research* vol. 37, pp. 343–349.

Blaney B 2005. *Weed seeds toxic to pigs*. Queensland Department of Primary Industries and Fisheries. www.dpi.qld.gov.au/pigs/4473.html.

Campbell MH, Bowman AM, Bellotti WD, Munich DJ and Nicol HI 1996. Recruitment of curly Mitchell grass (*Astrebla lappacea*) in north-western NSW. *Rangeland Journal* vol. 18, pp. 179–187.

Cheam AH, Storrie AM, Koetz EA, Holding DJ, Bowcher AJ and Barker JA 2008. Managing wild radish and other brassicaceous weeds in Australian cropping systems. Cooperative Research Centre for Australian Weed Management. Adelaide, Australia.

Cousens RD, Armas G and Barweja R 1994. Germination of *Rapistrum rugosum* from NSW, Australia. *Weed Research* vol. 34, pp. 127–135.

Cousens RD and Pheloung P 1996. What limits the geographic distributions of cruciferous weeds in Australia? *Proceedings of the 2nd International Weed Control Congress*. Denmark, pp. 55–60.

Cunningham CM, Mulham WE, Milthorpe PL and Leigh JH 1981. *Plants of Western New South Wales*. Soil Conservation Service of New South Wales.

Hussey BJM, Keighery GJ, Cousens RD, Dodd J. and Lloyd SG 1997. *Western Weeds: A Guide to the Weeds of Western Australia*. Plant Protection Society of Western Australia.

Marley JM and Robinson GR 1990. Strategies for Broadleaf Weed Control in Barley. Final Report, Barley Research Committee for Queensland.

Manalil S, Ali HH, and Chauhan BS 2018. Germination ecology of turnip weed (*Rapistrum rugosum* (L.) All.) in the northern regions of Australia. *PloS one*, vol. 13, e0201023.

Retter, L and Harden G 1990. Brassicaceae. *Flora of New South Wales* (*vol 1*). University of NSW Press, Sydney, Australia.

Walker SW, Wilson B, Wu H, Widderick M and Taylor I 2007. Seed persistence of key northern region weeds. www.dpi.qld.gov.au/26_4428.htm

Whish JPM, Sindel BM, Jessop RS and Felton WL 2002. The effect of row spacing and weed density on yield loss of chickpea. *Australian Journal of Agricultural Research*, vol. 53, pp. 1335–1340.

Wilson BJ and Wilson JT 1981. Effect of time of seedling emergence on seed production and time to flowering of eight weeds, Proceedings of 6th Australian Weeds Conference.' Gold Coast, Queensland, Australia, Queensland Weed Society.

Weed 23. Wild oats

McNamara DW 1976. Wild oat density and the duration of wild oat competition as it influences wheat growth and yield. *Australian Journal of Experimental Agriculture and Animal Husbandry,* vol. 16, pp. 402–406.

Martin RJ, Cullis BR and McNamara DW 1987. Prediction of wheat yield loss due to competition by wild oats (Avena spp.). *Australian Journal of Agricultural Research,* vol. 38, pp. 487–499.

Nugent T, Storrie A, and Medd R 1999. Managing Wild Oats. Cooperative Research Centre for Weed Management Systems and Grains Research and Development Corporation.

Philpotts H 1975. The control of wild oats in wheat by winter fallowing and summer cropping. *Weed Research,* vol. 15, pp. 221–225.

Quail PH and Cater OG 1968. Survival and seasonal germination of seeds of *Avena fatua* and *A. ludoviciana*. *Australian Journal of Agricultural Research,* vol. 19, pp. 721–729.

Walker SR, Robinson GR and Medd RW 1998. Management of wild oats and paradoxa grass with reduced dependence on herbicides. *Proceedings of the 9th Australian Agronomy Conference*, Wagga Wagga, New South Wales. pp. 572–574.

Weed 24. Wild radish

Blackshaw R, Lemerle D, Mailer R and Young K 2002. Influence of wild radish on yield and quality of canola. *Weed Science*, vol. 50, pp. 344–349.

Cheam AH, Storrie AM, Koetz EA, Holding DJ, Bowcher AJ, and Barker JA 2008. Managing wild radish and other brassicaceous weeds in Australian cropping systems. Cooperative Research Centre for Australian Weed Management, Adelaide, Australia.

Cheam AH 1984. Coat-imposed dormancy controlling germination in wild radish and fiddle dock seeds. *Proceedings of the 7th Australian Weeds Conference*, pp. 184–190.

Cheam AH 1986. Seed production and seed dormancy in wild radish (*Raphanus raphanistrum* L.) and some possibilities for improving control. *Weed Research*, vol. 26, pp. 405–413.

Cheam AH and Code GR 1995. The biology of Australian weeds – 24, *Raphanus raphanistrum* L. *Plant Protection Quarterly,* vol. 10, pp. 2–13.

Cheam A and Lee S 2003. Seedicidal potential of green wild radish pods on crop seeds. *Proceedings of the 19th Asian-Pacific Weed Science Society Conference*, pp. 169–173.

Cheam A and Lee S 2004. Diflufenican resistance in wild radish (*Raphanus raphanistrum* L): its discovery and consequences for the lupin industry. *Proceedings of the 14th Australian Weeds Conference*, pp. 414–417.

Cheam A, Lee S, Nicholson D and Clarke M 2003. Managing a biotype of wild radish (*Raphanus raphanistrum*) resistant to diflufenican and triazines. *Proceedings of the 19th Asian-Pacific Weed Science Society Conference*, pp. 766–772.

Code GR, Walsh MJ and Reeves TG 1987. Effect of depth and duration of burial of wild radish seed on seed viability and seedling emergence. *Proceedings of the Weed Seed Biology Workshop*, Orange, New South Wales, pp. 136–138.

Cousens RD, Warringa JW, Cameron JE and Hoy V 2001. Early growth and development of wild radish (*Raphanus raphanistrum* L.) in relation to wheat. *Australian Journal of Agricultural Research*, vol. 52, pp. 755–769.

Dellow JJ and Milne BR 1987. *Wild Radish*. Department of Agriculture, New South Wales, Agfact P7.6.6.

Hashem A and Wilkins N 2002. Competitiveness and persistence of wild radish (*Raphanus raphanistrum* L.) in a wheat–lupin rotation. *Proceedings of the 13th Australian Weeds Conference*, Perth, Western Australia, pp. 712–715.

Moore JH 1979. Influence of weed species and density on the yield of crops. *Proceedings of the Western Australian Weeds Conference*, Muresk, Western Australia, pp. 92–94.

Panetta FD, Gilbey DJ and D'Antuono MF 1988. Survival and fecundity of wild radish (*Raphanus raphanistrum* L.) plants in relation to cropping, time of emergence and chemical control. *Australian Journal of Agricultural Research*, vol. 39, pp. 385–397.

Peltzer SC 2004 Understanding and driving annual weed seedbanks to very low levels – Project DAW613. Department of Agriculture and Food WA, Albany, WA.

Reeves TG, Code GR and Piggin CM 1981. Seed production and longevity, seasonal emergence and phenology of wild radish (*Raphanus raphanistrum* L.). *Australian Journal of Experimental Agriculture and Animal Husbandry,* vol. 21, pp. 524–530.

Walsh M, Duane R and Powles S 2001. High frequency of chlorsulfuron-resistant wild radish (*Raphanus raphanistrum*) populations across the Western Australian wheatbelt. *Weed Technology*, vol. 15, pp. 199–203.

Walsh M, Powles S, Beard B, Parkin B and Porter S 2004. Multiple-herbicide resistance across four modes of action in wild radish (*Raphanus raphanistrum*). *Weed Science*, vol. 52, pp. 8–13.

Young KR 2001. Germination and emergence of wild radish (*Raphanus raphanistrum* L.). PhD thesis, University of Melbourne.

Weed 25. Windmill grass

Borger C, Riethmuller G and Hashem A 2010. Control of windmill grass over the summer fallow increases wheat yield. *Proceedings of the 17th Australasian Weeds Conference*. http://caws.org.nz/old-site/awc/2010/awc201010481.pdf, Viewed 13 December 2018.

Chauhan BS, Manalil S, Widderick M, Werth J, Street M, Cook T, Congreve M 2016. Northern IWM fact sheet Windmill grass. https://qaafi.uq.edu.au/files/5958/Windmill-grass-ecology-and-management Viewed 30 November 2018.

Cunningham GM, Mulham WE, Milthorpe PL and Leigh JH 1981. *Plants of Western NSW*. Soil Conservation Service of New South Wales.

Hawkes JR and Jones RAC 2005. Incidence and distribution of barley yellow dwarf virus and cereal yellow dwarf virus in over-summering grasses in a Mediterranean-type environment. *Australian Journal of Agricultural Research*, vol. 56, pp. 257–270.

Huxtable CHA and Whalley RDB 1999. Emergence and survival of three native grass species sown on roadsides on the Northern Tablelands, New South Wales, Australia. *Australian Journal of Botany*, vol. 47, pp. 221–235.

Kleinschmidt HE and Johnson RW 1977. *Weeds of Queensland*. Queensland Department of Primary Industries, AGDEX 642.

Lodge GM 1981. Establishment of warm- and cool-season native perennial grasses on the north-west slopes of New South Wales. II. Establishment and seedling survival in the field. *Australian Journal of Botany*, vol. 29, pp. 121–133.

Lodge GM and Whalley RDB 1981. Establishment of warm- and cool-season native perennial grasses on the north-west slopes of New South Wales. I. Dormancy and germination. *Australian Journal of Botany*, vol. 29, pp. 111–119.

Maze KM and Goodridge MR 1991. The effect of four broadleaf herbicides on seedlings of five native and one introduced grass species. *The Rangeland Journal,* vol. 13, pp. 91–95.

Maze KM, Koen TB and Watt LA 1993. Factors influencing the germination of six perennial grasses of Central New South Wales. *Australian Journal of Botany*, vol. 41, pp. 79–90.

Stanley TD and Ross EM 1989. *Flora of south-eastern Queensland* (*vol. III*). Queensland Department of Primary Industries, Miscellaneous publication QM88001.

Stewart V 2002. Herbicide options for the control of *Chloris truncata* (windmill grass). *Weeds Update Western Australia*. Department of Agriculture, Western Australia, pp. 122–123.

Street M 2011. Windmill grass (*Chloris truncata*) – the current state of play. *GRDC Research Updates*. Grains Research and Development Corporation, Dubbo, New South Wales.

Syme H, Acuna TLB, Abrecht D and Wade LJ 2007. Nitrogen contributions in a windmill grass (*Chloris truncata*) wheat (*Triticum aestivum* L.) system in south-western Australia. *Soil Research*, vol. 45, pp. 635–642.

Werth J, Thornby D and Walker S 2011. Assessing weeds at risk of evolving glyphosate resistance in Australian sub-tropical glyphosate-resistant cotton systems. *Crop and Pasture Science*, vol. 62, pp. 1002–1009.

Wheeler DJB 1982. *Grasses of New South Wales*. University of New England Publishing Unit, Armidale, New South Wales, Australia.

Wilson BJ, Hawton D and Duff AA 1995. Crop *Weeds of Northern Australia – identification at seedling and mature stages*. Department of Primary Industries, Queensland.

Weed 26. Wild mustard

Cheam AH, Storrie AM, Koetz EA, Holding DJ, Bowcher AJ and Barker JA 2008. *Managing wild radish and other brassicaceous weeds in Australian cropping systems*. Adelaide, Australia: CRC for Australian Weed Management.

Heap IM and Morrison IN 1992. Resistance to auxin-type herbicides in wild mustard (*Sinapsis arvensis* L.) populations in Western Canada. *Weed Science Society of America*, vol. 32, pp. 164.

Jugulam M, McLean MD and Hall JC 2005. Inheritance of picloram and 2,4-D resistance in wild mustard (*Brassica kaber*). *Weed Science*, vol. 53, pp. 417–423.

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S and Ouzman J 2016. *Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices.* Grains Research and Development Corporation, Canberra, ACT, Australia.

Moore CB and Moore JH 2005. HerbiGuide – the pesticide expert on a disk, Version 19.3. 1–5–2005. Albany, Western Australia 6331.

Richardson FJ, Richardson RG and Shepherd RCH 2016. Weeds of the south-east: an identification guide for Australia. Third Ed. CSIRO, Meredith, Australia, p 197.

Salisbury PA, Potter TD, Gurum AM, Mailer RJ and Williams WM 2018. Potential impact of weedy *Brassicaceae* on oil and meal quality of oilseed rape (canola) in Australia. *Weed Research*, vol. 58, pp. 200–209.

Storrie A, Moylan P and Cook T 2006. Seed set control of charlock and turnip weed in chickpeas. *In Proceedings of the Wild Radish and other Cruciferous Weeds Symposium*, Perth, Western Australia, (ed AH Cheam), pp 57–65.

Veldhuis LJ, Hall L M and O'Donovan JT 2000. Metabolism-based resistance of a wild mustard (*Sinapis arvensis* L.) biotype to ethametsulfuron-methyl. *Journal of Agricultural Food Chemistry*, vol. 48, pp. 2986–2990.

Warwick S I, Beckie H, Thomas J and Donald TM 2000. The Biology of Canadian Weeds. 8. *Sinapis arvensis* L. *Canadian Journal of Plant Science*, vol. 82, pp. 473–480.

Wilson BJ, Hawton D and Duff A 1995. *Crop weeds of northern Australia: identification at seedling and mature stages*, pp. 48–51. Queensland Department of Primary Industries.

Weed 27. Wild turnip

Chauhan BS, Gill G and Preston C 2006. African mustard (*Brassica tournefortii*) germination in southern Australia. *Weed Science,* vol. 54, pp. 891–898.

Gill G, Kleemann S and Fleet B 2018. Latest research on brome grass and susceptibility of emerging weed species to harvest weed seed capture, GRDC Update Papers, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/brome-grass-and-susceptibility-of-emerging-weed-species. Accessed Nov 2018.

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S and Ouzman J 2016. Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. *Grains Research and Development Corporation, Canberra, ACT, Australia.*

Mahajan G, Mutti NK, Jha P, Walsh, M and Chauhan BS, 2018. Evaluation of dormancy breaking methods for enhanced germination in four biotypes of *Brassica tournefortii*. *Scientific reports*. vol. 8, p. 17103.

Moore CB and Moore JH 2005. HerbiGuide – the pesticide expert on a disk, Version 19.3. 1–5–2005. Box 44, Albany, Western Australia 6331.

Salisbury PA, Potter TD, Gurum AM, Mailer RJ and Williams WM 2018. Potential impact of weedy Brassicaceae on oil and meal quality of oilseed rape (canola) in Australia. *Weed Research,* vol. 58, pp. 200–209.

Wilson BJ, Hawton D and Duff A 1995. Crop weeds of northern Australia. p. 48 – 51.

Weed 28. Wireweed

Alsaadawi IS and Rice EL 1982. Allelopathic effects of *Polygonum aviculare* L. I. Vegetational patterning. *Journal of Chemical Ecology*, vol. 8, pp. 993–1009.

Amor RL and Francisco TM 1987. Survey of weeds in field peas, chickpeas and rapeseed in the Victorian Wimmera. *Plant Protection Quarterly*, vol. 2, pp. 124–127.

Auld BA and Medd RW 1987. *Weeds: An Illustrated Botanical Guide to the Weeds of Australia*. Inkata Press, Melbourne, Australia.

Batlla D and Benech-Arnold RL 2004. A predictive model for dormancy loss in *Polygonum aviculare* L. seeds based on changes in population hydrotime parameters. *Seed Science Research*, vol. 14, pp. 277–286.

Batlla D and Benech-Arnold RL 2005. Changes in the light sensitivity of buried *Polygonum aviculare* seeds in relation to cold-induced dormancy loss: development of a predictive model. *New Phytologist*, vol. 165, pp. 445–452.

Burnett V, Norng S, Walsh M, McLaren D and Lemerle D 2010. Competitive effects of wireweed (*Polygonum aviculare* L.) on lucerne (*Medicago sativa* L.) during the establishment phase. *Proceedings of the 15th Agronomy Conference*, Lincoln, New Zealand. www.regional.org.au/au/asa/2010/pastures-forage/weeds-insects/6923_burnettv.htm

Courtney AD 1968. Seed dormancy and field emergence in *Polygonum aviculare*. *Journal of Applied Ecology*, vol. 5, pp. 675–684.

Dorado J, del Monte JP and Lopez-Fando C 1999. Weed seedbank response to crop rotation and tillage in semi-arid agroecosystems. *Weed Science*, vol. 47, pp. 67–73.

Hall DG, Fitzgerald RD, Wolfe EC and Cullis BR 1980. Beef production from lucerne and subterranean clover pastures. 3. Composition and quality of the diet selected. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 20, pp. 695–702.

Khan MA and Ungar IA 1998. Seed germination and dormancy of *Polygonum aviculare* L. as influenced by salinity, temperature and gibberellic acid. *Seed Science and Technology*, vol. 26, pp. 107–117.

King LJ 1966. *Weeds of the World*. Interscience Publishers Inc., New York.

Kloot PM and Boyce KG 1982. Allelopathic effects of wireweed (*Polygonum aviculare*). *Australian Weeds*, pp. 11–14.

Knight PR 1979. Suspected nitrite toxicity in horses associated with the ingestion of wireweed (*Polygonum aviculare*). *Australian Veterinary Practitioner*, vol. 9, pp. 175–177.

Lamp C and Collet F 1976. *A Field Guide to Weeds in Australia*. Inkata Press, Melbourne, Australia.

Lawson HM, Wright GMcN, Wilson BJ and Wright KJ 1993. Seedbank persistence of five arable weed species in autumn-sown crops. *Proceedings of the Brighton Crop Protection Conference*, Brighton, United Kingdom. British Crop Protection Council, Farnham, United Kingdom 305–310.

Lemerle D, Blackshaw RE, Smith AB, Potter TD and Marcroft SJ 2001. Comparative survey of weeds surviving in triazine tolerant and conventional canola crops in south-eastern Australia. *Plant Protection Quarterly*, vol. 16, pp. 37–40.

Lemerle D, Tang HY, Murray GM and Morris S 1996. Survey of weeds and diseases in cereal crops in the southern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture*, vol. 36, pp. 545–554.

Martin, RJ and McMillan, MG 1984. Some results of a weed survey in northern New South Wales. *Australian Weeds*, vol. 3, pp. 115–116.

Medd RW 1986. Research into buried weed seed pools and their manipulation. A final report for the Wheat Research Council, Project No. DAN 57.W.

Pollard F and Cussans GW 1981. The influence of tillage on the weed flora in a succession of winter cereal crops on a sandy loam soil. *Weed Research*, vol. 21, pp. 185–190.

Roberts HA and Neilson JE 1981. Changes in the soil seed bank of four long-term crop/herbicide experiments. *Journal of Applied Ecology*, vol. 18, pp. 661–668.

Saunders AE and Field RJ 1983. The germination behaviour of wireweed seed. *Proceedings of the 36th New Zealand Weed and Pest Control Conference*, pp. 180–184.

Wilding JL, Barnett AG and Amor RL 1998. *Crop Weeds*. R.G. and F.J. Richardson, Inkata Press, Melbourne, Australia.

Wilson KL 1990. Polgonaceae. *Flora of New South Wales* (*vol. 1*). University of NSW Press, Sydney, Australia, pp. 287–288.

Weed 29. Yellow burrweed

Cuthbertson E G and Parson W T 2001. *Noxious Weeds of Australia*. 2nd edn, CSIRO Publishing, Melbourne, Australia.

Department of Agriculture and Food 2002. *Declared Plants in Western Australia, Yellow Burr Weed* (*Amsinckia* spp.). 6th edn, Western Australia, Department of Agriculture and Food.

Department of Environment and Water 2015. Pest plant – Yellow burrweed. *Fact sheet*, https://www.naturalresources.sa.gov.au/samurraydarlingbasin/publications/pest-plant-yellow-burrweed, Viewed November 2018.

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S and Ouzman J 2016. *Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices*. Grains Research and Development Corporation, Canberra, ACT, Australia.

Meadly GRW 1968. Amsinckia or yellow burr-weed (*Amsinckia* spp.). *Journal of the Department of Agriculture, Western Australia*, vol. 9, pp. 125–128.

Moerkerk M, Wurst M and Yeatman T 2004. *Weeds; the Ute Guide*. 2nd edn.Version 2. Barton NSW. Grains Research and Development Corporation.

Victorian Government Department of Primary Industries 2010. Regionally prohibited weeds information sheet – Amsinckia

SECTION 3: HERBICIDE RESISTANCE

Herbicide resistant weed populations are now found throughout all cropping areas of Australia from Western Australia to central Queensland. Currently, there are 91 weed species in Australia that have developed resistance to one or more herbicide mode-of-action (MOA) groups.

The number of herbicide resistant populations and areas affected will continue to increase until integrated weed management (IWM) practices are widely adopted in Australian cropping systems.

The future

Despite herbicide resistance first being identified in Australia in 1982, growers continue to engage in high-risk activities that rely predominantly on herbicides with little focus on seedbank management. The effects of over 20 years of minimum tillage and heavy glyphosate use are only just being expressed in weed populations, with 17 populations being found resistant to glyphosate ( ). This increasing trend for herbicide resistance in Australian cropping systems is likely to continue, at least in the near future. The great success of herbicides improving weed control and farmer returns over the last 35 years, has resulted in non-herbicide management being neglected by the majority of growers.

Herbicide resistance is the impetus for learning integrated weed management. Growers in more favourable climatic areas have more options available and better cash flow to fund necessary changes in management. Growers in drier areas, however, face greater challenges in managing highly variable seasonal conditions and cash flow, which determine their ability to adopt and implement change. Convincing growers to introduce changes in weed management sooner rather than later is a challenging and long-term task for all farm advisors.Glyphosate-resistant weeds in Australia (Preston 2018. The Australian Glyphosate Sustainability Working Group, www.glyphosateresistance.org.au/)

Species	Common name	Year first documented
Lolium rigidum	Annual ryegrass	1996
Echinochloa colona	Barnyard grass	2007
Urochloa panicoides	Liverseed grass	2008
Conzya bonariensis	Flaxleaf fleabane	2010
Chloris truncata	Windmill grass	2010
Raphanus raphanistrum	Wild radish	2010
Bromus diandrus	Great brome	2011
Conzya sumatrensis	Tall fleabane	2012
Sonchus oleraceus	Sowthistle	2014
Bromus rubens	Red brome	2014
Moorochloa eruciformis	Sweet summer grass	2014
Lactuca seriola	Prickly lettuce	2014
Chloris vigrata	Feathertop Rhodes grass	2015
Tridax procmbens	Tridax daisy	2016
Poa annua	Winter grass	2017
Lactuca saligna	Willow-leaved lettuce	2017

Herbicides

The first herbicide was released on to the Australian market in 1946, but it was not until highly effective and low-priced herbicides were released in the late 1970s that herbicides quickly became the most heavily relied upon weed control method for farmers. Even today, despite high use of herbicides leading to high frequencies of resistant weed populations, herbicide control represents the main, and sometimes only, weed management decision made by many farmers.

The widespread adoption of conservation cropping systems has led to an even greater reliance on herbicides due to a corresponding decline in use of alternative weed control methods (such as cultivation). This in turn has resulted in high selection pressure for herbicide resistance in weed populations.

Understanding the implications and evolutionary processes of herbicide resistance results in appropriate weed management strategies being developed that minimise the impact of herbicide-resistant weeds and delay development of further resistance.

This section explains how herbicide resistance has developed in weeds through over-reliance on herbicidal control. For information on herbicide tolerant crops see *Agronomy 3 Herbicide tolerant crops*.

What is herbicide resistance?

Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type. In a plant, resistance may be naturally occurring or induced by techniques such as genetic engineering or selecting variants produced by tissue culture or mutagenesis.

Herbicide tolerance is the inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant.

Herbicide resistance fact box

- Resistance is the inherited ability of an individual plant to survive and reproduce following a herbicide application that would kill susceptible 'wild type' individuals of the same species.
- Ninety-one weed species in Australia currently have populations that are resistant to at least one herbicide mode-of-action (MOA).
- Australian weed populations have developed resistance to 12 distinct MOA groups.
- Herbicide-resistant individuals are present at very low frequencies in weed populations before the herbicide is first applied.
- The frequency of naturally resistant individuals within a population will vary greatly within and between weed species.
- A weed population is defined as resistant when a herbicide at a label rate that once controlled the population is no longer effective (sometimes an arbitrary figure of 20% survival is used for defining resistance in testing).
- The proportion of herbicide resistant individuals will rise (due to selection pressure) in situations where the same herbicide MOA is applied repeatedly and the survivors are not subsequently controlled.
- Herbicide resistance in weed populations is permanent as long as seed remains viable in the soil. Only weed density can be reduced, not the ratio of resistant to susceptible.

Figure HR1 Dead (glyphosate-susceptible) annual ryegrass surrounded by glyphosate resistant individuals.
Photo: Andrew Storrie

Commonly used terms

Herbicide MOA groups

Herbicides act by targeting specific plant processes. This process-specific activity is termed mode of action or MOA. In Australia all herbicides are classified into groups based on their MOA and named with a group letter from A to Z. MOA group classifications are included on all herbicide labels to identify the group to which a herbicide belongs.

MOA groups can be ranked according to the risk of weed populations becoming resistant to those herbicides. Groups A and B are high risk; Groups C to Z are moderate risk. There are no low-risk herbicides.

MOA subgroup chemical classes

Within a herbicide MOA there may be two or more subgroups. With the exception of Group Z, the subgroups are different chemical classes that inhibit the same plant process. Subgroups within a MOA group can differ in their efficacy on a species. In Group I, for example, 2,4-D (phenoxy subgroup) is highly effective on brassica weeds such as mustards and turnips, while dicamba (benzoic subgroup) is not.

There can also be differences in resistance genes frequency for different subgroups.

Group Z contains herbicides with unknown modes of action.

Selection pressure

Selection pressure describes how strongly herbicides select for resistant individuals in a weed population. Every time a herbicide is used, susceptible individuals are killed while resistant individuals survive and produce viable seed. Over time, and with repeated applications of the same herbicide MOA, the population naturally shifts from mostly susceptible to mostly resistant. A high selection pressure herbicide application kills the greatest number of susceptible individuals possible, whereas a low selection pressure spray kills a smaller proportion of susceptible individuals. These susceptible survivors can then add a higher number of susceptible individuals to the next generation, slowing the overall shift to a population dominated by resistant plants.

Resistance mechanisms

Resistance mechanisms describe the specific processes that enable the plant to survive a herbicide application. Resistance mechanisms are divided into two broad categories so that weed populations may have either target-site or non-target-site based resistance mechanisms or both.

Target-site resistance

Target-site resistance occurs when the herbicide target site is altered. The alteration occurs at the normal herbicide site of action in the form of a structural change. This means that the herbicide will no longer be able to bind to its site of action, allowing the plant to survive the herbicide application.

Non-target-site resistance

Non-target-site resistance describes mechanisms other than changes at the target site that enable an individual plant to survive a herbicide application. The potential mechanisms include reduced herbicide uptake, reduced translocation, reduced herbicide activation, enhanced herbicide detoxification, changes in intra- or inter-cellular compartmentalisation, and enhanced repair of herbicide-induced damage.

Cross-resistance

Cross-resistance is the ability of a weed population to express resistance to more than one herbicide. It may arise without the weed population ever being exposed to one of the herbicides. There are two types of cross-resistance:

1. *Across herbicide subgroups*. This occurs when a weed population is resistant to more than one herbicide subgroup within a specific MOA. For example, populations of wild oats (*Avena* spp.) that are resistant to Group A 'fops' may also be resistant to Group A 'dims', even though they have not been exposed to a herbicide from the 'dim' subgroup. This is usually target-site based resistance.
2. *Across herbicide MOA groups*. This occurs when a weed population is resistant to herbicides from within more than one MOA group. For example, a population of annual ryegrass (*Lolium rigidum*) selected with only Group A herbicides may also be resistant to Group B herbicides. This is usually non-target-site based resistance.

Multiple resistance

Multiple resistance describes weed populations that exhibit more than one resistance mechanism, allowing the plant to withstand herbicides from different groups or subgroups. Some populations of resistant annual ryegrass possess both target- and non-target-site resistance to more than one MOA.

Developing resistance

Developing resistance describes situations where only a small proportion (often less than 20%) of the population survives the standard application rate of the herbicide in question. Weed populations are normally classified by testing services as resistant when more than 20% of the population survives the standard application rate of herbicide.

How does a weed population develop herbicide resistance?

There are two major ways in which resistance may arise within a weed population:

1. *Pre-existing resistance*. Within any weed population there may be some plants that already contain a rare change in a gene (or genes) that enables them to survive the application of a particular herbicide that would normally kill this species.

   Genetic variation may alter the shape of the target site and/or physiological traits that enable herbicide uptake, translocation and activation at the site of action. Alternatively, changes may influence the plant's ability to detoxify herbicides, or enable transport to a site within the plant where the herbicide is not lethal.

   Each time the herbicide is applied, susceptible plants die and resistant individuals survive (*Figure HR2*).

   The initial frequency of plants with pre-existing resistance is usually very low. Therefore, the majority of plants in a wild weed population will be susceptible to herbicides effective on that species. Persistent use of herbicides with the same MOA will kill the susceptible portion of the population, resulting in the gradual increase in the proportion of resistant individuals (Figure HR3).

   This process is described as applying selection pressure. By removing (killing) susceptible plants from the population, plants that can survive herbicide application (at the given rate) are 'selected'.

2. *Introduction of resistance*. It is possible that resistance may not be present in the population initially, but is introduced as a weed seed contaminant in crop seed or fodder, on machinery or on/in animals. Alternatively, resistance can appear through the arrival of wind- or water-driven resistant seeds or pollen. For example, species such as sowthistle (*Sonchus oleraceus*) and fleabane (*Conyza* spp.) can be spread up to 2 km by wind. Pollen can also be dispersed great distances although the percentage able to successfully pollinate another plant at distances greater than 10 m is low. Fei and Nelson (2003) found that grass pollen survives in the environment for up to three hours, with only 1% remaining viable after two hours. However, Busi et al (2008) found that annual ryegrass pollen can fertilise plants up to 3 km away when pollen competition from nearby plants is low. Flood water also has the potential to move a wide range of weed seeds over large distances.

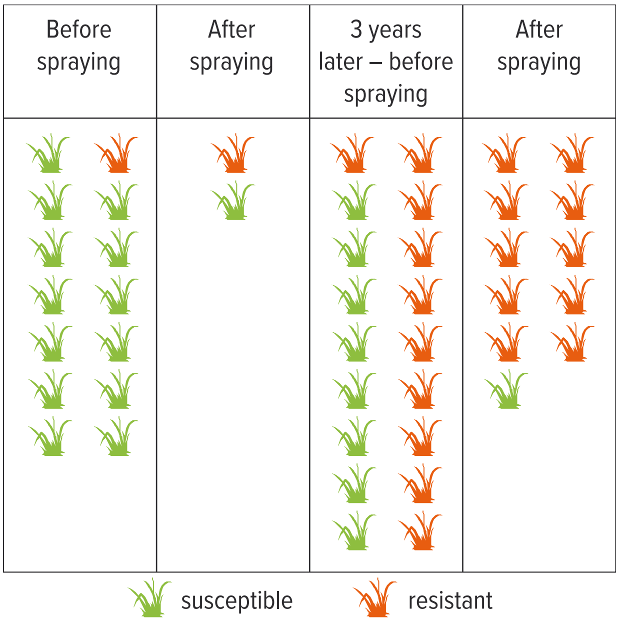

Figure HR 2 Genes for herbicide resistance may pre-exist in a weed population. The proportion of resistant to susceptible weeds will change under selection pressure.

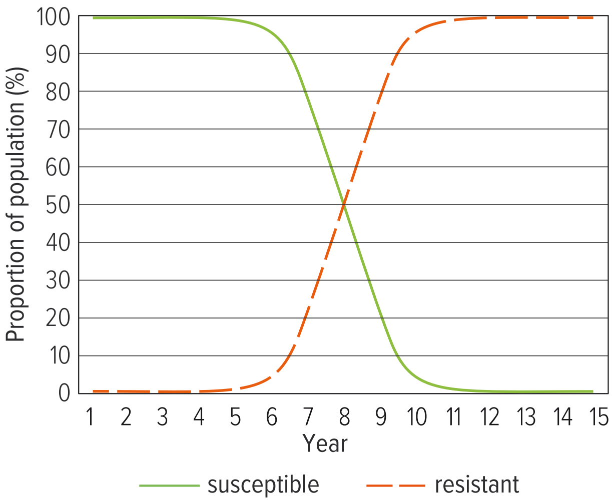

Figure HR 3 A generalised graph of the impact that the repeated application of herbicides with the same MOA has on the proportion of susceptible and resistant plants.

Factors influencing the development of resistance

Herbicide resistance is normally present in some individual plants of weed populations before herbicides are first applied. Several factors will affect the number of herbicide applications that are possible before the general population becomes resistant to that herbicide.

These include:

- initial frequency of resistance gene(s) and MOA of the applied herbicide
- weed population size
- proportion of the weed population treated
- herbicide efficacy
- weed biological factors.

Initial frequency of resistance gene

The frequency of resistant individuals present in a population before herbicide application varies for different herbicide MOA groups.

For example, high initial resistance in three untreated annual ryegrass populations (*Table HR 1*) explains the rapid evolution of resistance to Group B herbicides in this weed species once the herbicides are used. This is due to the high numbers of individual plants able to survive and reproduce after herbicide application.

Table HR 1 Initial frequency of individuals resistant to two Group B herbicides in three previously untreated annual ryegrass populations (Preston and Powles 2002).

Herbicide MOA group	Active ingredient	Frequency range
Group B	sulfometuron-methyl	1 plant in 45,000 to 1 in 8,000
Group B	imazapyr	1 plant in 100,000 to 1 in 17,000

For other herbicides the initial frequency may be as high as one plant in every 10,000 or as low as one plant in every billion (*Table HR 2*). Where initial frequencies of resistance are higher, fewer herbicide applications are necessary for resistance to develop.

Table HR 2 Initial frequency of individuals of annual ryegrass, estimated by modelling (Diggle and Neve 2001).

	Estimated initial frequency
Group A e.g. diclofop-methyl	1 plant in 1,000,000
Group B e.g. chlorsulfuron	1 plant in 10,000
Group M e.g. glyphosate	1 plant in 100,000,000

Neve et al. (2003) simulated the evolution of glyphosate resistance in annual ryegrass. Using an initial resistance frequency of one plant in one million, the model predicted resistance would evolve in less than 10 years in all populations where glyphosate is used. Changing the model parameters to make the resistance gene less frequent increased the length of time glyphosate would be effective to more than 10 years, before resistance evolved.

The frequency of resistant genes influences the number of times a herbicide can be applied before herbicide resistance emerges in a weed population. *Table HR 3* shows some rules of thumb regarding the number of years herbicide application remains effective before resistance evolves, according to the MOA of the herbicide being used. Simply rotating between MOA groups only delays herbicide resistance development, the number of 'shots' determines how long before resistance occurs. Research by Roberto Busi (2007) at the Australian Herbicide Resistance Initiative (AHRI) has shown that mixing two herbicides at full rates from different MOA groups in conjunction with rotating herbicides will buy extra 'shots'.

With herbicides such as triazines (Group C) and dinitroanilines (Group D), the frequency of individuals with a resistant gene (enabling plants to survive the herbicide application) is lower than for Group A and B herbicides. Longer exposure to the selection pressure (10 or more years of application) is required for weed populations to become resistant to these herbicides.

The following Australian examples indicate the variation in time lag from initial herbicide application to resistance development:

- In Western Australia, annual ryegrass populations have developed resistance to 'fops' (Group A) after only six applications and sulfonylureas (Group B 'SU') after four applications (Gill 1995).
- In New South Wales, annual ryegrass developed resistance to glyphosate (Group M) after 15 years of application (Powles et al. 1998) and elsewhere developed resistance to trifluralin (Group D) after 14 years of application (McAlister et al. 1995).

- Wild oat populations have become resistant to 'fops' (Group A) and to a lesser extent 'dims' (Group A) after eight applications in most wheat growing areas of Australia (Mansooji et al. 1992); *Table HR 3*.
- In South Australia, barley grass (*Hordeum* spp.) has developed resistance to paraquat (Group L) in no-tillage systems after approximately 15 years of application (Alizadeh et al. 1998).

Table HR 3 Number of years of herbicide application before resistance evolves (based on Preston et al. 1999).

Herbicide group	Years of application	Herbicide resistance risk
A	6–8	High
B	4	High
C	10–15	Medium
D	10–15	Medium
F	10	Medium
I	>20	Medium
L	>15	Medium
M	>12	Medium

- Broadleaf weeds such as wild mustard (*Sinapis arvensis*), indian hedge mustard (*Sisymbrium orientale*) and common sowthistle have developed resistance to 'SU' herbicides (Group B) after only two to four applications to weed populations in grain regions across Australia (Boutsalis and Powles 1995).
- In the northern grain belt of Western Australia, wild radish (*Raphanus raphanistrum*) is now resistant to 2,4-D as well as Group B and F herbicides following seventeen years of intense wheat–lupin rotation where wheat was sprayed with pre-emergent triasulfuron (Group B) followed by 2,4-D (Group I) post-emergent every year and lupins where sprayed with simazine/atrazine (Group C) followed by diflufenican (Group F) most years; no seed set management tactics were used (Walsh et al. 2003).
- Although it should take several years of herbicide application for resistance to appear, this can be accelerated by the development of cross-resistance. In 2014, annual ryegrass populations from south-east South Australia were confirmed resistant to pyroxasulfone (Sakura®, Group K), despite the herbicide only being released in 2012. For these populations, resistance was caused by metabolic cross-resistance, which had been developed from the application of other herbicides previously.

Herbicide rate and the development of resistance: does rate really matter?

Agronomists and growers often question whether high rates or low rates of herbicide lead to resistance.

Using herbicides selects for resistance if survivors are allowed to set seed.

Use of sub-optimal herbicide rates will enable individuals carrying any possible resistance mechanisms or genes to survive – both strong and weak resistance mechanisms, along with some susceptible individuals. Applying herbicides at robust rates at the right growth stage and under optimal conditions results in high mortality and individuals carrying weak resistance mechanisms or genes will not survive. Individuals carrying strong resistance mechanisms will survive.

When spraying herbicides, target a high level of weed control to avoid crop yield loss. Herbicide efficacy rather than rate determines the level of control. For example, weed control in the order of 95% may be obtained under optimal spraying conditions, while twice the recommended rate would be required to obtain the same level of control under poor spraying conditions or with poor application techniques.

ALWAYS USE ROBUST RATES OF HERBICIDE APPLIED TO MAXIMISE THEIR EFFICACY.

It is important to use a robust rate for maximum weed kill, but it is also necessary to kill survivors of the herbicide application using other tactics.

Herbicide efficacy

The level of kill, or efficacy, of the herbicide used will also affect resistance development. Highly effective herbicides exert strong resistance selection pressure. Modelling by Powles et al. (1997) showed that herbicides resulting in 95% weed control increased the rate of resistance development to a greater extent than herbicides resulting in 80% weed control.

Weed population size

The larger the weed population, the greater the likelihood there will be of naturally occurring herbicide-resistant individuals within the population.

A useful analogy to understand the influence of weed population size is the presence of white-flowered individuals in a Paterson's curse (*Echium plantagineum*) population. In a small population white-flowered individuals are unlikely to be present, but their numbers increase as population density increases. The gene controlling white flower colour is rare but, importantly, is already present in the population.

Similarly, genes controlling herbicide resistance are relatively rare. As with white-flowered Paterson's curse, the likelihood of resistant individuals being present will increase with increasing weed population. Unfortunately, unlike the white-flowered Paterson's curse, resistant plants look exactly the same as susceptible plants and will not be detected until they survive herbicide application.

Figure HR4 Paddock of purple Paterson's curse with single white Paterson's curse flower circled. The white flower indicates a rare change in a gene.
Photo: Steve Sutherland

The proportion of the weed population treated

If a greater proportion of the weed population is treated with the herbicide, more susceptible individuals will be killed and the selection pressure will increase. This might occur where multiple herbicide applications are made in one season, such as the use of glyphosate to control barnyard grass (*Echinochloa* spp.) in summer fallows in the northern cropping region. It could also occur where a herbicide is applied late after more weeds have emerged (e.g. a late post-emergent application of metsulfuron to control broadleaf weeds in winter cereals). Herbicides with a long persistence in the soil such as chlorsulfuron (used as a pre-emergent herbicide on light-textured alkaline soils) can also increase the selection pressure on very susceptible species.

Weed biological factors

There are a number of key biological factors that will influence the number of years herbicide can be applied before a weed population becomes resistant. These include:

- *Seedbank life*
  Resistance is slower to appear in weed species that have higher seed dormancy levels. While the seed produced after each herbicide application may contain a higher proportion of resistant individuals, susceptible seed from the seedbank will dilute resistance levels.
- *Fitness of resistant biotypes*
  In some instances herbicide-resistant weeds may be less vigorous than susceptible plants of the same species. The ability of the weed to compete with other plants and set seed may therefore be reduced. Resistance development may be slower where there is a significant fitness penalty associated with the resistance mechanism.
  For example, triazine (e.g. atrazine) resistance has a fitness penalty because the resistance mechanism involves a mutation in photosynthesis, the engine for plant growth. Hence, triazine tolerant canola varieties have a lower yield potential compared with conventional lines.
  Despite this, most fitness penalties incurred by herbicide resistance will be too small to have any effect on management within the paddock.
- *Seed production*
  The greater the number of seeds produced by a resistant plant, the greater the number of resistant plants that will need to be controlled in the following year. Annual ryegrass can produce up to 80,000 seeds/m^2 and wild radish and wild mustard around 30,000 seeds/m^2.
- *Importation of resistance*
  It is possible for resistance to be introduced into a weed population, although the impact it has will depend on the weed numbers involved. Resistance can be introduced by various seed dispersal mechanisms: resistant seed in stock feed, hay, crop seed, machinery and soil or animal movement. This is particularly important with forms that are naturally rare within a weed population such as glyphosate resistance.
- *Chance*
  Resistant individuals are not distributed uniformly within a population. On average, all ryegrass populations start off with about one plant in 17,000 with resistance to Group B herbicides. In reality, some populations have one plant in 8,000, and others one in 100,000, purely as a function of chance.

Herbicide resistance in Australia

Herbicide resistance is an increasing problem throughout the world. Information compiled by Dr Ian Heap at: www.weedscience.org/in.asp provides details of worldwide and Australian herbicide resistant weeds.

Worldwide, more weed species have developed resistance to Group B herbicides than to any other MOA group. A large number of grass (*Table HR 4*) and broadleaf (*Table HR 5*) weed species have populations with confirmed resistance to a range of herbicides across Australia.

Figure HR 5 Glyphosate-resistant awnless barnyard grass in grain sorghum, northern NSW.
Photo: Andrew Storrie

Table HR 4 Known populations of herbicide-resistant grass weeds in Australia (compiled by Storrie 2013, updated by Koetz 2018).

Weed species	Herbicide group		Example herbicide	States with confirmed resistant populations					
				WA	SA	VIC	NSW	TAS	QLD
Annual ryegrass (*Lolium rigidum*)	A	'fops'	diclofop-methyl	X	X	X	X	X	
	A	'dims'	sethoxydim	X	X	X	X	X	
	B	sulfonylureas	chlorsulfuron	X	X	X	X	X	
	B	imidazolinones	imazapic, imazapyr	X	X	X	X	X	
	C	triazines	simazine, atrazine	X	X	X			
	C	substituted ureas	diuron		X	X			
	D	dinitroanilines	trifluralin	X	X	X	X	X	
	J	thiocarbamates	triallate			X	X		
	K	isoxazolines	pyroxasulfone		X				
	L	bipyridiliums	paraquat	X	X	X	X		
	M	glycines	glyphosate	X	X				
	Q	triazoles	amitrole	X	X				
Annual bluegrass (*Poa annua*)	B	'fops'	iodosulfuron, foramsulfuron		X	X	X		
	C	triazines	simazine		X	X	X		
	M	glycines	glyphosate		X	X	X		
	D	benzamides	propyzamide		X	X	X		
Awnless barnyard grass (*Echinochloa colona*)	C	triazines	atrazine				X		
	M	glycines	glyphosate	X			X		X
Barley grass (*Hordeum leporinum*)	A	'fops'	haloxyfop, fluazifop		X	X	X	X	
	A	'dims'	sethoxydim		X				
	L	bipyridiliums	paraquat	X	X	X	X	X	
	B	sulfonylureas	sulfosulfuron/sulfometuron	X					
	B	imidazolinones	imazamox, imazapic	X					
Barley grass (*Hordeum glaucum*)	A	'fops'	fluazifop		X				
	B	sulfonylureas	sulfosulfuron/sulfometuron	X					
	L	bipyridiliums	paraquat		X	X			
	M	glycines	glyphosate		X				
Brome grass (*Bromus diandrus*)	A	'fops'	haloxyfop			X			
	B	sulfonylureas	mesosulfuron		X	X			
	B	sulphonamides	pyroxsulam		X	X			
	M	glycines	glyphosate		X	X			
Brome grass (*Bromus rigidus*)	A	'fops'	quizalofop	X	X				
	B	sulfonylureas	mesosulfuron	X	X				
Red brome (*Bromus rubens*)	M	glycines	glyphosate	X					
Feathertop Rhodes grass (*Chloris virgata*)	M	glycines	glyphosate		X		X		
Giant Parramatta grass (*Sporobolus fertilis*)	J	alkanoic acids	flupropionate				X		
Goosegrass (*Eleusine indica*)	L	bipyridyl	paraquat						X
Large crabgrass (*Digitaria sanguinalis*)	A	'fops'	fluazifop, haloxyfop	X	X				
	B	imidazolinones	imazethapyr	X	X				

Weed species	Herbicide group		Example herbicide	States with confirmed resistant populations					
				WA	SA	VIC	NSW	TAS	QLD
Little seed canary grass (*Phalaris minor*)	A	'fops'	clodinafop			X			
Liverseed grass (*Urochloa panicoides*)	C M	triazines glycines	atrazine glyphosate				 X		X
Longflowered veldtgrass (*Ehrharta longiflora*)	A	'fops' 'dims'	haloxyfop, quizalofop clethodim	X X X					
Paradoxa grass (*Phalaris paradoxa*)	A A	'fops' 'dims'	fluazifop sethoxydim			X	X X		
Serrated tussock (*Nasella trichotoma*)	J	alkanoic acids	flupropanate			X			
Silver grass (*Vulpia* spp.)	L C	bipyridiliums triazines	paraquat simazine	 X		X			
Sweet summer grass (*Moorochloa eruciformis*)	M	glycines	glyphosate	X					X
Wild oat (*Avena* spp.)	A A B Z	'fops' 'dims' sulfonylureas aminopropionates	diclofop-methyl tralkoxydim iodosulfuron-methyl-sodium flamprop-methyl	X X	X X X X	X X X	X X X X		X X X
Windmill grass (*Chloris truncata*)	M	glycines	glyphosate	X		X	X		
Winter grass (*Poa annua*)	Z	dicarboxylic acid	endothal			X			

Note: Collated from information presented at www.weedscience.org/in.asp and other published literature.

Table HR 5 Known populations of herbicide-resistant broadleaf weeds in Australia (compiled by Storrie 2013, updated by Koetz 2018).

Weed species	Herbicide group		Example herbicide	States with confirmed resistant populations					
				WA	SA	VIC	NSW	TAS	QLD
African turnip weed (*Sisymbrium thellungi*)	B	sulfonylureas	chlorsulfuron						X
Arrowhead (*Sagittaria montevidensis*)	B	sulfonylureas	bensulfuron				X		
Black bindweed (*Fallopia convolvulus*)	B	sulfonylureas	chlorsulfuron						X
Black Nightshade (*Solanum nigrum*)	L	bipyridyl	paraquat						X
Calomba daisy (*Pentzia suffruticosa*)	B	sulfonylureas	metsulfuron-methyl		X				
Capeweed (*Arctotheca calendula*)	L	bipyridiliums	paraquat, diquat			X			
	I	phenoxys	2,4-D		X				
Common sowthistle (*Sonchus oleraceus*)	B	sulfonylureas	chlorsulfuron		X	X	X		X
	I	synthetic auxins	2,4-D		X	X			
	M	glycines	glyphosate				X		X
Dense-flowered fumitory (*Fumaria densiflora*)	D	dinitroanilines	trifluralin		X		X		
Flaxleaf fleabane (*Conyza bonariensis*)	M	glycines	glyphosate		X		X		X
	L	bipyridyl	paraquat				X		
Ice plant (*Mesembryanthemum crystallinum*)	B	sulfonylureas	chlorsulfuron		X				
Indian hedge mustard (*Sisymbrium orientale*)	B	sulfonylureas	chlorsulfuron	X	X	X	X		X
	B	sulfonamides	metosulam	X	X		X		X
	B	imidazolinones	imazethapyr		X				
	I	phenoxies	2,4-D		X				
Paterson's curse / salvation Jane (*Echium plantagineum*)	B	sulfonylureas	chlorsulfuron	X	X				
	B	sulfonamides	metosulam	X	X				
Pennsylvania Everlasting (*Gamochaeta pensylvania*)	L	bipyridyl	paraquat						X
Prickly lettuce (*Latuca serriola*)	B	sulfonylureas	triasulfuron		X	X			
	B	imidazolinones	imazethapyr		X				
	M	glycines	glyphosate			X			
Sand rocket (*Diplotaxis tenuifolia*)	B	sulfonylureas	chlorsulfuron		X				
Small square weed (*Mitracarpus hirtus*)	L	bipyridyl	paraquat						X
Starfruit (*Damasonium minus*)	B	sulfonylureas	bensulfuron				X		

Note: Collated from information presented at www.weedscience.org/in.asp and other published literature.

Weed species	Herbicide group		Example herbicide	States with confirmed resistant populations					
				WA	SA	VIC	NSW	TAS	QLD
Stinging nettle (*Urtica urens*)	C	triazines	simazine, atrazine			X			
Sumartran fleabane (*Conzya sumatrensis*)	L	bipyridyl	paraquat						X
Three-horned bedstraw (*Galium tricornutum*)	B	sulfonylureas	sulfometuron		X				
	B	imidazolinones	imazapyr		X				
	B	sulfonamides	metosulam		X				
Coat buttons (*Tridax procumbens*)	M	glycines	glyphosate	X					
Turnip weed (*Rapistrum rugosum*)	B	sulfonylureas	chlorsulfuron				X		X
Wild mustard (*Sinapis arvensis*)	B	sulfonylureas	chlorsulfuron				X		
Wild radish (*Raphanus raphanistrum*)	B	sulfonylureas	chlorsulfuron	X	X	X	X		
	B	sulfonamides	metosulam	X	X				
	B	imidazolinones	imazapic, imazapyr	X	X				
	C	triazines	simazine, atrazine	X					
	C	triazinones	metribuzin	X					
	F	nicotinanalides	diflufenican	X	X	X			
	I	phenoxies	2,4-D	X	X	X			
Wild turnip (*Brassica tournefortii*)	B	sulfonylureas	chlorsulfuron	X	X				
	B	sulfonamides	metosulam	X	X				
Willow leaved lettuce (*Lactuca saligna*)	M	glycines	glyphosate	X					

Note: Collated from information presented at www.weedscience.org/in.asp and other published literature.

Extent of resistance to selective herbicides in Australia

Herbicide resistance surveys have been conducted across the cropping regions of Australia for more than 20 years. During this time herbicide resistance in annual ryegrass has increased with resistance to multiple modes of action and cross resistance now common. Herbicide resistance is now on the rise in wild radish populations, especially in Western Australia with a reduction in efficacy in all modes of action. This increase in herbicide resistance has facilitated a change in how growers control weeds in their cropping systems. In addition to herbicide control, harvest weed seed control (HWSC) is now an integral component of most farming systems.

Annual ryegrass

The increase in herbicide resistance in annual ryegrass has occurred at a rapid rate. Irrespective of the cropping region within Australia, resistance to the majority of Group A, B and D chemistry is common and the levels of glyphosate-resistant populations is on the rise. Annual ryegrass is still rated as the most difficult cropping weed to control and the most prolific across all cropping zones (Llewellyn 2016). *Table HR 6* summarises the results of multiple weeds surveys evaluating the number of annual ryegrass populations with herbicide resistance across Australia.

A review of herbicide resistance testing over a 25-year period (1991–2016) conducted by Charles Sturt University found that the resistance level in ryegrass samples remained relatively constant across the years, although the number of postcode areas where samples originated has increased (Broster et al. 2019). This suggests that herbicide resistance was increasing in newer or previously less intensively cropped areas.

Wild radish

AHRI have conducted random weed surveys across the Western Australian wheatbelt since 2003. Population screening has detected high resistance levels to three MOA groups (*Table HR 7*) Cross resistance in 70% of populations has also been confirmed between the Group B 'SU' and Group B 'Imi' herbicides, an increase of 10% since the 2003 survey (Walsh et al. 2007).

Table HR 6 The extent of annual ryegrass resistance in Australia (John Broster. WA data: Owen et al. 2014; VIC and SA data: Boutsalis et al. 2012).

Herbicide group	NSW (2010–17)	WA (2015)	SA (2007–08)	VIC (2005–09)
A 'fop'	64	96	48	46
A 'dim'	10	44	16	8
B 'SU'	57	99	73	16
B 'Imi'	53	–	–	20
D	9	30	25	8
J/K	0	–	–	0
K	0	–	–	0
M*	3	7	–	0
Sample No	629	466	606	318

*Testing for glyphosate resistance is a component of all commercial testing services.

Figure HR 6 2,4-D resistant wild radish in a wheat crop, Wongan Hills, WA.
Photo: Andrew Storrie

Table HR 7 The change in Wild radish resistance levels in Western Australia, from random surveys, 2003–2015 (Owen 2018, GRDC Crop Updates).

Herbicide group	2003	2010	2015
B 'SU'	54	84	88
B 'Imi'	–	49	71
I 'synthetic auxin'	60	76	61
F 'PDS inhibitor'	46	49	65
C 'PSII inhibitor'	15	2	14

There has been a significant rise in 'Imi' resistance from 2010 to 2015. Atrazine resistance levels remained low and no populations were found to have resistance to Velocity (Group H and C) or glyphosate.

Wild oats

Testing of wild oat populations in NSW, Queensland and Western Australia reported high resistance levels to Group A 'fop' chemistry and resistance in other MOA groups (*Table HR 8*). Very low resistance levels were recorded for Group A 'dim' and Group B 'SU' chemistry. Importantly no populations have been recorded with resistance to pre-emergent Group J chemistry or the non-selective Group M, glyphosate.

Overall, 25% of the wild oat samples in NSW that were resistant to fenoxaprop and clodinafop also had resistance to flamprop methyl which is in Group Z (Widderick and Cook 2011).

Table HR 8 Results of herbicide resistance testing in wild oat populations (J Broster. WA: Owen et al. 2016).

Herbicide group	NSW (2017)	QLD (2016)	WA (2010)
A 'fop'	38	34	48
A 'dim'	1	0	8
B 'SU'	7	3	2
J	0	0	0
M	0	0	0
Sample No	523	64	118

Extent of resistance to non-selective herbicides in Australia

Glyphosate

In 1996, glyphosate resistance was confirmed for the first time in annual ryegrass in Australia (Pratley et al. 1996). It was documented in populations of:

- awnless barnyard grass (*Echinochloa colona*) in NSW in 2007
- liverseed grass (*Urochloa panicoides*) in NSW in 2008
- flaxleaf fleabane (*Conyza bonariensis*) in Queensland and NSW in 2010
- windmill grass (*Chloris truncata*) in NSW in 2010
- brome grass (*Bromus diandrus*) in South Australia in 2011 (Preston 2011).

Since 2011 another 11 weeds have been confirmed as glyphosate-resistant (Preston 2018).

In November 2018 there were 858 documented glyphosate-resistant populations of annual ryegrass, 103 of awnless barnyard grass, 64 of fleabane, 11 of windmill grass, four of liverseed grass and five of great brome.

As with all other herbicides at risk of evolving resistant weed populations, selection for resistance to glyphosate is enhanced by particular management activities (*Table HR 9*). It is important to avoid 'risk-increasing' actions and include 'risk-decreasing' tactics.

Knockdown herbicides are a critical weed management tool in our current farming systems. As with all weed control tactics, non-selective herbicides should always be used as part of a planned weed management program in conjunction with a number of other practices from different tactic groups.

Figure HR 7 Field heavily infested with glyphosate resistant annual ryegrass having been sprayed with 2 L glyphosate 450 per ha.
Photo: Andrew Storrie

Table HR 9 Factors that influence the risk of the evolution of resistance to glyphosate (Australian Glyphosate Sustainability Working Group 2013).

Risk-increasing actions	Risk-decreasing actions
▪ **continual reliance** on glyphosate before seeding ▪ lack of tillage ▪ **lack of effective** in-crop weed control ▪ **frequent** glyphosate-based chemical fallow ▪ **inter-row** glyphosate use (unregistered) ▪ **frequent** late season weed control and in-crop spray-topping with glyphosate ▪ **over-reliance** on glyphosate-resistant crops ▪ **high weed** numbers	▪ **non-herbicide** practices to prevent formation of **viable weed seed** ▪ using crops with **high competition levels** with weeds ▪ adopting HWSC tactics ▪ using **late season weed control** and in-crop spray-topping with alternative herbicide groups ▪ farm hygiene to **prevent movement** of resistant seed ▪ the **double knock** technique* ▪ **strategic** use of **alternative** knockdown groups ▪ use of **alternative** herbicide groups or tillage for inter-row and fallow weed control ▪ **effective** in-crop weed control ▪ **full-disturbance** cultivation at sowing ▪ applying **stewardship plans** when growing glyphosate-resistant crops

*The double knock technique is defined as using full-disturbance cultivation OR the full label rate of a paraquat-based product (Group L herbicide) following the glyphosate (Group M herbicide) knockdown application.

Paraquat

Three populations of paraquat-resistant annual ryegrass were confirmed in south-eastern South Australia in 2010 in glasshouse experiments. One population was also resistant to glyphosate. Glyphosate resistance evolved on an irrigation channel and subsequently moved into the paddock, where it was then selected with paraquat. In September 2013 an annual ryegrass population from a Western Australian vineyard was confirmed resistant to both glyphosate and paraquat following a history of using both herbicides. Several populations of tall fleabane from NSW and Queensland have also been confirmed resistant to paraquat.

Other species have previously developed resistance to Group L herbicides in Australia, the first case being northern barley grass (*Hordeum glaucum*) in 1983 (*Table HR 10*). Small square weed (*Mitracarpus hirtus*) was the first case of paraquat resistance in Australia that developed outside broadacre agriculture.

All cases of paraquat resistance are in situations with a long history of use (more than 15 years).

Table HR 10 Species that have developed resistance to paraquat in Australia.

Species	Common Name	Year confirmed	State	Crop	Resistance to other modes-of-action / herbicides
Hordeum glaucum	northern barley grass	1983	Victoria	lucerne	diquat (L)
Arctotheca calendula	capeweed	1984	Victoria	lucerne	diquat (L)
Hordeum leporinum	brley grass	1988	Victoria	lucerne	diquat (L)
Vulpia bromoides	silver grass	1990	Victoria	lucerne	diquat (L)
Mitracarpus hirtus	small square weed	2007	Queensland	mangoes	diquat (L)
Lolium rigidum	annual ryegrass	2010	South Australia	pasture seed	A / M – 2 populations
Gamochaeta pensylvanica	cudweed	2015	Queensland	tomatoes, sugar cane	
Solanum nigrum	blackberry nightshade	2015	Queensland	tomatoes, sugar cane	
Eleusine indica	crowsfoot grass	2015	Queensland	tomatoes, sugar cane	
Conyza bonariensis	flaxleaf fleabane	2016	New South Wales	grape vines	
Conzya sumartrensis	tall fleabane	2018	New South Wales	Summer crops	

Weed species at risk

A wide range of crop weeds in Australia have populations confirmed resistant to a range of herbicide MOA groups (*Table HR 4* and *Table HR 5*). It is also important to know which weeds are likely to develop resistance and this will depend on the biological characteristics of the plant and the farming system in which it grows.

Global examples of herbicide resistance are presented in *Table HR 11*. Although these weeds are present in Australia, no populations have been reported with resistance to these herbicide groups.

Table HR 11 Resistance watch: confirmed resistance in overseas populations of common weed species in crops that pose a potential threat in Australian cropping systems (updated by Storrie 2012, updated by Koetz 2018).

Weed Species	Herbicide group		Example herbicide	Country with confirmed resistant populations
Ball mustard (*Neslia paniculata*)	B	sulfonylureas	metsulfuron-methyl	Canada
Barnyard grass (*Echinochloa* spp.)	A	'fops'	fenoxaprop, quizalofop	Japan, Thailand, United States of America
	B	imidazolinones	imazethapyr	Ukraine, Yugoslavia
	B	sulphonamides	penoxsulam	Japan, Turkey, United States of America
	C	amides	propanil	Greece, Italy, Thailand, United States of America
	D	dinitroanilines	pendimethalin	Bulgaria
	J	thiocarbamates	molinate	China, United States of America
	I	quinolines	quinclorac	Brazil
Brome grass (*Bromus* spp.)	C	triazines	atrazine	France, Spain
	C	substituted ureas	chlorotoluron	Spain
Wild mustard (*Sinapis arvensis*)	B	imidazolinones	imazethapyr	United States of America
	C	triazines	atrazine	Canada
	C	triazinones	metribuzin	Canada
	I	phenoxies	2,4-D	Canada
	I	pyridines	picloram	Canada
	I	benzoic acids	dicamba	Canada, Turkey
Common chickweed (*Stellaria media*)	B	sulfonylureas	chlorsulfuron	Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Latvia, New Zealand, Norway, South Africa, Sweden, United Kingdom, United States of America
	C	triazines	atrazine	Germany
	I	phenoxies	mecoprop	China, United Kingdom
Crowsfoot grass (*Eleusine indica*)	A	'fops'	fluazifop	Bolivia, Brazil, Malaysia
	A	'dims'	clethodim	Boliva, Brazil, Malaysia
	B	imidazolinones	imazapyr	Costa Rica
	C	triazinones	metribuzin	United States of America
	D	dinitroanalines	trifluralin	United States of America
	G	oxadiazole	oxadiazon	United States of America
	M	glycines	glyphosate	Argentina, Bolivia, Brazil, China, Colombia, Costa Rica, Indonesia,
	N	phosphinic acids	glufosinate	Japan, Malaysia, United States of America
				Malaysia
Fleabane (*Conyza* spp.)	B	imidazolinones	imazapyr	Israel, Poland
	B	sulfonylureas	chlorsulfuron	Brazil, France, Israel, Paraguay, Poland, United States of America
	B	triazolopyrimidines	cloransulam-methyl	Canada, United States of America
	C	triazines	atrazine	Belgium, Czech Republic, France, Israel, Poland, Spain, Switzerland, United Kingdom , United States of America
	C	substituted ureas	linuron	France, United States of America
	G	pyrimidindiones	saflufenacil	Brazil
	I	phenoxies	2,4-D	Brazil
Lesser canary grass (*Phalaris minor*)	B	sulfonylureas	sulfosulfuron,	India, South Africa
	C	substituted ureas	isoproturon	India
Paradoxa grass (*Phalaris paradoxa*)	C	triazines	atrazine	Israel

Note: Collated from information presented at www.weedscience.org/in.asp and other published literature.

Weed Species	Herbicide group		Example herbicide	Country with confirmed resistant populations
Shepherd's purse (*Capsella bursa-pastoris*)	B	sulfonylureas	tribenuron-methyl	Canada, China, Denmark
	B	imidazolinones	imazethapyr	Canada, Israel
	C	triazines	atrazine	Poland
	C	triazinones	metribuzin	United States of America
Summer grass (*Digitaria sanguinalis*)	C	triazines	atrazine	Czech Republic, France, Poland
Summer grass (*Digitaria ciliaris*)	A	'fops'	fluazifop-p	Brazil
Wild oat (*Avena* spp.)	D	benzamides	propyzamide	United States of America
	J	thiocarbamates	tri-allate	Canada, United States of America
	K	isoxazolines	pyroxasulfone	Canada
Wireweed (*Polygonum aviculare*)	C	triazines	atrazine	Belgium, Netherlands
	Q	triazoles	amitrole	Belgium

Note: Collated from information presented at www.weedscience.org/in.asp and other published literature.

It is mostly winter weeds that are at greatest risk of developing resistance in southern and western cropping zones of Australia, whereas a mix of both summer and winter weeds are at risk in northern NSW and southern Queensland. Summer weeds are at the greatest risk of developing resistance in central Queensland (Walker et al. 2004).

A large number of weed species are present in the cropping region of north-eastern Australia. A survey of this region, which includes northern NSW, southern Queensland and central Queensland, identified 105 weeds from 95 genera, with the major weeds being sowthistle, turnip weed, barnyard grass and liverseed grass (Osten et al. 2007).

With such a large number of weeds occurring in diverse farming systems it was considered important to rank weeds species and farming systems at risk of developing glyphosate resistance (Thornby et al. 2010; Thornby et al. 2011; Werth et al. 2011). The top 20 weeds in the north-east grain region are shown in *Table HR 12*. The highest risk farming systems were summer fallow and both glyphosate-resistant and non-glyphosate resistant, non-irrigated cotton. It is interesting to note that five species on the list have already developed glyphosate resistance in this region. This research has also shown that growers should identify their high-risk weeds and rotations and tailor their management strategies around these rather than their most prevalent weeds.

Glyphosate resistance development in annual ryegrass, awnless barnyard grass and liverseed grass will see the risks for Group A and Group L resistance increase in these species.

Table HR 12 Top 20 species in the north-eastern grain region at risk of developing glyphosate resistance or increasing resistance occurrence (in bold) (Werth et al. 2011).

Species	Common name
Moorochloa eruciformis	Sweet summer grass
Conyza bonariensis	Flaxleaf fleabane
Urochloa panicoides	Liverseed grass
Chloris virgata	Feathertop Rhodes grass
Sonchus oleraceus	Sowthistle
Echinochloa colona	Awnless barnyard grass
Eleusine indica	Crowsfoot grass
Phalaris paradoxa	Paradoxa grass
Hordeum spp.	Barley grass
Lolium rigidum	Annual ryegrass
Dactyloctenium radulans	Button grass
Digitaria ciliaris	Summer grass
Chloris truncata	Windmill grass
Amaranthus hybridus	Redshank
Cirsium vulgare	Spear thistle
Silybum marianum	Variegated thistle
Sorghum halepense	Johnson grass
Eragrostis cilianensis	Stink grass
Avena spp.	Wild oats
Lactuca serriola	Prickly lettuce

The risk for winter weeds is mainly the expansion of currently known problems such as glyphosate resistance in annual ryegrass and wild oats, Group B resistance in brassica weeds and Group A and Z resistance in wild oats.

The extensive use of trifluralin (Group D) in no-till farming systems in southern Australia is a continuing high risk for resistance in annual ryegrass. Shepherd's purse (*Capsella bursa-pastoris*) is also at risk of developing Group B resistance.

A national survey conducted in 2016 listed the 10 most prolific cropping systems weeds across all regions (Llewellyn, 2016). The list includes several species that already have multiple resistance to a number of MOA groups (*Table HR 13*). Other emerging weed threats, especially in the northern cropping region where summer crops are grown, include barnyard grass and feathertop Rhodes grass.

Table HR 13 National ranking of most problematic weeds in all crops.

Rank	Weed
1	Annual ryegrass
2	Wild radish
3	Wild oats
4	Brome grass
5	Wild turnip
6	Wild mustard
7	Fleabane
8	Sow/Milk thistle
9	Barley grass
10	Cape weed

Prevention/delay of herbicide resistance

Preventing the spread of herbicide resistance will require the integration of chemical, cultural and non-chemical weed control tactics. Stopping seed set and depleting the weed seedbank are the key components of an integrated weed control system. *Section 4: Tactics for managing weed populations* contains detailed information on weed control tactics.

Herbicide resistance testing

Testing herbicide resistance status provides essential information about weed populations for planning weed management and enterprise sequence.

If done properly, herbicide resistance testing will tell the adviser and grower which herbicides are still effective on the target weeds in certain paddocks. This can save the unnecessary use of ineffective herbicides that are unable to kill the weeds in question; it will also optimise crop yield and provide essential information on in-crop and future weed management.

Testing can determine which herbicides will work in the current or next season. For example, ryegrass may not be controlled by diclofop-methyl (Group A 'fop') but may still be susceptible to pinoxaden (Group A 'den'), which allows some flexibility with cereal crops. Knowing which herbicides are still effective will allow future planning of enterprise sequence and help determine which cultural management techniques to use.

Testing can be conducted in situ or by a commercial testing service. In situ tests provide visual identification of resistance for growers, but can be more difficult to interpret due to variable paddock conditions and the increasing size of weeds before they can be re-treated.

Commercial testing services grow the plants under glasshouse conditions, removing any climatic or paddock variability that may affect the results, as well as using laboratory quality spraying equipment. They are able to easily test a number of different herbicides at several rates and compare the results to standard susceptible and resistant biotypes sprayed at the same time.

For information on how to test for resistance, see *Section 6: Implementing an IWM program using tactic groups* and the Australian Glyphosate Sustainability Working Group website www.glyphosateresistance.org.au/.

Figure HR 8 Foreground (left) trifluralin susceptible, (centre) trifluralin resistant biotype with intermediate resistance and (right) trifluralin resistant biotype with strong resistance. The array of pots in the background represent randomly collected ryegrass samples from Victoria in 2005 (Mallee and Wimmera regions). A pot test was conducted in winter 2006. Each pot represents seed collected from one paddock.
Photo: Peter Boutsalis

Further information

Australian Glyphosate Sustainability Working Group

The Australian Glyphosate Sustainability Working Group is a collaborative initiative involving research, industry and extension representatives. Its purpose is to promote the sustainable use of glyphosate in Australian agriculture.

Its priority goals are to:

1. Increase glyphosate usage sustainability by developing and delivering clear and consistent information based on industry consensus.
2. Increase collaboration and consistency among the glyphosate research and extension activities of key research, extension and industry groups.
3. Contribute to the development of research, development and extension initiatives aimed at improving glyphosate management.

The Australian Glyphosate Sustainability Working Group's website is supported by the Grains Research and Development Corporation, and key research- and development-based crop protection companies with an interest in glyphosate sustainability. (www.glyphosateresistance.org.au/). It is used as the main method of information exchange.

The group has developed a simple list of factors that have an influence on the risk of weed populations developing glyphosate resistance (*Table HR 9*) and this information is available as industry-specific posters on the website.

There is also an active register, containing information about all the known weed populations resistant to glyphosate and paraquat in Australia. Populations are added to the register after confirmation by one of the testing services or researchers.

CropLife Australia Ltd Herbicide Resistance Management Committee

CropLife Australia Ltd (formerly Avcare, the National Association for Crop Production and Animal Health) has developed a series of Resistance Management Strategies (www.croplifeaustralia.org.au) for herbicides from most MOA groups. The specific guidelines for using crop protection products are designed to reduce the selection pressure for resistance.

Developing and implementing an Integrated Weed Management plan that incorporates tactics from a number of tactic groups (see *Section 4: Tactics for managing weed populations*) and follows the recommendations listed in the Resistance Management Strategies, can extend the effective life of herbicides in crop paddocks and help manage herbicide resistant weed populations.

Contributors

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References

Alizadeh HM, Preston C and Powles SB 1998. Paraquat-resistant biotypes of *Hordeum glaucum* from zero-tillage wheat. *Weed Research*, vol. 38, pp. 139–142.

Boutsalis P and Powles SB 1995. Resistance of dicot weeds to acetolactate synthase (ALS)-inhibiting herbicides in Australia. *Weed Research*, vol. 35, pp. 149–155.

Boutsalis P, Preston C and Broster JC 2006. Management of trifluralin resistance in annual ryegrass (*Lolium rigidum* Gaudin) in southern Australia. *Managing weeds in a changing climate: 15th Australian Weeds Conference*, Adelaide, South Australia, (eds JH Watts, C Preston and ND Crossman), pp. 507–510, Weed Management Society of South Australia.

Boutsalis P, Gill GS and Preston C 2012. Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across south-eastern Australia. *Weed Technology*, vol. 26, pp. 391–398.

Broster JC, Pratley JE, Ip RHL, Ang L, Seng KP. A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Crop and Pasture Science*, vol. 70, pp. 283–293.

Broster JC, Koetz EA and Wu H 2011. Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) in southern New South Wales. *Plant Protection Quarterly*, vol. 26, pp. 22–28.

Busi R, Yu Q, Barrett-Lennard R and Powles SB 2008. Long distance pollen-mediated flow of herbicide resistance genes in *Lolium rigidum*. *Theoretical and Applied Genetics*, vol. 117, pp. 1281–1290.

Busi R and Powles SB 2017. Managing metabolic resistance in ryegrass with the existing pre emergence chemistries. GRDC Update paper, Wagga Wagga, 19–20 February 2017, www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/managing-metabolic-resistance-in-ryegrass-with-the-existing-pre-emergence-chemistries. Viewed on 12 December 2018

Diggle AJ and Neve P 2001. The population dynamics and genetics of herbicide resistance – a modelling approach. SB Powles and DL Shaner (eds). *Herbicide resistance and world grains*. CRC Press Inc., Boca Raton, Florida, United States of America, pp. 61–100.

Fei S and Nelson E 2003. Estimation of pollen viability, shedding pattern, and longevity of creeping bent grass on artificial media. *Crop Science*, vol. 43, pp. 2177–2181.

Gill GS 1995. Development of herbicide resistance in annual ryegrass populations (*Lolium rigidum* Gaud.) in the cropping belt of Western Australia. *Australian Journal of Experimental Agriculture*, vol. 35, pp. 67–72.

Llewellyn RS and Powles SB 2001. High levels of herbicide resistance in rigid ryegrass (*Lolium rigidum*) in the wheat belt of Western Australia. *Weed Technology*, vol. 15, pp. 242–248.

Llewellyn RS, Ronning D, Ouzman J, Walker S, Mayfield A and Clarke M 2016. Impact of weeds in Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. Report for the Grains Research and Development Corporation, CSIRO.

McAlister FM, Holtum JAM. and Powles SB 1995. Dinitroaniline herbicide resistance in rigid ryegrass (*Lolium rigidum*). *Weed Science*, vol. 43, pp. 55–62.

Mansooji AM, Holtum JAM., Boutsalis P, Matthews JM and Powles SB 1992. Resistance to aryloxyphenoxypropionate herbicides in two wild oat species (*Avena fatua* and *Avena sterilis* ssp. *ludoviciana*). *Weed Science*, vol. 40, pp. 599–605.

Neve P, Diggle AJ, Smith FP and Powles SB 2003. Simulating evolution of glyphosate resistance in *Lolium rigidum*. I: Population biology of a rare resistance trait. *Weed Research*, vol. 43, pp. 404–417.

Osten VA, Walker SR, Storrie A, Widderick M, Moylan P, Robinson GR and Galea K 2007. Survey of weed flora and management relative to cropping practices in the north-eastern grain region of Australia. *Australian Journal of Experimental Agriculture*, vol. 47, pp. 57–70.

Owen MJ, Walsh MJ, Llewellyn RS and Powles SB 2007. Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Australian Journal of Agricultural Research*, vol. 52, pp. 527–548.

Owen MJ, Martinez NJ and Powles SB 2014. Multiple herbicide-resistant *Lolium rigidum* (annual ryegrass) now dominates across the Western Australian grain belt. *Weed Research*, vol. 54, pp. 314–324.

Owen MJ and Powles SB 2018. Current levels of herbicide resistance in key weed species in the Western Australian grain belt. GRDC Crop Updates February, 2018. Viewed 8 Dec 2018

Powles SB, Lorraine-Colwill DF, Dellow JJ and Preston C 1998. Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science*, vol. 46, pp. 604–607.

Powles SB, Preston C, Bryan IB and Jutsum AR 1997. Herbicide resistance: Impact and management. *Advances in Agronomy*, vol. 58, pp. 57–84.

Pratley JE, Baines P, Eberbach P, Incerti M and Broster JC 1996. Glyphosate resistance in annual ryegrass. *The Art of Grazing Management: 11th Annual Conference of the Grasslands Society of New South Wales*. Wagga Wagga, Australia, p. 122, The Grasslands Society of NSW Inc.

Preston C and Powles SB 2002. Evolution of herbicide resistance in weeds: initial frequency of target site-based resistance to acetolactate synthase-inhibiting herbicides in *Lolium rigidum*. *Heredity,* vol. 88, pp. 8–13.

Preston C, Roush RT and Powles SB 1999. Herbicide resistance in weeds of southern Australia: why are we the worst in the world? *Weed management into the 21st century: do we know where we're going?: 12th Australian Weeds Conference*, Hobart, Australia, (eds AC Bishop, M Boersma and CD Barnes), pp. 454–459, Tasmanian Weed Society.

Preston C 2018. The Australian Glyphosate Sustainability Working Group, glyphosateresistance.org.au. Viewed 19 December 2018.

Storrie AM and Cook T 2002. Glyphosate resistance in northern New South Wales – a growing concern. *Weeds 'threats now and forever': 13th Australian Weeds Conference*. Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 601–604, Plant Protection Society of WA.

Thornby D, Werth J, Curr M and Walker S 2010. Risks and RATs: assessing glyphosate resistance risk in paddocks in north-eastern Australia. *New Frontiers in New Zealand: Together we can beat the weeds: 17th Australasian Weeds Conference*. Christchurch, New Zealand, (ed SM Zydenbos), pp.246–249, Plant Protection Society.

Thornby D, Werth, J and Walker S 2011. Finding and fixing glyphosate resistance risk in diverse subtropical Australian farming systems. *Weed Management in a Changing World: 23rd Asian-Pacific Weed Science Society Conference*. Cairns, Australia (eds R McFadyen, N Chandrasena, S Adkins, A Hashem, S Walker, D Lemerle, L Weston and S Lloyd), pp. 549–554.

Walker S, Widderick M, Storrie AM and Osten, V 2004. Preventing glyphosate resistance in weeds of the northern grain region. *Weed management: balancing people, planet, profit: 14th Australian Weeds Conference*. Wagga Wagga, NSW, (eds BM Sindel and SB Johnson), pp. 428–431, Weed Society of New South Wales, Sydney, Australia for the Council of Australian Weed Societies.

Walsh MJ, Owen MJ and Powles SB 2007. Frequency and distribution of herbicide resistance in *Raphanus raphanistrum* populations randomly collected across the Western Australian wheatbelt. *Weed Research*, vol. 47, pp. 542–550.

Walsh MJ, Powles SB, Beard B, Parkin B and Porter S 2003. Multiple herbicide resistance across four modes of action in wild radish (*Raphanus raphanistrum* L.). *Weed Science,* vol. 52, pp. 8–13.

Werth J, Thornby D and Walker S 2011. Assessing weeds at risk of evolving glyphosate resistance in Australian sub-tropical glyphosate-resistant cotton systems. *Crop & Pasture Science,* vol. 62, pp. 1002–1009.

Widderick M and Cook T 2011. Strategies for optimising the life of Group A herbicides and patterns of herbicide resistance in wild oats. Northern Grower Alliance, https://www.nga.org.au/results-and-publications/download/70/grdc-update-papers-weeds/wild-oat-management-1/grdc-adviser-update-paper-warialda-february-2011-nindigully-march-2011/ Downloaded 12 Dec 2018.

Widderick M and Galea K 2004. The current state of herbicide resistance in the northern grain region. *Northern Herbicide Resistance Reporter*, September 2004, pp. 1–7.

Further reading

Busi R and Powles SB 2009. Evolution of glyphosate resistance in a *Lolium rigidum* population by glyphosate selection at sublethal doses. *Heredity*, vol. 103, pp. 318–325.

Duke SO and Powles SB 2008. Glyphosate: A once-in-a-century herbicide. *Pest Management Science,* vol. 64, pp. 319–325.

Duke SO and Powles SB 2009. Glyphosate-resistant crops and weeds: Now and in the future. *AgBioForum,* vol. 12, pp. 1–12.

Heap I 2018. *The International Survey of Herbicide Resistant Weeds*, www.weedscience.org. Viewed 1 Dec 2018

Lorraine-Colwill DF, Hawkes TR, Williams PH, Warner SJ, Sutton PB, Powles SB and Preston C 1999. Resistance to glyphosate in *Lolium rigidum*. *Pesticide Science,* vol. 55, pp. 486–503.

Lorraine-Colwill DF, Powles SB, Hawkes TR and Preston C 2001. Inheritance of evolved glyphosate resistance in *Lolium rigidum*. *Theoretical and Applied Genetics,* vol. 102, pp. 545–550.

Lorraine-Colwill DF, Powles SB, Hawkes TR, Hollinshead PH, Warner SAJ and Preston C 2003. Investigations into the mechanism of glyphosate resistance in *Lolium rigidum*. *Pesticide Biochemistry and Physiology,* vol. 74, pp. 62–72.

Neve P, Diggle AJ, Smith FP and Powles SB 2003a. Simulating evolution of glyphosate resistance in *Lolium rigidum*. I. Population biology of a rare resistance trait. *Weed Research,* vol. 43, pp. 404–417.

Neve P, Diggle AJ, Smith FP and Powles SB 2003b. Simulating evolution of glyphosate resistance in *Lolium rigidum*. II. Past, present and future glyphosate use in Australian cropping. *Weed Research,* vol. 43, pp. 418–427.

Neve P, Sadler J and Powles SB 2004. Multiple herbicide resistance in a glyphosate-resistant rigid ryegrass (*Lolium rigidum*) population. *Weed Science,* vol. 52, pp. 920–928.

Owen MJ, Owen RK and Powles SB 2009. A survey in the southern grain belt of Western Australia did not find *Conyza* spp. resistant to glyphosate. *Weed Technology,* vol. 23, pp. 492–494.

Owen MJ, Goggin DE and Powles SB 2012. Identification of resistance to either paraquat or ALS-inhibiting herbicides in two Western Australian *Hordeum leporinum* biotypes. *Pest Management Science,* vol. 68, pp. 757–763.

Pedersen BP, Neve P, Andreasen C and Powles SB 2007. Ecological fitness of a glyphosate resistant *Lolium rigidum* population: Growth and seed production along a competition gradient. *Basic and Applied Ecology,* vol. 8, pp. 258–268.

Powles, SB 2003. My View: Will glyphosate continue to aid world food production? *Weed Science,* vol. 51, p. 471.

Powles, SB 2008a. Evolution in action: Glyphosate-resistant weeds threaten world crops. *Outlooks on Pest Management,* vol. 19, pp. 256–259.

Powles, SB 2008b. Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. *Pest Management Science,* vol. 64, pp. 360–365.

Powles, SB 2010. Gene amplification delivers glyphosate-resistant weed evolution. *Proceedings of the National Academy of Sciences*, vol. 107, pp. 955–956.

Powles SB and Preston C 2006. Evolved glyphosate resistance in plants: Biochemical and genetic basis of resistance. *Weed Technology,* vol. 20, pp. 282–289.

Powles SB, Lorraine-Colwill DF, Dellow JJ and Preston C 1998. Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science,* vol. 46, pp. 604–607.

Stanton RA, Pratley JE, Hudson D and Dill GM 2008. A risk calculator for glyphosate resistance in *Lolium rigidum* (Gaud.). *Pest Management Science,* vol. 64, pp. 402–408.

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CM and Powles SB 2007. Evolution of glyphosate-resistant Johnson grass (*Sorghum halepense*) in glyphosate-resistant soybeans. *Weed Science,* vol. 55, pp. 566–571.

Walsh MJ, Duane RD and Powles SB 2001. High frequency of chlorsulfuron resistant wild radish (*Raphanus raphanistrum*) populations across the Western Australian wheatbelt. *Weed Technology,* vol. 15, pp. 199–203.

Walsh MJ, Owen MJ and Powles SB 2007. Frequency and distribution of herbicide resistance in *Raphanus raphanistrum* populations randomly collected across the Western Australian wheatbelt. *Weed Research,* vol. 47, pp. 542–550.

Yu Q, Cairns A and Powles SB 2007. Glyphosate, paraquat and ACCase multiple herbicide resistance in a *Lolium rigidum* biotype. *Planta,* vol. 225, pp. 499–513.

Yu Q, Abdallah I, Han H, Owen MJ and Powles SB 2009. Distinct non-target site mechanisms endowing resistance to glyphosate, ACCase and ALS-inhibiting herbicides in multiple herbicide resistant *Lolium rigidum*. *Planta,* vol. 230, pp. 713–723.

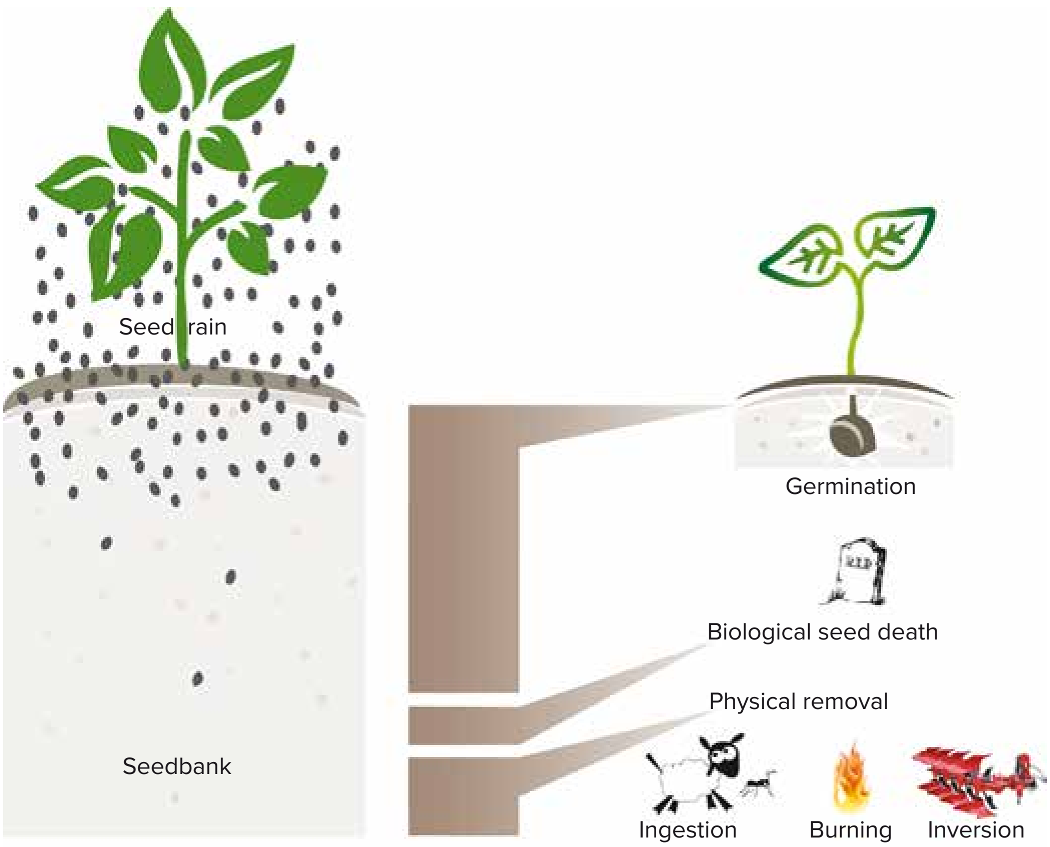
SECTION 4: TACTICS FOR MANAGING WEED POPULATIONS

'Used singly, none of the currently available cultural techniques provide an adequate level of weed control. However when used in carefully planned combinations extremely effective control can be achieved.'

Gill and Holmes 1997

The above quote is from a research and extension paper written in 1997. The concept of using as many weed control tactics in combination within the one season to prevent the production of new weed seeds still holds true today and will continue to hold for as long as we farm. There are no 'silver bullets' and this section looks at all the tactics that can be used in combination to keep weed numbers down and farming profitable.

The illustration below shows the relationship between seed rain, the soil seedbank and how seeds are removed or prevented from entering the seedbank. Germination is the largest path where herbicides or cultivation can be used. A small proportion of seeds die through natural causes while we can also bury, burn or eat seeds using a range of IWM tactics.



Tactic Group 1 Deplete weed seed in the target area soil seedbank

Tactic 1.1 Burning residues

Despite summer fires being able to effectively destroy the surface seedbanks of many weeds, including annual ryegrass (*Lolium rigidum*), the environmental hazard of burning at this time of the year in Australia is extreme (Gill and Holmes 1997) and therefore illegal.

Autumn burns are an effective alternative and have been shown to successfully decrease weed seed densities. Strategic late burning (in March) to manage weed seedlings and surface weed seeds is therefore useful for growers on soils with low erosion potential.

Crop residue burning may challenge the stubble retention principles of many grain growers and advisers. However, when used strategically as a one-off tactic and in conjunction with other management strategies, it can be quite effective in reducing viable weed seed numbers.

Figure T1.1–1 Narrow windrows being burnt in autumn.
Photo: Di Holding

Benefits

Key benefit #1

Burning can reduce viable weed seed numbers in the seedbank.

The weed management benefits of burning crop residues have been widely researched. *Table T1.1–1* provides the outcomes from a number of research projects where reductions in soil surface seedbanks have resulted from burning.

Burning is more effective at higher temperatures and therefore more effective with high levels of stubble. Seeds on or very close to the soil surface are more likely to be killed than seeds buried more deeply (greater than 5 mm) in the soil.

All crop residues (canola, wheat and lupin) can produce a sufficiently hot burn provided that adequate tonnage of residue is present. Hence higher temperature burns will be obtained by concentrating residue into a narrow windrow (see *Tactic 4.1a Narrow header trail*).

Figure T1.1–2 Chaff dumps can be burnt in autumn, killing a high proportion of seeds present.
Photo: Andrew Storrie

Table T1.1–1 Reduction in weed seed numbers following crop residue burning.

Location	Situation	Weeds species	Control achieved	Reference
New South Wales	Continuous cropping	Annual ryegrass	97–98%	Fettell 1998
Victoria	Pasture	Annual ryegrass	35–57% control when stubble grazed	Davidson 1992
Victoria	Pasture	Annual ryegrass	35–66%	Reeves and Smith 1975
South Australia	Cereal	Annual ryegrass	60%	Matthews et al. 1996
Western Australia	Wheat, canola, lupin trash windrows (harvest spreaders removed, trash concentrated with chute)	Annual ryegrass Wild radish	98% 75%	Newman and Walsh 2005
Western Australia	Wheat: straw spread (equivalent to 2.3 t dry matter/ha)	Annual ryegrass	82% control of total annual ryegrass on soil surface	Chitty and Walsh 2003
	Wheat: concentrated trash windrow (equivalent to 15 t dry matter/ha)	Annual ryegrass	99% control of annual ryegrass in the windrow	

Figure T1.1–3 High density annual ryegrass controlled with clethodim in canola, Eyre Peninsula.
Photo: Andrew Storrie

Figure T1.1–4 Same paddock as Figure T1.1–3 above, however this section had a full stubble burn in December.
Photo: Andrew Storrie

Key benefit #2

Combining burning with other tactics (e.g. seed collection or narrow header trails) will increase the overall weed control impact.

Weed management using burning can be made more effective by combining it with other techniques such as seed collection, windrowing or modifying the header's trash placement (*see Tactic 4.1 Weed seed control at harvest*).

The effectiveness of burning for weed seed destruction is directly related to the amount of residue (fuel) available for burning. Simply removing or disengaging the straw spreaders leaves the straw and chaff in a narrow trail or windrow approximately 1.5 m wide. Alternatively, a chute attached to the rear of the header will concentrate harvest residues into narrow windrows or header trails (Walsh et al. 2005). The WeedSmart website, https://weedsmart.org.au/?s=windrow+burning, provides comprehensive further reading.

A windrow will burn at a higher temperature for longer than spread stubble, thereby improving weed kill. Burning a narrow windrow also reduces the percentage of the paddock that is burnt, thereby reducing the area prone to wind erosion.

Seed which is not collected in the windrow will not be burnt and therefore remains viable. This could be a problem if large amounts of seed are shattered before windrowing or the seeds are below harvest height. For example, over 300 annual ryegrass seedlings/m^2 emerged in the area between the windrows in one study at Mt Barker, Western Australia (Peltzer et al. 2005).

Key benefit #3

Late autumn burning of crop residues can kill weed seedlings.

In addition to reducing weed seed numbers, stubble burning in autumn can kill weed seedlings, including self-sown crop volunteers such as wheat. The effectiveness of the burn will depend on the size and density of the weed seedling population. Cooler ambient temperatures and the presence of non-flammable green material will reduce the temperature of the burn, resulting in lower efficiency of both seed and seedling control.

Figure T1.1–5 Stubble can be burnt along narrow windrows creating a hot burn and killing a high proportion of weed seeds in the chaff.
Source: Warwick Holding

Key benefit #4

Burning can stimulate weed germination of some weed species for subsequent control with another tactic.

While stubble burning can destroy wild oat (*Avena* spp.) seed on the soil surface, it can also stimulate seedling emergence by modifying seed dormancy of the survivors (Nietschke et al. 1996). Fire can be very effective at stimulating germination of hard or dormant seeds for subsequent control with another tactic.

Experience in southern New South Wales (NSW) found that plant densities of wild oat, wild radish (*Raphanus raphanistrum*) and vulpia (*Vulpia* spp.) doubled in the year following stubble burning compared with stubble retention. This may be due to either stimulation of germination or suppression by stubble (E. Koetz pers. comm. 2004).

Key benefit #5

Burning removes residues and thereby allows more effective incorporation of pre-emergent herbicides.

Soil residual herbicides that need incorporation can be more effectively mixed with soil when high stubble loads are removed via burning. This also helps prevent herbicides from binding to stubble which can cause crop safety issues when subsequent rain washes herbicide into the soil around emergence.

It should be noted, however, that spraying soon after burning can result in binding of herbicide to ash. Ash needs to be dispersed by rainfall or physical incorporation before spraying with soil-residual herbicides.

Whole-farm benefits

Burning crop residues has additional benefits including:

- residue removal to ease sowing of the subsequent crop
- foliar disease and pest management
- eliminating short-term nitrogen tie-up.

These benefits improve crop health and, therefore, crop competitive ability against weeds and the effectiveness of pre-emergent herbicides.

Practicalities

Key practicality #1

A high temperature burn will achieve the best result, accounting for seasonal risks.

Reducing weed seed numbers by burning is highly variable and dependent on the exposure of the seeds to high temperatures. This in turn is dependent on the quantity, quality and distribution of residue, the conditions at time of burning, the weed species present and the placement of the weed seeds.

Chitty and Walsh (2003) identified that a temperature of 400 °C for 10 seconds is required to kill annual ryegrass seed and that wild radish pods will be destroyed by 400 °C for 20 to 30 seconds or 500 °C for 10 seconds (Walsh et al. 2005). Walsh et al. (2005) also demonstrated that it was possible to achieve temperatures above 500 °C for over three minutes in a lupin trash windrow, where dry matter in the windrow was estimated at 15 t/ha.

Figure T1.1–6 Unburned windrows need to be sprayed due to a concentration of weed seeds.
Source: Warwick Holding

Key practicality #2

Prepare the burn area to ensure seeds are best placed.

Ideally weed seed should be on or just above the soil surface. Avoid or, at least, reduce grazing in paddocks targeted for a weed management stubble burn to ensure that quality residue remains for the burn.

Reducing the disturbance of harvest residues caused by grazing, will retain the potential for maximum burning efficiency. Additionally, stock movement across a paddock frequently pushes weed seed into the soil, where it is unlikely to be exposed to high temperatures during burning.

Key practicality #3

Time burning to suit residue conditions and legislative limitations.

Although burning early in the season is likely to achieve best weed seed control, in many instances this is not practical due to weather conditions, the risk of fire spread and the increased risk of erosion to paddocks bared for longer periods. Early stubble removal in a fallow period also reduces water conservation efficiency.

Very high temperatures are required to kill annual ryegrass seed following short exposure periods (Chitty and Walsh 2003). Although a hot burn earlier in the summer reduces seed viability to a greater extent (Pearce and Holmes 1976), there are practical and legislative limitations to burning during summer.

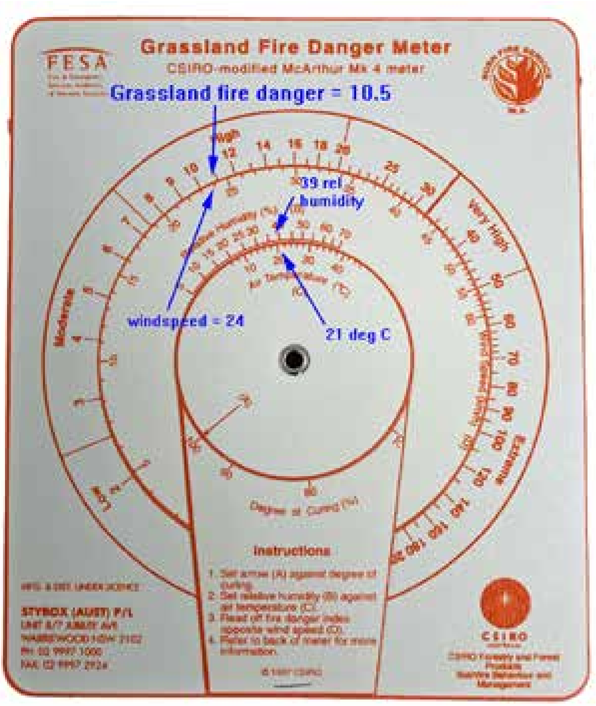


Figure T1.1–7 A FESA grass fire index which can be used to evaluate when to burn windrows and chaff dumps.

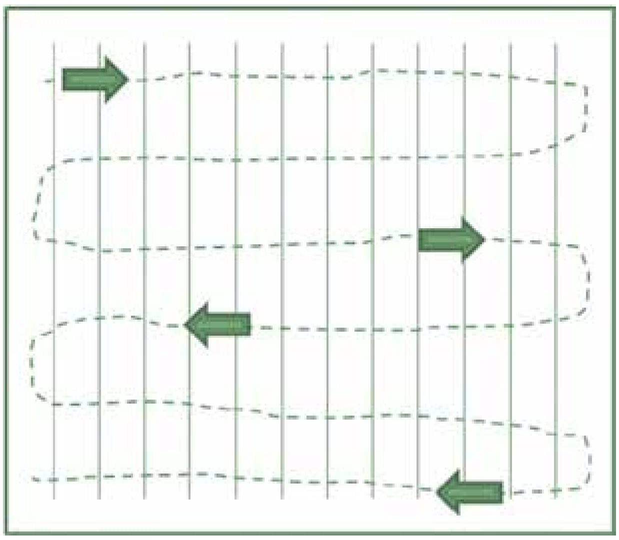


Figure T1.1–8 Recommended lighting strategy for up-and-back harvesting.
Source: Sally Peltzer

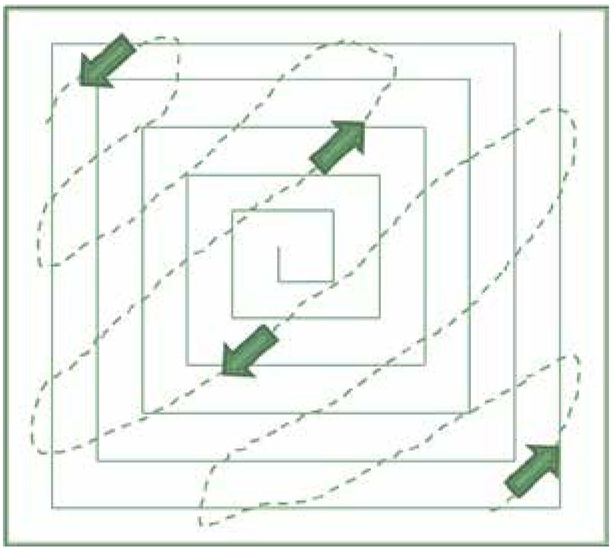


Figure T1.1–9 Recommended lighting strategy for around the paddock harvesting.
Source: Sally Peltzer

Chitty and Walsh (2003) found that lower temperatures can also be effective if exposure periods are increased. Late autumn (or 'cool') burning of residues reduces the viability of seeds susceptible to heat treatment to some extent. In north-eastern Victoria, for example, Davidson (1992) achieved a 57% reduction in annual ryegrass establishment with a late autumn burn.

Preliminary data from experiments on the Darling Downs, Queensland (Walker pers. comm. 2005), found that an autumn stubble burn reduced turnip weed (*Rapistrum rugosum*) seeds by 28%, wild oat seeds by 34% and paradoxa grass (*Phalaris* spp.) seeds by 43% in the top 10 cm of soil.

Key practicality #4

Burning effectiveness depends on residue placement and quantity.

An alternative to burning in summer is to concentrate the crop residue into windrows to achieve a slower, hotter burn. It is important to burn windrows in dry conditions with a light wind to ensure that the windrow burns all the way to the soil surface. Burning wet windrows and/or burning in still conditions will often result in a layer of unburnt residue left at the soil surface.

The environment also plays a key role in determining the success of burning to reduce weed seed numbers through the influence it has on the amount of post-harvest residue available. Studies in South Australia found that, in drier environments with less reliable rainfall (Roseworthy, mean annual rainfall 441 mm), burning stubble did not significantly reduce annual ryegrass seed numbers due to the lack of fuel available to generate a destructive fire. However, in more favourable environments (Auburn, mean annual rainfall 596 mm) there was an average 58% reduction in annual ryegrass seed numbers following burning (Matthews et al. 1996).

Key practicality #5

Burning is not a suitable tool to manage all weed species.

Effective burning will not decrease all weed seedbanks (*Table T1.1–2*). Some weeds are not affected by burning and others benefit from burning.

Table T1.1–2 Likely impact of burning versus retaining crop residue before sowing on autumn weed seedling emergence in southern NSW (D. Heenan pers. comm. 2004).

Weed species	Crop residue treatment	
	Burned	Retained
Wireweed (*Polygonum aviculare*)	No change	Decrease
Fumitory (*Fumaria* spp.)	Decrease	Decrease
Brome grass (*Bromus diandrus*)	Decrease	Increase
Barley grass (*Hordeum leporinum*)	Decrease	Increase
Silver grass (*Vulpia* spp.)	Increase	Increase
Annual ryegrass (*Lolium rigidum*)	Decrease	Increase
Wild oat (*Avena* spp.)	Increase	Decrease

Whole-farm considerations

The benefits of burning for weed management must be weighed up against a number of concerns. These include:

- environmental concerns about pollution and carbon dioxide emissions from burning crop residues
- potential respiratory health issues (e.g. asthma)
- soil erosion risk following burning, especially after a total residue burn
- adverse effects on soil fertility, organic matter and soil structure, especially if burning is used frequently
- reduced soil water infiltration and increased evaporation and run-off due to crop residue removal
- reduced numbers of macro- and micro-organisms, especially earthworms, and therefore reduced biopores
- a shortened sowing window after rain.

In the past grain growers across Australia have regularly used crop residue burning and so they understand the following practicalities associated with the tactic:

- Burning must be conducted following state rural fire service regulations.
- Chaff dumps can take a long time to burn, creating smell and smoke issues. Extended burning time also heightens fire risk.
- Legislation to ban burning has been introduced in some countries around the world due to concerns over greenhouse gas emissions, global warming and health issues.
- There is public pressure in Australia to ban burning, especially in areas in close proximity to large urban centres.

Contributors

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References

Chitty D and Walsh M 2003. The burning issues of annual ryegrass seed control. In 'Agribusiness Crop Updates'. Perth, Western Australia pp. 32-33 (Department of Agriculture Western Australia).

Davidson RM 1992. Population dynamics of herbicide resistant annual ryegrass, *Lolium rigidum*, in pasture. *Proceedings of the 1st International Weed Control Congress*, vol. 2, pp. 141–143

Fettell N 1998. Lessons from the Condobolin long term tillage trial. In Central West Farming Systems Research Compendium, pp. 23

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Matthews JM, Llewellyn R, Powles S and Reeves T 1996. Integrated weed management for the control of herbicide resistant annual ryegrass. *Proceedings of the 8th Australian Agronomy Conference*, Toowoomba.

Newman P and Walsh M 2005. The art of burning. In Proceedings of Agribusiness Crop Updates 2005, Weeds, pp. 9–12.

Nietschke BS, Reeves TG, Matthews JM and Powles SB 1996. Components of an integrated weed management strategy to control herbicide resistant *Avena* spp. – an Australian perspective. *Proceedings of the 2nd International Weed Control Congress*, Denmark, pp. 493–498.

Pearce GA and Holmes JE 1976. The control of annual ryegrass. *Journal of Agriculture*, Western Australia, vol. 17, pp. 77–81

Peltzer SC, Minkey D. and Walsh M 2005. Ingest, incinerate or invert? The pros and cons of three weed seed removal tactics. *Proceedings of Crop Updates, Technical Information for Agribusiness*, Perth. February 2005, pp. 6–8

Reeves TG and Smith IS 1975. Pasture management and cultural methods for the control of annual ryegrass (*Lolium rigidum*) in wheat. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 15, pp. 527–530.

Walsh MJ, Newman P and Chitty D 2005. Destroy wild radish and annual ryegrass seeds by burning narrow windrows. *Proceedings of GRDC Southern Region Research Updates*, Adelaide, South Australia.

Tactic 1.2 Encouraging insect predation of seed

The contribution that insects make to seedbank reduction is often overlooked, despite weed seeds comprising a major component of many insect diets. This seed predation is often termed 'natural mortality' to partly explain why less seed is returned to the seedbank than is produced. Minimum and zero tillage increases ants and other invertebrate populations which encourages predation. Experiments conducted in WA by Evans and Gleeson (2016) showed that in a natural dispersed environment, ants were capable of reducing weed population. These results and other studies suggest that ants may be a useful component of an integrated weed management program.

Understanding the role that insects play in removing weed seeds could potentially help develop farming systems that encourage greater seed removal from the seedbank. A range of invertebrates (such as ants and carabid beetles) and vertebrates (birds and rodents) are significant post-dispersal weed seed predators (Wu 2015). In NSW seed theft by ants has commonly caused pasture failure, so it is feasible that weed seedbanks also could be decreased by encouraging ant predation.

Figure T1.2–1 Ant seed removal of liverseed grass (*Urochloa panicoides*) in the summer in southern Queensland, Australia (left: general view, right: close-up).

Benefits

Key benefit #1

Insect predation of annual ryegrass can reduce seedbank numbers.

Predation levels can be quite variable, with removal rates ranging from 0% to 100% depending on seedbank proximity to ant colonies. Ants were responsible for reducing weed numbers by 50% in Western Australian studies in 2006 (Evans and Gleeson, 2016). Predation by insects was found to be significantly higher for annual ryegrass (*Lolium rigidum*) seed than wild radish (*Raphanus raphanistrum*) seed in a study in the Western Australian wheatbelt. Three months into the study 81% of the original annual ryegrass seed had been removed, compared with 46% of wild radish seed (*Table T1.2–1*). Original seed numbers were 2,000 seeds/m^2 for annual ryegrass and 1,000 seeds/m^2 for wild radish.

Wu (2015) reported that ants collected large amount of livergrass seed (*Urochloa panicoides*) in the summer in southern Queensland and deposited it in a well-structured pattern around the nest entrance (*Figure T1.2–1*).

Table T1.2–1 Effect of time on cumulative weed seed removal across a 16 ha cropping paddock in Merredin, Western Australia. Figures represent the average percentage of seed removed for annual ryegrass and wild radish (Spafford Jacob et al. 2006).

Weed species	Seed removal %	
	January	March
Annual ryegrass	69	81
Wild radish	21	46

Figure T1.2–2 *Pheidole hartmeyri* is a seed consuming specialist and can be seen here removing annual ryegrass seed from a cropping field in Merredin, Western Australia.
Photo: David Minkey

Practicalities

Key practicality #1

Predation levels tend to be higher in locations near 'refuge'.

Predation appears to be higher for some species such as annual ryegrass and wild radish in situations close to refuge areas (e.g. remnant vegetation or fencelines), and decreases with increasing distance from the refuge (*Figure T1.2–3*).

Although not confirmed by research, it is possible that providing refuges or 'island' habitats (e.g. remnant vegetation strips and commercial tree planting) within a field may benefit seed predation, as most ant species are opportunistic and will invade disturbed habitats.

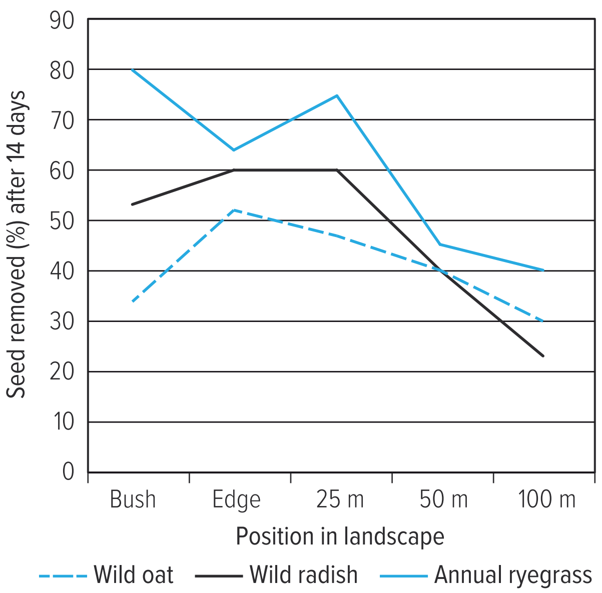

Figure T1.2–3 Effect of landscape position (distance from fenceline) and environment type on seed removal from seed caches (Spafford Jacob et al. 2006).

Key practicality #2

Predation can be maximised by avoiding the overuse of broad spectrum insecticides.

Recent work in Western Australia has suggested that ants are responsible for 75% of total seed losses on the edges, and close to 100% at the centre, of paddocks. Farming practices that affect ant populations therefore have the biggest impact on potential seed predation.

Prolonged broad spectrum insecticide use will decrease the number of 'friendly' insects in paddocks. For example, insecticides used to control the Australian plague locust (e.g. fenitrothion, an organophosphate) may greatly reduce ant populations. Minimising the use of such insecticides and choosing to use more selective products can reduce the impact on the key predating species. This is especially important during the warmer months, when ants are most active.

Figure T1.2–4 Grass seeds collected by ants.
Source: Andrew Storrie

Key practicality #3

Manage stubble according to the type of seed predator present.

Retaining stubble is a two-edged sword. Stubble can provide a refuge for predatory insects but it also discourages heat-loving ant species which prefer open spaces. Most ant species also prefer a perfect line of sight, which is needed for insects (especially ants) to be efficient seed predators.

Stubble type is also important. Compared with cereal, canola stubble can reduce the numbers of some ant seed removal by grain-eating insects.

Key practicality #4

Minimum tillage improves weed seed predation.

It is thought that a cropping system that minimises soil disturbance is optimal (e.g. using a tined seeder with knife points).

Tillage, especially in heavy clay soils, reduces ant populations. However, zero disturbance encourages dominant, non-seed-preferring species such as the Australian meat ant, which will displace other grain-eating ant species.

Key practicality #5

Soil disturbance over summer reduces seed predation.

Any soil disturbance over the summer months, including grazing livestock, will dramatically reduce ant species and, consequently, the level of wild radish seed pod removal, particularly early in summer.

Contributor

David Minkey and Eric Koetz

References

Evans TA and Gleeson PV 2016. Direct measurement of ant predation of weed seeds in wheat cropping. *Journal of Applied Ecology*, vol. 53, pp. 1177–1185.

Wu H 2015. Integrating belowground non-chemical approaches for future weed management; I.S. Travlos, D. Bilalis and D. Chachalis (eds). *Weed and Pest control: Molecular Biology, Practices and Environmental Impact*., pp. 55–84. Nova Science Publishers, Inc. NY, USA.

Spafford Jacob HS, Minkey DM, Gallagher RS and Borger CP 2006. Variation in post dispersal weed seed predation in a crop field. *Weed Science*, vol. 54, 148–155.

Further reading

Minkey DM, Spafford Jacob HS, and Majer J 2005. Can ants be used as a biological control weapon against annual ryegrass? In *Western Australian No Tillage Farmers Association Annual Conference Proceedings.*

Tactic 1.3 Inversion ploughing

Inversion ploughing is used to fully invert the soil to ensure that weed seeds that were on or just below the soil surface are placed at a depth from which they cannot germinate. This can be practised every 10 to 15 years without detrimental effect to the environment, where zero or reduced tillage is used in the intervening years. This timeframe is required for weed seeds to die and non-wetting waxes to break down. Inversion ploughing is particularly effective at resetting the weed seedbank and is very useful if herbicide-resistant weeds are a problem.

Inversion ploughing has been adopted in Western Australia using commercial two-way machines, a modified mouldboard plough with skimmers to assist with total soil inversion. The technique is used after the season break when the soil profile is wet to a depth of at least 40 cm. The WeedSmart website, https://weedsmart.org.au/?s=inversion+ploughing has more up to date information.

The process has been successful on a range of soil types, including duplex sands over clay, loamy clays and deep sands. It should be noted that for self-mulching soils many weed seeds will already be deeply buried in soil cracks and inversion ploughing will not be needed on this soil type.

Although whole paddock inversion ploughing is expensive (estimated at the time of writing at $70 to $100/ha on deep sands for an owner/operator machine and $125/ha plus diesel for a contractor), there are long-term benefits for weed seedbank reduction and soil amelioration for problems such as water repellence and subsurface acidity.

Benefits

Key benefit #1

In suitable soil types, weed seed burial is an effective way to kill weed seeds.

After long-term reduced tillage most weed seed is located in the top few centimetres of soil, where it readily germinates. Nearly all annual weeds of cool season cropping emerge from the top 10 cm of soil and annual grasses have relatively short-lived seeds. However, burial of all seeds at depth extends the seedbank longevity. Therefore it is recommended that inversion ploughing for weed management occurs 10 to 15 years apart (*see Tactic 2.1 Fallow and pre-sowing cultivation – Table T2.1–1*).

Weed seeds fail to establish and eventually die when soil is fully inverted to a depth of greater than 20 cm using a specialist mouldboard plough fitted with skimmers (Douglas and Peltzer 2004). The skimmers relocate topsoil to the bottom of the previous plough furrow, thus burying seed at a greater and more uniform depth than the mouldboard plough alone would do.

Figure T1.3–1 Mouldboard plough working near Geraldton showing skimmers in action.
Source: Peter Newman

A single soil inversion event reduced annual ryegrass (*Lolium rigidum*) numbers by over 95% at Katanning and Beverley, Western Australia, for a period of two years (Douglas and Peltzer 2004). This resulted in substantially higher grain yields (*Figure T1.3–2*) due to a combination of reduced weed competition and an increase in soil nitrogen (the mineralisation rate is higher in disturbed soil). Over nine experiments in the northern cropping belt of Western Australia between 2007 and 2010 the average control of annual ryegrass and wild radish (*Raphanus raphanistrum*) was 96% and 83% respectively (Newman 2011).

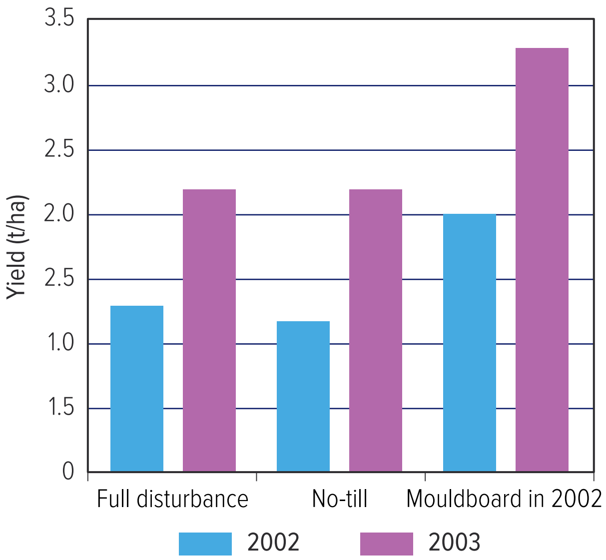

Figure T1.3–2 The effect of three tillage treatments (full-cut cultivation, no-till and mouldboard ploughing in 2002 only) on the yield of barley (mean of four replicates) in 2002 and 2003 at Katanning (Douglas and Peltzer 2004).

Figure T1.3–3 Effective depth of mouldboarding to bury weed seeds for the long term.

Photo: Peter Newman

Whole-farm benefits

Additional benefits from inversion ploughing include:

- disease and insect control due to the burial of stubble
- amelioration of non-wetting soils
- nitrogen mineralisation
- removal of any nutrient stratification in the soil (i.e. mixing of nutrients concentrated in one layer of the soil, usually the surface)
- opportunities for soil ameliorant (e.g. lime) application at depth.

Practicalities

Key practicality #1

Soil inversion is most effective in reducing seedbank numbers of weeds with limited dormancy.

Soil inversion is not suitable for the control of all weed species. Although most species are unable to emerge from depths greater than 10 cm, a reinversion in later years may bring up viable seed of dormant weed species. Knowledge of the seed survival characteristics of the target weed is important (see *Section 2: Profiles of common cropping weeds*).

Key practicality #2

Appropriate soil type is needed for effective soil inversion.

Soil inversion is limited to soil types where there is sufficient topsoil to allow full inversion. Shallow duplex soils where the clay is less than 15 cm deep, for example, are unsuitable. It is also difficult to achieve the complete inversion needed for effective weed control in soils with a large number of rocks and/or stumps. Auto-reset mouldboard ploughs are able to plough soils with rocks and/or stumps as the plough jumps the rock or stump. However, soil inversion is compromised when the plough jumps.

Avoid soil inversion in situations where soils exhibit problems at depth (e.g. rocks, clay, sodicity, salinity, boron, magnesium, manganese), as it may bring these problems to the surface. Conduct soil tests where problems are suspected.

Key practicality #3

Inversion ploughing of moist soil followed by the immediate sowing of a crop will reduce wind and water erosion risk.

Inversion ploughing is best performed with a moist soil profile, and is immediately sown to a cereal crop. Cultivation of dry soil will lead to incomplete inversion and increase the draught requirement. Rolling following ploughing is essential on sandy soils. Cereal crops are less prone to sandblasting compared with broadleaf crops (Newman 2011). Also if sowing a pulse it is highly recommended that the seed is inoculated because much of the soil containing rhizobia from previous crops is likely to be below 20 cm, and may therefore delay or prevent nodulation.

Be aware that yield reductions might occur due to the delay in sowing while waiting for the soil profile to become wet; however, yields from later sown crops are higher if serious weed and soil issues are ameliorated.

Key practicality #4

Mouldboard ploughs must be operated and set up correctly to achieve total inversion.

Considerations include:

- Eight to 14 furrow ploughs cutting 3 to 6 m at a speed of 8 to 8.5 kph equates to 2.5 to 5 ha per hour.
- Ploughs work to a depth of 30 to 35 cm.
- The horsepower required is roughly 35 hp per board and perhaps 40 hp for big machines (12 to 14 furrow) due to the weight of the machine.
- Cost of a new mouldboard is approximately $80,000 to $100,000 for an 8 to 10 furrow machine and $120,000 to $150,000 for a 12 to 14 furrow machine.
- Three-point linkage on the tractor is best but alternatively a tool carrier can be used.
- The paddock needs either light rolling or to be sown with lightweight seeding machinery such as an air drill where the weight of the seeding bar is carried by presswheels.

Key practicality #5

Occasional inversion ploughing is unlikely to damage soil structure.

Tillage can have different effects on different soil types. For example, Chan and Hulugalle (1999) found tillage practices to be more harmful on hard-setting red soil than on self-mulching clays.

One concern with inversion ploughing is the effect it has on both soil structure and stability. Studies in the USA reported that five years after full soil inversion, most soil properties return to the levels of no-tillage systems (Pierce 1994; Kettler et al. 2000).

Chan et al. (2001) found that incorporating a pasture phase into a cropping system could improve the soil fertility of a hard-setting red soil in central western NSW. If using inversion ploughing, a pasture phase may be useful in repairing any soil structural damage caused by the inversion.

Key practicality #6

Inversion ploughing can impact pre-emergent herbicide activity

Inversion ploughing can impact topsoil structure and reduce organic matter, causing less herbicide to be adsorbed and potentially leach deeper into the soil profile, reducing crop establishment. Can impact strength of fallow wall. Also can change behaviour of herbicide from “normal” if sub soil has significantly different texture/pH etc

Contributors

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References

Chan KY, Bowman AM, Smith W and Ashley R 2001. Restoring soil fertility of degraded hardsetting soils in semi-arid areas with different pastures. *Australian Journal of Experimental Agriculture*, vol. 41, pp. 507–514.

Chan KY, and Hulugalle NR 1999. Changes in some soil properties due to tillage practices in rainfed hardsetting Alfisols and irrigated Vertisols of eastern Australia. *Soil & Tillage Research*, vol. 53, pp. 49–57.

Douglas A and Peltzer SC 2004. Managing herbicide resistant annual ryegrass (*Lolium rigidum* Gaud.) in no-till systems in Western Australia using occasional inversion ploughing. *In Proceedings of the 14th Australian Weeds Conference, Wagga Wagga*, pp. 300–303.

Kettler TA, Lyon DJ, Doran JW, Powers WL and Stroup WW 2000. Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. *Soil Science Society of America Journal* 64: 339–346.

Peltzer SC 2004. Management of header trails for annual ryegrass control. *In Department of Agriculture field day booklet*. Great Southern Research Station (Katanning) and Mt Barker Research Station.

Peltzer SC, Minkey D and Walsh M 2005. Ingest, incinerate or invert? The pros and cons of three weed seed removal tactics. *In Proceedings of Crop Updates, Technical Information for Agribusiness, Weed Updates*, Perth, pp. 6–8.

Pierce FJ 1994. Periodic plowing effects on soil properties in a no-till farming system. *Soil Science Society of America Journal* vol. 58, pp. 1782–1787.

Further reading

Douglas A, Peltzer SC and Matson P 2004. A one-off mouldboard operation gives two years of increased barley yield and annual ryegrass control. *In Proceedings of Crop Updates, Technical Information for Agribusiness, Weed Updates*, Perth, pp. 36–38.

Peltzer SC and Matson PT 2003. Weed control through soil inversion. *In Proceedings of Crop Updates, Technical Information for Agribusiness, Weed Updates*, Perth, pp. 30–31.

Tactic 1.4 Autumn tickle

Autumn tickling (also referred to as an 'autumn scratch' or shallow cultivation) stimulates weed seed germination by placing seed in a better physical position in the soil (Gill and Holmes 1997). At a shallow depth of 1 to 3 cm the seed has better contact with moist soil and is protected from drying. Because weeds that germinate after an autumn tickle can be controlled, this process will ultimately deplete weed seed reserves.

A range of equipment can be used to conduct an autumn tickle, including tyned implements, skim ploughs, heavy harrows, pinwheel (stubble) rakes, dump rakes and disc chains.

Tickling can increase the germination of some weed species but has little effect on others (see *Key practicality #5* and *Section 2: Profiles of common cropping weeds*).

Tickling needs to be used in conjunction with delayed sowing (*Tactic 1.5*) for the greatest opportunity to control emerging weeds and deplete the seedbank.

Benefits

Key benefit #1

A well-timed autumn tickle will promote earlier and more uniform germination of some weed species for subsequent control.

Between seed dispersal and the autumn break only 10 to 30% of wild radish (*Raphanus raphanistrum*) seeds will germinate from the seedbank without stimulation (Murphy et al. 2000). As a result, late germination flushes are common. These affect crop growth and yield, create management problems and further contribute to the weed seedbank.

Weeds that germinate as a result of an autumn tickle (including wild radish) are often subsequently controlled with a non-selective herbicide before crop sowing (Cheam et al. 1998). This reduces in-crop weed pressure as well as reliance on selective herbicides.

Experiments in Western Australia (Hashem et al. 1998) showed that an autumn tickle followed by a non-selective herbicide application can be very effective in depleting annual ryegrass (*Lolium rigidum*) and wild radish seedbanks (*Table T1.4–1* and *Table T1.4–2*). *Table T1.4–1* shows the effect of climate on the success of an autumn tickle, comparing results from the Wongan Hills site (medium) with those from the Merredin site (dry). Adequate soil moisture is needed to achieve the best weed seed germination.

Research on paradoxa grass (*Phalaris paradoxa*) in southern Queensland has shown that, compared with uncultivated soil, shallow cultivation in autumn increased overall seedling emergence by 40% (Taylor et al. 2005). The shallow cultivation also increased paradoxa grass emergence in May, which would have otherwise reached peak emergence in July (*Figure T1.4–1*).

Table T1.4–1 Effect of autumn tickle on annual ryegrass seedbank at Wongan Hills and Merredin, Western Australia (Hashem et al. 1998).

Treatment	Depletion of annual ryegrass seedbank before sowing (%)	
	Wongan Hills (medium)	Merredin (dry)
With tickle	63	51
Without tickle	31	1

Practicalities

Key practicality #1

Autumn tickle should be used in conjunction with another tactic.

Failure to kill weeds germinated by an autumn tickle may cause transplantation of weeds during sowing, creating a significant in-crop weed problem. If the time between tickle, germination and crop sowing is insufficient, a mass germination is likely to occur as the crop establishes.

Table T1.4–2 Effect of autumn tickle on wild radish soil seed reserves in Western Australia (Hashem et al. 1998).

Treatment	Wild radish seedling emergence pre-sowing (plants/m²)	Wild radish plant density post-sowing (plants/m²)	Wild radish seedbank depletion before sowing (%)
With tickle	160	66	55
Without tickle	3	201	4

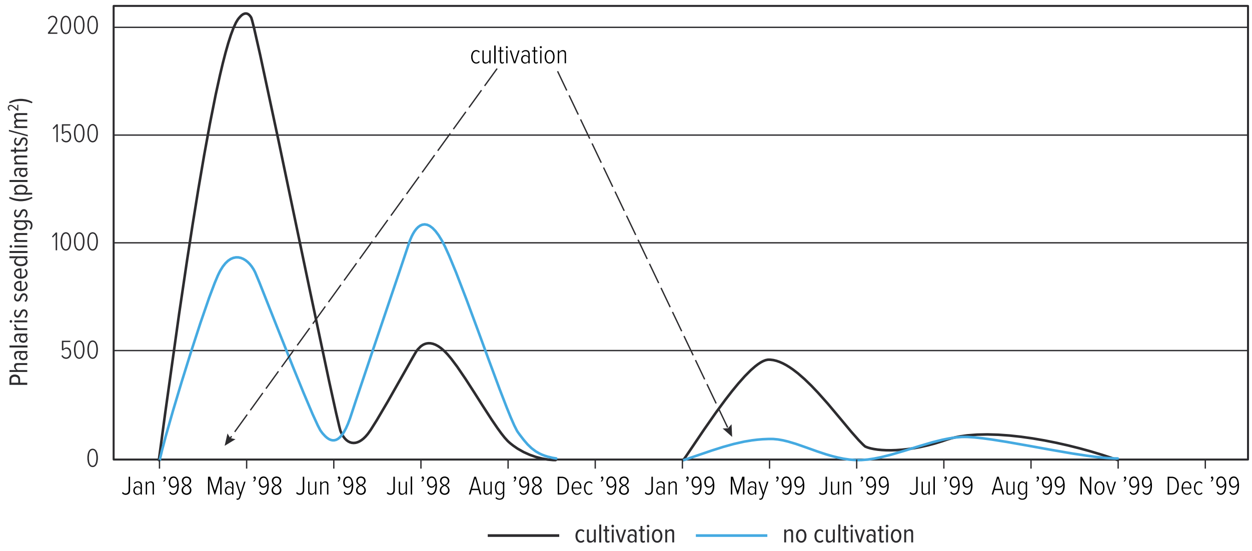

Figure T1.4–1 Comparing the effect of presence and absence of cultivation on emergence of paradoxa grass seedlings over two years after sowing in 1997 (Taylor et al. 2005).

Key practicality #2

Autumn tickling success depends on environmental conditions before and after implementation.

Autumn tickle can be performed any time in autumn or winter, but post-cultivation erosion risk will be minimised when cultivation occurs closer to sowing.

Ideal conditions for an autumn tickle are following a rainfall event of 20 mm or more when the topsoil is wet and germination occurs evenly. The top 4 cm of soil must be moist for at least 10 days, and other conditions (e.g. the diurnal temperature) must be conducive to germination for the majority of non-dormant seeds to germinate and emerge. Marginal moisture conditions may result in staggered weed germination.

An autumn tickle is usually only effective after a timely break. Its impact is often greatest in paddocks that are to be sown last (see *Tactic 1.5 Delayed sowing*) and in situations where a high weed density is expected.

Key practicality #3

Soil type is critical for a successful autumn tickle.

Light-textured (sandy) soils, non-wetting soils and those where moisture has trouble penetrating the soil profile are not suited to autumn tickling. Where soils wet unevenly, weed seeds may be buried in pockets of dry soil. These pockets may become wet during the season, with seeds subsequently germinating to cause in-crop problems.

On sandy soils even light cultivation can leave the surface exposed to wind erosion, and cultivating dry soil exacerbates the erosion problem. Avoid using an autumn tickle in paddocks prone to sandblasting (e.g. sandhills and sandplains).

Key practicality #4

Use autumn tickling in non-crop situations to stimulate germination of weeds which can then be managed with grazing or a non-selective herbicide.

An autumn tickle is a useful tool to consider in non-crop years because it can increase the proportion of the seedbank that germinates. Using grazing pressure and non-selective weed management tactics can ensure that minimal weed seed is set. In these paddocks early germination of weeds can provide valuable feed for livestock while newly sown legume pastures in other paddocks establish.

Key practicality #5

The efficacy of an autumn tickle will vary with weed species.

Autumn tickling is a tactic best suited to weeds that are easily released from dormancy.

Seeds that germinate readily in the top layer of soil and in response to changing light exposure are ideal. Annual ryegrass, paradoxa grass, wild radish and fumitory (*Fumaria* spp.) all respond well to an autumn tickle (see *Section 2: Profiles of common cropping weeds*).

Light affects dormancy in annual ryegrass and paradoxa grass. Movement of seed to the surface or flashes of sunlight during cultivation may be enough to stimulate germination (Steadman et al 2004; Taylor et al. 2004). The autumn tickle will only be effective weed management tactic if adequate seedset control is applied after stimulated germination in the first year, preventing further seedset.

Figure T1.4–1 shows the increased germination of paradoxa grass over two years after cultivation in March in both seasons, compared with no cultivation. Cultivation stimulated increased germination of paradoxa grass in both years, with an additional response to cultivation in the second year.

A similar response can be achieved with annual ryegrass, although it will be limited to the first year after seedset because dormancy mechanisms are lost as the seed ages in the soil (Peltzer and Matson 2002).

An autumn tickle will increase wild radish emergence, but predominantly in the second year after seedset (*Figure T1.4–2*). Wild radish seeds have seed coat dormancy and are enclosed in a hard pod which also delays germination (Young and Cousens 1999). The suggestion is that a year in the soil in combination with tillage is needed to cause the pod to break down and allow the seed to germinate. The response to autumn tickle in the first year after seedset (*Figure T1.4–2*) is explained by germination of damaged pods, which occurs when wild radish that has passed through the header is dropped back into the header trail (Peltzer and Matson 2002).

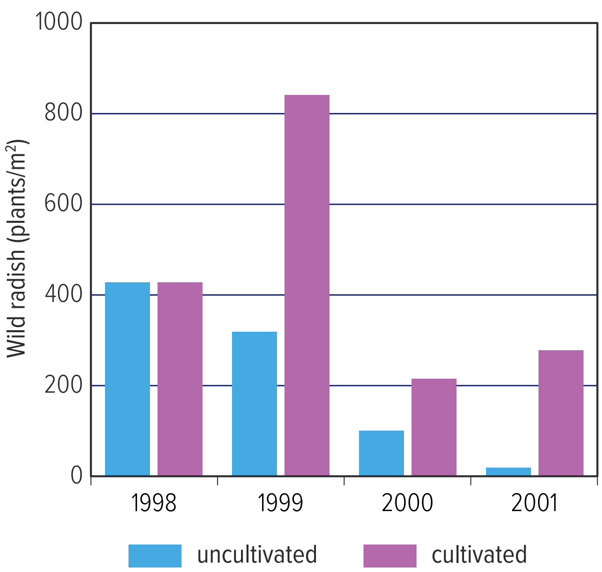

Figure T1.4–2 The number of tickled (cultivated) and uncultivated wild radish seedlings emerging per year at Mount Barker, Western Australia (Peltzer and Matson 2002).

Where weeds such as barley grass (*Hordeum* spp.), great brome (*Bromus diandrus*) and vulpia (*Vulpia* spp.) are the main problem, autumn tickling is an unnecessary tactic. These weeds have little or no dormancy and will germinate with the break in the first season without stimulation. However, some barley grass populations are evolving a cold requirement and germinating later than other barley grass populations (see *Section 2: Profiles of common cropping weeds*). These populations will be unsuitable for tickling.

Whole-farm considerations

Determine the suitability of autumn tickle as a weed management tactic by considering the following points:

- Soil disturbance before sowing can reduce soil moisture, placing the sowing operation at risk in a dry season.
- Soil disturbance before sowing can incorporate stubble and, as a result, significant amounts of soil nitrogen will be tied up by microbes that proliferate to degrade the stubble.
- In the early stages of no-till adoption, short-term nitrogen deficiencies are likely if stubble levels are high.

Contributors

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References

Cheam A, Hashem A, Bowran D and Lee A 1998. Autumn tickle can influence dormancy and breakdown of wild radish and annual ryegrass seedbanks. *Crop Updates 1998: Weeds,* Department of Agriculture, Western Australia

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Hashem A, Cheam A, Bowran D and Piper T 1998. Annual ryegrass control in wheat by chemical and non-chemical options. *Crop Updates 1998: Weeds*, Department of Agriculture, Western Australia.

Murphy C, Craddock T and Peltzer S 2000. Weed seeds – breaking the bank. *Advice Sheet for southern region*. Grains Research and Development Corporation.

Peltzer SC and Matson PT 2002. How fast do the seedbanks of five annual cropping weeds deplete in the absence of weed seed input. *Proceedings of the 13th Australian Weed Conference*, Perth, Western Australia, pp. 553–555.

Steadman KJ, Bignell GP and Michael PJ 2004. Stimulating dormancy release and emergence of annual ryegrass (*Lolium rigidum*) seeds using short term hydrated storage in darkness. *Australian Journal of Agricultural Research*, vol. 55, pp. 787–795.

Taylor IN, Peters NCB, Adkins SW and Walker SR 2004. Germination response of *Phalaris paradoxa* L. seed to different light qualities. *Weed Research*, vol. 44, pp. 254–264.

Taylor IN, Walker SR and Adkins SW 2005. Burial depth and cultivation influence emergence and persistence of *Phalaris paradoxa* L. in an Australian sub-tropical environment. *Weed Research*, vol. 45, pp. 33–40.

Young K and Cousens R 1999. Factors affecting the germination and emergence of wild radish (*Raphanus raphanistrum*) and their effect on management options. *In Proceedings of 12th Australian Weeds Conference*, Hobart, Tasmania.

Further reading

Kettler TA, Lyon DJ, Doran, JW, Powers, WL and Stroup, WW 2000. Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. *Soil Science Society of America Journal*, vol. 64, pp. 339–346.

Pierce FJ 1994. Periodic ploughing effects on soil properties in a no-till farming system. *Soil Science Society of America Journal*, vol. 58, pp. 1782–1787.

Tactic 1.5 Delayed sowing

Delayed sowing (seeding) involves planting the crop beyond the optimum time for yield in order to maximise weed emergence. Weeds that emerge in response to the break in season can then be killed using a knockdown herbicide or cultivation before crop sowing.

This tactic is most commonly used for paddocks that are known to have high weed burdens. Paddocks with low weed burdens are given priority in the sowing schedule, leaving weedy paddocks until later. This allows sufficient delay for the tactic to be beneficial on the problem paddock without interrupting the whole-farm sowing operation.

Choosing a crop or cultivar with a later optimum sowing time can reduce the risk of reduced yield.

Benefits

Key benefit #1

Delayed sowing can dramatically reduce early crop competition and deplete the weed seedbank.

Delayed sowing can reduce early crop competition via management of early germinating weeds before sowing. For this tactic to be successful, sowing must be delayed until the first flushes of weeds have emerged and have been controlled either by knockdown herbicides, cultivation or a combination of the two (see *Tactic 2.1 Fallow and pre-sowing cultivation, Tactic 2.2a Knockdown (non-selective) herbicides for fallow and pre-sowing control* and *Tactic 2.2b Double knockdown or 'double knock'* for information on controlling weeds after they have germinated and before delayed sowing).

Up to 80% of annual ryegrass (*Lolium rigidum*) emergence occurs within four weeks of opening rain (Gill and Holmes 1997). Allowing this seed to germinate and providing subsequent control measures will deplete the weed seedbank.

Research in South Australia (Matthews et al. 1996; Matthews and Powles 1996) clearly demonstrated that a sowing delay of three weeks decreased in-crop annual ryegrass by an average of 52%, and the quantity of weed seed produced by 21% (*Table T1.5–1*).

In field studies Gill and Holmes (1997) found that 11 to 30% of in-crop annual ryegrass density could be reduced with each progressive week of sowing delay.

Key benefit #2

Delayed sowing is very effective when used in conjunction with additional weed management tactics.

Delayed sowing is most effective when used in conjunction with another tactic. *Figure T1.5–2* shows the additional benefit which can be obtained by combining an autumn tickle with a delayed sowing tactic.

Figure T1.5–1 Delayed sowing allows use of knockdown herbicides or cultivation to control small weeds prior to sowing and reducing the pressure on selective herbicides.
Photo: Di Holding

Table T1.5–1 Effect of a three-week delay in sowing on the number of mature annual ryegrass plants in the crop and on the following seedbank (Matthews et al. 1996).

Crop species	Annual ryegrass plants or seeds/m²			
	Early sowing		Late sowing	
	Plants	Seeds	Plants	Seeds
Field peas	234	15,955	104	12,011
Barley	367	2,240	152	1,060
Wheat	419	5,557	237	5,791

In experiments at Wongan Hills, Western Australia, autumn tickling conducted three weeks before normal sowing time (equivalent to six weeks before late sowing) stimulated emergence of 1,700 seedlings/m^2 of annual ryegrass before sowing, compared with 460 seedlings/m^2 in the 'untickled' treatment.

These seedlings were subsequently controlled using knockdown herbicides. At this stage, two sowing treatments were imposed (normal sowing and delayed sowing) and in-crop annual ryegrass numbers were reassessed three weeks after sowing time in each instance (*Figure T1.5–2*).

In the crop sown under optimum conditions for crop yield (normal sowing time – 31 May and with 120 kg/ha seed) a weed management benefit was seen in the autumn tickle treatment. There were 24% less in-crop annual ryegrass plants when compared with the 'untickled' plots (*Figure T1.5–2*).

However, the greatest weed management benefit was obtained from the autumn tickle used in conjunction with delayed sowing (three weeks after normal sowing time – 20 June). Compared with the normal sowing time, the density of in-crop annual ryegrass that emerged was reduced by 37% in the untickled and 70% in the tickled treatment. The later sowing time allowed for more weed seedlings to emerge and be adequately controlled before sowing of the crop (*Figure T1.5–2*).

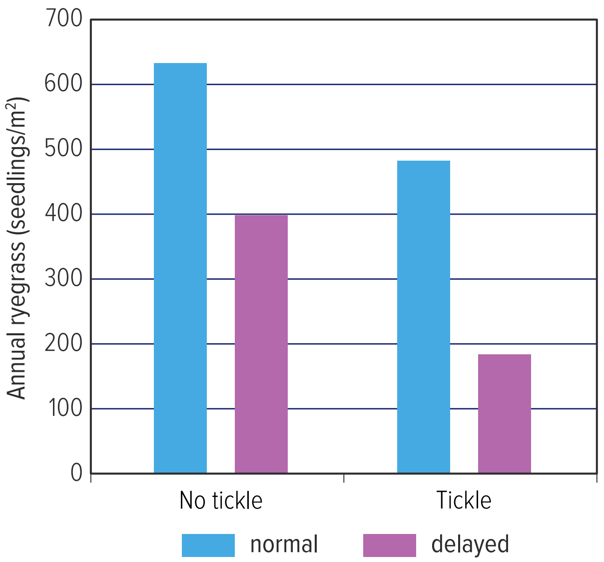

Figure T1.5–2 Comparison of delayed sowing versus normal sowing time and the impact of autumn tickling (with follow-up knockdown herbicides used before sowing) on reductions in annual ryegrass seedlings in-crop three weeks after sowing, Wongan Hills, Western Australia (Hashem et al. 1998).

Practicalities

Key practicality #1

Target problem paddocks first.

The benefits of delayed sowing for weed control have to be offset against reduced crop yield potential. Most crops will have reduced yields as a direct outcome of delayed sowing.

Use delayed sowing in paddocks with high numbers of a weed that will germinate on the first significant rain, or in paddocks with herbicide-resistant weed populations. In these situations a calculated risk of a potential lower yield may be the best option to enable weed seedbank reduction.

For wheat it has been estimated that yield potential declines approximately 4 to 7% for every week that sowing is delayed past the optimum sowing window (Matthews et al. 2012). *Table T1.5–2* shows the impact of this decline on yield and gross margin for up to 12 weeks' delay in sowing. It highlights the importance of choosing a crop and variety suited to later sowing to reduce the costs associated with this tactic.

The impact of delayed sowing on crop yields will be influenced by the type of growing season experienced in the area. Crop variety sowing guides produced by the different state departments of agriculture and primary industry around Australia will give a guide to optimal sowing windows for different crops and their respective varieties.

Key practicality #2

When planning to delay sowing in a problem paddock, choose a crop or variety that is suited to later sowing in order to reduce the risk of yield loss.

Crops such as chickpeas, field peas or barley can be sown later in the cropping program, making them more suited to delayed sowing as a weed management tactic than early sown crops such as canola and lupins.

French and Maiolo (2007) found delaying lupin sowing nine days after the break in Merredin in 2006 did not reduce annual ryegrass numbers due to rapid drying of the soil surface and subsequent lack of weed emergence. Later sown lupins also yielded less than lupins sown on the breaking rain as the weed numbers were the same in both treatments.

When planning delayed sowing with wheat choose a quick maturing variety suited to the later sowing window.

Key practicality # 3

Seasonal conditions will influence delayed sowing opportunities.

Delays to the start of the growing season will severely restrict the potential to wait for the first flushes of weed germination and subsequent pre-sowing control. In such seasons good paddock planning will help to identify paddocks that are likely to have high weed burdens.

If the season has a late break, consider omitting very weedy paddocks from the cropping program. This will allow other weed management tactics to be used in readiness for the following season.

Table T1.5–2 The impact of sowing time on yield and gross margin of short fallow wheat given a yield penalty of 5.5% per week and in the absence of weeds.

Number of weeks delay	Yield estimate (t/ha)	Variable cost ($/ha)[a]	Gross margin ($/ha)
0	3.5	230	295
4	2.7	220	185
6	2.3	210	135
8	1.9	200	85
12	1.2	190	0

[a] Variable cost decline with delay due to likely reductions in fertiliser input and lower freight costs associated with lower yield.
Note: Gross margin for zero weeks delay sourced from NSW Department of Primary Industries crop budgets handbook.

Contributors

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References

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Hashem A, Cheam A, Bowran D and Piper T 1998. Annual ryegrass control in wheat by chemical and non-chemical options. *Crop Updates 1998: Weeds*, Department of Agriculture, Western Australia.

McRae FJ, McCaffery DW and Matthews PW 2005. *Winter Crop Variety Sowing Guide, 2005*, New South Wales Department of Primary Industries, p. 7.

Matthews JM, Llewellyn R, Powles SB and Reeves T 1996. Integrated weed management for the control of herbicide resistant annual ryegrass. *Proceedings of the 8th Australian Agronomy Conference, Toowoomba.*

Matthews JM and Powles SB 1996. Managing herbicide resistant annual ryegrass, southern Australian research. *Proceedings of the 11th Australian Weeds Conference*, Melbourne, pp. 537–541. New South Wales Department of Primary Industries.

Tactic Group 2 **Kill weeds in the target area**

Killing weeds in the target area with cultivation has been the focus of weed management since agriculture was first developed. Since the release of glyphosate and Group A and B herbicides in the early 1980s herbicides have become the primary tool for controlling weeds due to their cost effectiveness, high levels of control and ease of use. However, as discussed in *Section 3 Herbicide resistance*, this approach to controlling weeds has led to the development of herbicide resistance. Despite herbicide resistance, herbicides remain an important tool, but require support from a range of non-herbicide tactics to remain effective.

Tactic 2 includes fallow and pre-sowing cultivation, double knock, pre- and post-emergent herbicides, weed detector spraying, wide row cropping and biocontrol.

Tactic 2.1 **Fallow and pre-sowing cultivation**

Cultivation, as a function of fallowing and pre-sowing operations, can kill many weeds including herbicide-resistant populations (see *Section 5 Agronomy 5 Fallow phase* and *Tactic 1.3 Inversion ploughing*). It is useful as a one-off tactic in reduced tillage or no-till operations, and can be used as a non-herbicide component of a 'double knock' system (see *Tactic 2.2b Double knockdown or 'double knock'*).

Benefits

Key benefit #1

Well-timed cultivation effectively kills weeds.

Cultivation destroys weeds via a number of processes, including:

- plant burial
- seed burial, thus reducing the ability to germinate
- root severing
- plant desiccation, where plants are left on the soil surface to die
- breaking seed dormancy
- placing seed in a more favourable environment to encourage germination for subsequent control.

The impact of cultivation will depend on the weed species. Surface germinating weeds such as sowthistle (*Sonchus* spp.), prickly lettuce (*Lactuca serriola*), feathertop Rhodes grass (*Chloris virgata*) and fleabane (*Conyza* spp.) revert to minor problems once cultivation is practised as seed is buried deeper than is ideal for these species. Annual ryegrass seed (*Lolium rigidum*) will more rapidly lose viability at greater soil depths than when shallowly buried. Strategic cultivation and deep burial of annual ryegrass seed is therefore an ideal one-off tactic to reduce the size of the seedbank (Cheam and Lee 2005). Similar viability reduction responses to burial depth have been noted in feathertop Rhodes grass in limited northern grain region studies (Osten 2011), and current experiments are validating this.

Key benefit #2

In preparing a seedbed, cultivation provides a weed-free environment for the emerging crop.

Pre-sowing cultivation following early rain can achieve a weed-free seedbed. Cultivation will also break up remaining weed residues and crop stubble that may impede sowing.

Different cultivation implements cause varying levels of soil disturbance. Selecting suitable equipment will depend on availability, weed species present, soil type, soil moisture and land use.

Key benefit #3

Cultivation can control weeds in situations where herbicides are ineffective or not an option.

Cultivation can control seedlings or mature weeds in situations where herbicides do not provide effective control. This includes situations where weeds are stressed (e.g. dry conditions, nutrient deficiencies) or resistant to available herbicide options, or when herbicide sensitive crops are present nearby.

Cultivation can be a better option in situations where herbicides are perceived as high risk options such as near urban areas and schools.

Key benefit #4

Pre-sowing cultivation or full disturbance cultivation at sowing reduces the reliance on knockdown herbicides and therefore the likelihood of weed populations developing herbicide resistance.

(See *Tactic 2.2a Knockdown (non-selective) herbicides for fallow and pre-sowing control* and *Tactic 2.2b Double knockdown or 'double knock'*).

Incorporating strategic cultivation into a no-till farming system adds diversity to the weed management options used at sowing. Used in conjunction with stubble burning (see *Tactic 1.1 Burning residues*), cultivation enables the effective use of pre-emergent herbicides (see *Tactic 2.2c Pre-emergent herbicides*).

Cultivation before sowing, or full disturbance cultivation at sowing, will decrease the reliance on knockdown herbicides for weed control. Although environmental factors such as damage to soil structure and increased erosion risk must be considered when choosing to use multiple cultivations to control weeds in herbicide resistant paddocks, it may be the most environmentally sound option available.

Whole-farm benefits

Weed management can be an additional benefit obtained when cultivation is used for:

- incorporating soil ameliorants (e.g. lime or gypsum)
- overcoming nutrient stratification
- breaking up a plough pan
- pupae busting (e.g. breaking the life cycle of *Helicoverpa* spp. in cotton cropping systems).

Figure T2.1–1 Cultivation can be used to disrupt plough pans.

Photo: Andrew Storrie

Practicalities

Key practicality #1

Strategic cultivation must take into account whole-farm practicalities.

Avoid repeated cultivation: use it strategically in situations where no suitable alternatives are available. Over-reliance on cultivation can increase weed control costs through increased labour and machinery inputs.

Cultivation should be carried out when weeds are relatively small before flowering starts. The soil should be neither completely dry nor completely wet.

Cultivation aims to displace plant roots from the soil matrix and leave the weeds to die. Root systems of large weeds may be extensive, making removal difficult. Weeds which are not fully dislodged by the cultivation may re-root if the surface soil remains moist. Some weeds, particularly perennials such as skeleton weed (*Chondrilla juncea*), silver-leaf nightshade (*Solanum elaeagnifolium*) and field bindweed (*Convolvulus arvensis*), can regenerate from roots left in the soil.

Key practicality #2

Maintain soil structure by cultivating at suitable soil moisture levels and appropriate implement ground speed.

Cultivating when the soil is too wet can cause ‘smearing’ and compaction. On the other hand, cultivation when the soil is too dry can also destroy soil structure. Both will lead to reduced water infiltration and storage and soil aeration. Travelling faster than the recommended ground speed for a particular implement type will greatly increase the damage to soil structure.

Key practicality #3

The tillage implement used will influence the level of soil disturbance and thereby the effect on the weeds present.

Choose the right implement for the job. Depending on the target weed species, the best strategy may be to use a disc plough or mouldboard plough to invert the soil and bury a high proportion of weed seed (see *Tactic 1.3 Inversion ploughing*).

If burial prolongs the life of the weed seed, future cultivations may lead to germination and the problem may resurface (see *Section 2: Profiles of common cropping weeds*). For these target weeds, scarifiers and cultivators that cause minimal soil disturbance (operating at less than 10 cm depth) may be the most suitable implements.

Alternatively a chisel plough fitted with narrow points can be used for deeper cultivation. Fitting of wider sweeps equips the implement for shallow cultivation and weed killing.

Figure T2.1–2 Cultivation failed to control the turnip weed.
Photo: Andrew Storrie

Key practicality #4

Choice of cultivation practice can influence weed density and spectrum.

Knowledge of the target weed's biological traits will assist seedbank depletion. Growth of weeds that reproduce vegetatively (e.g. skeleton weed, nut grass (*Cyperus rotundus*), silver-leaf nightshade and field bindweed) will be encouraged by cultivation. In contrast, zero till and a dependence on herbicides will encourage the growth of weeds such as fleabane, common sowthistle, prickly lettuce and vulpia (Felton et al 1994).

Common sowthistle (*Sonchus oleraceus*) is recognised as a weed of zero and reduced tillage systems. As most seedlings emerge from the soil surface (0 to 2 cm), tillage is often used as a control tactic. However, although it reduces the initial impact from sowthistle, the practice also prolongs the problem as the small seeds are able to survive at a depth of 10 cm for as long as 30 months (Widderick et al 2002).

Figure T2.1–3 shows the effect of burying seed of common sowthistle, comparing conventional tillage (disc plough followed by chisel plough) with zero tillage. Because buried common sowthistle seeds are much less likely to germinate than those left at the soil surface, zero tillage may be a beneficial practice to reduce the seedbank, providing that effective management tactics are used to control emerging weeds.

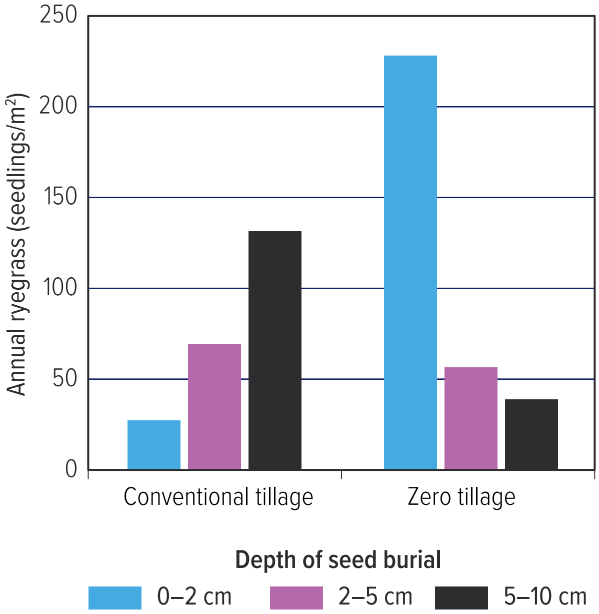

Figure T2.1–3 Burial of common sowthistle seed under different tillage treatments. The conventional tillage treatment is a disc plough followed by a chisel plough (Widderick et al. 2002).

Ongoing research in 2011 to 2012 (Widderick and McLean, 2017) has also demonstrated the impact of different tillage types on the germination of the zero till favouring weeds, fleabane and feathertop Rhodes grass (*Figure T2.1–4*). Results showed germination for both weeds was significantly reduced by all tillage types but the greatest impact was measured in the one-way disc treatments.

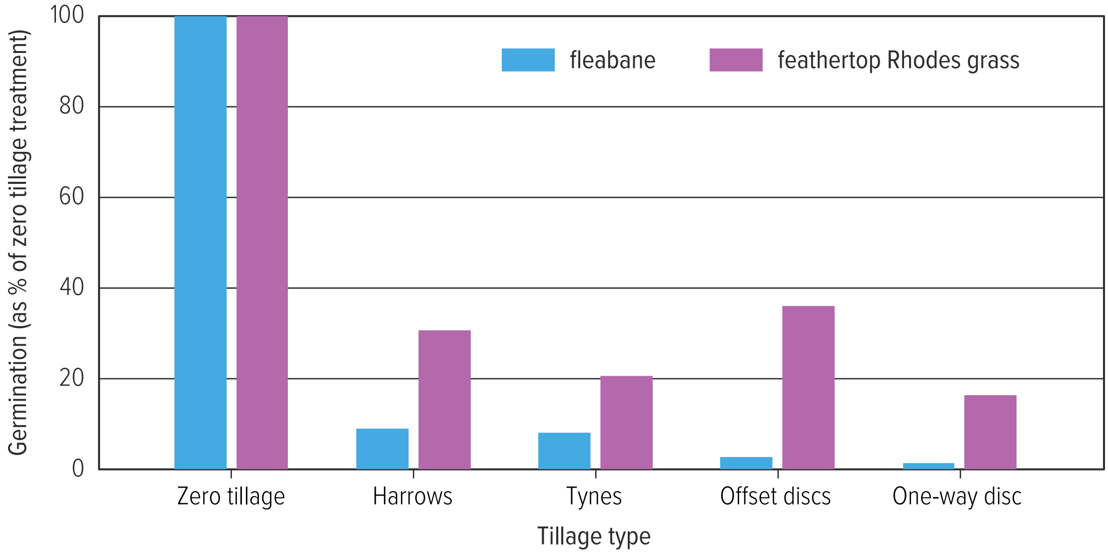

Figure T2.1–4 Germination (expressed as a % of the zero tillage treatment) of fleabane and feathertop Rhodes grass following different tillage types (data courtesy DAFF, Queensland).

Deep burial of wild radish seed also lengthens its survival. Code et al. (1987) found that the number of viable seeds remaining after four years was much greater when seed was buried at 10 cm depth in the soil, compared with shallow burial (1 or 5 cm) or being left on the surface (*Table T2.1–1*). The seeds persist in the soil for a longer period of time because the seedlings cannot emerge from depth (*Table T2.1–2*). Subsequent cultivations following deep seed burial would need to be shallow, to avoid raising the seeds to soil depths where germination would be promoted.

Murphy et al. (1999) found that wild radish emergence was significantly greater after direct drilling than after tillage using a scarifier, disc plough or mould-board plough. Emergence was also greatest when the seed was shallowly buried (less than 5 cm).

Table T2.1–1 Wild radish survival in the soil (% of total remaining) depending on depth of burial in the soil (Code et al. 1987).

Depth of burial (cm)	Survival in the soil (% of total remaining) Duration of burial (years)					
	0.5	1	2	3	4	6
0	43	19	5	4	5[a]	0
1	10	12	16[a]	5	3	1
5	55	47	52[a]	27	21	7
10	75	57	53	44	43	0

[a] Apparent increases in viability with time due to variation between samples.

Table T2.1–2 Emergence of wild radish from various depths (% of total seed sown in May 1977) (Code et al. 1987).

Depth of burial (cm)	Emergence (% of total seed sown)					
	1977	1978	1979	1980	1981	1982
0	33	4.0	1	0.60	0.1	0.13
1	73	0.5	1	0.30	0.0	0.10
5	16	0.1	1	0.02	0.1	0.02
10	0.6	0.0	0.02	0.00	0.0	0.00

Results indicated that under reduced tillage systems wild radish emergence may be enhanced. Provided that seedlings were effectively controlled and seedset was prevented, reduced tillage systems may more rapidly deplete viable wild radish seeds in the soil, compared with tillage systems that create a higher degree of soil disturbance (Murphy et al. 1999).

The outcome of shallow burial, compared with seeds left on the soil surface, will be dependent on the weed species being targeted.

Whole-farm considerations

Cultivation reduces surface stubble cover that would otherwise be maintained for as long as possible to reduce erosion risk and optimise soil moisture storage.

The type of seedbed produced by cultivation will depend on soil type and moisture content. Poorly timed cultivation, resulting in a poor seedbed, can lead to reduced crop emergence, herbicide damage and reduced herbicide performance.

Pre-season cultivation may improve the reliability of sowing time in some environments. In low rainfall environments pre-season cultivation may delay sowing.

Over-reliance on cultivation can:

- reduce soil cover from plant residues
- degrade soil structure
- reduce available soil water.

Contributors

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References

Cheam A and Lee S 2005. Survival of annual ryegrass seed at various soil depths. *Proceedings Agribusiness Crop Updates*, Perth. Department of Agriculture WA.

Code GR, Walsh MJ and Reeves TG 1987. Effect of depth and duration of burial of wild radish seed on seed viability and seedling emergence. *Proceedings of the Weeds Seed Biology Workshop*, Orange, New South Wales, pp. 136–138.

Felton WL, Wicks GA and Welsby SM 1994. A survey of fallow practices and weed floras in wheat stubble and grain sorghum in northern New South Wales. *Australian Journal of Experimental Agriculture*, vol. 34, pp. 229–236.

Murphy C, Lemerle D, Medd R and Cullis B 1999. Manipulation of wild radish emergence to accelerate seedbank decline: preliminary findings. *Weed management into the 21st Century : do we know where we're going?: 12th Australian Weeds Conference Papers and Proceedings*. Hobart, Tasmania, (eds AC Bishop, M Boersma and CD Barnes), pp. 256–260, Tamanian Weeds Society.

Osten V 2011. Biology/ecology of feathertop Rhodes grass (*Chloris virgata*). *Proceedings of the Chloris spp. biology and management symposium*. Brisbane, Queensland, pp. 37–45, Department of Employment, Economic Development and Innovation.

Widderick M, Sindel B and Walker S 2002. Emergence of *Sonchus oleraceus* is favoured under zero tillage farming systems. *Weeds 'threats now and forever': 13th Australian Weeds Conference*, Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 91–92, Plant Protection Society of WA Inc.

Widderick M and McLean A 2017. Tillage and farming system – impacts on weed germination and seedbank longevity. *GRDC Update paper,* July 2017, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/07/tillage-and-farming-system-impacts-on-weed-germination-and-seedbank-longevity, viewed 13 November 2018.

Further reading

Derkson DA, Lafond GP, Thomas AG, Loeppky HA and Swanton CJ 1993. Impact of agronomic practices on weed communities: tillage systems. *Weed Science*, vol. 41, pp. 273–280.

Murphy SD, Clements DR, Belaoussoff S, Kevan PG and Swanton CJ 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. *Weed Science*, vol. 54, pp. 69–77.

Widderick M, McLean AR and Walker SJ 2012. Non-chemical options for managing the seed bank of glyphosate-resistant weeds. *Developing Solutions to Evolving Weed Problems: 18th Australasian Weeds Conference*, Melbourne, Victoria, pp. 279–280, Weed Society of Victoria Inc.

Tactic 2.2 Herbicides

Herbicides have been used widely since the late 1940s. Western agriculture was significantly changed in the late 1970s when glyphosate, sulfonylureas and grass selective herbicides were released.

In the early years of herbicide use an integrated approach to weed management was seen as an unnecessary inconvenience to an effective and simple solution. The development of herbicide resistance is challenging this oversimplified approach.

Herbicides continue to play a vital role in integrated weed management. Better knowledge of the mechanisms and activity of herbicides will improve the impact and sustainability of herbicide use as a weed management tactic.

Development of new herbicides

The development of new herbicides is slow and expensive. To identify a single new compound that may become a potential herbicide, over 160,000 chemical compounds are screened (Beckie et al. 2019).

Development processes include identifying new molecules, efficacy testing, assessing crop and environment safety margins, and scoping of potential markets. The entire process can take up to 10 years to complete and cost almost USD $300 million. Even then, despite proven efficacy levels, many potential herbicides do not continue through to commercialisation because of environmental constraints or limited market potential.

Herbicides are broadly categorised according to their mode-of-action (MOA). This refers to the essential function(s) within the target plant (weed) that are disrupted when herbicide is used. MOA grouping aids resistance management by clearly identifying which herbicides belong to the same MOA.

In 2018 there were more than 270 registered herbicide active ingredients in the world, categorised into 19 different MOA groups. Over 50% of the herbicides lie within three MOA groups: Group B (e.g. sulfonylureas), Group C (e.g. triazines) and Group G (e.g. oxyfluorfen and carfentrazone).

In 2012 a new pre-emergent herbicide was released commercially for use in wheat and triticale, namely pyroxasulfone from the isoxazole chemical family. Despite being a new herbicide for this use, it is still a Group K MOA. There is a low likelihood of new MOA groups being released, making it essential that current herbicide use is conservative and supported with non-herbicide tactics.

Some definitions

Translocated herbicides

Translocated herbicides move to the site of action via the transport mechanisms within the plant (the xylem and phloem). The xylem transports water and nutrients from the soil to growth sites and the phloem transports products of photosynthesis (sugars, etc.) to growth and storage sites. It may take up to two weeks for symptoms to develop on the target weeds, depending on herbicide rate, conditions and species.

Glyphosate is an example of a foliar applied translocated herbicide. It moves within both the xylem and phloem to the whole plant. This two-way interior movement improves the ability of glyphosate to kill the whole plant, including the roots, even when the plant is well established (although seedlings are often more sensitive).

Soil applied translocated herbicides move within the plant via the xylem and are absorbed by germinating seeds, emerging roots and shoots and established roots. Examples of soil applied translocated herbicides are atrazine and metolachlor. In the case of atrazine, translocation can only occur in an upwards direction. As a result, when used as a post-emergent product, little of the herbicide gets to the roots and the control of established weeds is often very poor.

Contact herbicides

Contact herbicides have limited movement within the plant, so complete coverage of the target plant is critical. Compared to translocated herbicides (e.g. glyphosate), contact herbicides (e.g. paraquat, oxyfluorfen, diquat and bromoxynil) tend to show symptoms rapidly, usually within 24 hours.

As contact herbicides are not well translocated, they are best suited to controlling very small seedlings. Herbicides such as bipyridyls can also be quite effective at stopping seedset of annual weeds if applied late in the weed life cycle as a desiccant or 'spray-topping' application.

Selective and non-selective herbicides

Selective herbicides will kill target weed(s) but not desired plants (the crop or pasture) when applied at a specified application rate. The crop or pasture is able to survive this application rate because it may:

- have a slower rate of herbicide absorption. However, damage may be caused if inappropriate adjuvants are used, which modify the leaf surface and thus increase absorption.
- not have a relevant target site on which the herbicide can act (e.g. a grass selective herbicide used on a broadleaf crop)

- rapidly detoxify the herbicide, usually with enzymes called 'cytochrome P450', before the herbicide can reach the target site (e.g. fenoxaprop or a sulfonylurea used in wheat). However, these herbicides can damage the host crop or pasture if it is under stress or if the application rate is too high and the plant cannot produce sufficient enzymes to detoxify the herbicide.

Non-selective herbicides (also called knockdown herbicides) such as glyphosate or paraquat will damage most plants they contact. The recent inclusion of genes for resistance to glyphosate into crop DNA can enable a non-selective herbicide to be used selectively in crops that have been specifically bred to be tolerant (see *Section 5 Agronomy 3 Herbicide tolerant crops*).

Figure T2.2–1 Melons (*Citrullus lanatus*) about to be sprayed with glyphosate + triclopyr, Kellerberrin, WA. *Photo*: Anne Dixon

Residual versus non-residual

Residual herbicides remain active in the soil for an extended period of time (i.e. months) and can act on successive weed germinations. Residual herbicides must be absorbed through either the roots or the shoots, or through both. Examples of residual herbicides include imazapyr, chlorsulfuron, atrazine and simazine.

Residual herbicide persistence is determined by a range of factors including application rate, soil texture, organic matter levels, soil pH, rainfall or irrigation, temperature and the herbicide's characteristics. Persistence will affect enterprise sequence (e.g. a rotation of crops such as wheat–barley–chickpeas–canola–wheat).

Non-residual herbicides, such as the non-selective paraquat and glyphosate, have little or no soil activity and are quickly deactivated in the soil. They are either broken down or bound to soil particles, becoming less available to growing plants. They also may have little or no ability to be absorbed by roots.

Post-emergent and pre-emergent

These terms refer to the target and timing of herbicide application. Post-emergent refers to foliar herbicide application after the target weeds have emerged from the soil, while pre-emergent refers to herbicide application to the soil before the weeds have emerged.

Herbicide mixtures and sequential applications

Herbicide mixtures involve applying more than one herbicide in a single operation. From a weed management perspective the primary reason for mixing herbicides is to increase the spectrum of weed species controlled. Application costs are also reduced when applying herbicide mixtures in the one tank.

The MOA of every herbicide is clearly stated on the product label. Some herbicide pre-mixes comprise individual herbicides from different MOA groups. In such situations product packaging will identify which MOA groups are contained within the product.

Using tank mixes or sequential herbicide applications in the same season may help to delay herbicide resistance development if they control the survivors of the other herbicide in the mix. Modelling by Diggle et al. (2003) has shown that tank mixes (where both mix partners are applied at full label rates) and/or sequential applications are more effective at delaying resistance than application patterns that rotate MOA groups over a number of years. This approach is also more effective than pushing a weed population to resistance to one MOA group before progressing on to another group.

The long-term returns from delaying the onset of resistance will be high, particularly for highly valued herbicides such as glyphosate, and will balance the increased cost of weed management in that season. Tank mixes for resistance management should use the full registered rate of all products included in the mix. This will ensure that there is adequate alternate herbicide to kill those weeds that are resistant to the first product. Note that where the resistant proportion of the weed population is low, there will be little economic gain from including an alternate herbicide in that season.

Synergies between herbicide groups are uncommon. They are known to exist between some Group C (photosystem II inhibitors) when mixed with Group

I (synthetic auxins) or Group H (HPPD inhibitors) herbicides (Hugie et al. 2008).

Even where synergies are known to exist application rates should not be decreased to levels that are lower than if the products had been applied singularly.

Other combinations of herbicide products cannot be mixed due to antagonism. Mixtures of antagonistic products may damage crops and/or result in reduced weed control because of chemical or biological incompatibility. However, antagonistic herbicides can be applied in split (or sequential) applications, usually after a delay of one day to allow translocation of the first herbicide, but before symptoms appear.

Herbicide labels will contain some information on the antagonistic or synergistic status of herbicide mixtures. The quality of information varies between different labels so always seek advice before using unproven or novel mixtures. Using such mixtures can also occasionally result in physical incompatibility (e.g. undesirable tank or nozzle blockages and sludges).

Herbicide uptake by plants

Foliar applied herbicides

A foliar herbicide's effectiveness is influenced by meteorological conditions, spray droplet distribution and composition and the characteristics of the leaf surface on which it is deposited.

The herbicide enters the leaf either by diffusion through the leaf cuticle and epidermis, or directly through the stomata (although access via the stomata is minor with most herbicides).

The leaf cuticle protects plant cells from desiccation. It is coated in various types of wax and fatty acids, depending on the species and the growing conditions the plant has been exposed to. The structure of the cuticle will influence herbicide entry into the leaf. The cuticular wax is more like a sponge than a solid layer, and an aqueous and a lipid route provide two means of access through this sponge.

When a plant is actively growing and well hydrated, water-soluble herbicides (such as those from Group B MOA) diffuse rapidly via the aqueous route through the cuticular pores. This is possible because the pores are holes in the sponge and are full of water. In water stressed plants the pores form air pockets which disrupt the continuous aqueous path and slow the rate of diffusion.

The lipid route allows oil-soluble herbicides, such as emulsifiable concentrate formulations, to diffuse through the wax layer into the leaf. This route is less affected by moisture stress.

The effect of herbicide formulation and addition of adjuvants on diffusion through these pathways is complex and is not discussed here.

Herbicides in the soil

Both foliar and soil applied herbicides may be present in the soil and absorbed through plant roots. Some herbicides (e.g. picloram) leak from plant roots (this is also known as herbicide flashback) and can be absorbed by other plants or reabsorbed by the same plant.

Root absorption

Water-soluble herbicides (e.g. chlorsulfuron) are absorbed in water through root hairs and the area just behind the root tip.

Coleoptile and young shoot absorption

Some herbicides are primarily absorbed through the coleoptile and new shoots. These herbicides (e.g. triallate and trifluralin), which act mainly through root uptake with some shoot uptake, can be volatile and must be absorbed quickly to be effective. Non-volatile shoot uptake herbicides (e.g. diflufenican and metolachlor) rely on a moist soil surface for highest absorption levels.

Translocation within the plant

Movement of herbicide within the plant occurs through:

- the cell wall continuum and xylem. This movement (e.g. in most Group C MOA herbicides) occurs with water and nutrients from the roots to the shoots.
- the minute cytoplasmic threads that extend through openings in cell walls and connect protoplasts of adjacent living cells and phloem. This movement (e.g. in 2,4-D and MCPA) occurs with sugars produced in the leaves and to areas of new growth, the roots and storage organs.
- a combination of the above. This movement (e.g. in glyphosate, picloram and dicamba) occurs with circulation within the plant.

Stressed weeds: what level of control can be expected?

Stressed weeds are harder to kill than healthy, actively growing weeds. Plants can be stressed and not show any distinct visual signs. Stress can be caused by:

- lack of moisture due to dry conditions, and physical or chemical impediments to root growth
- lack of oxygen due to waterlogging
- extremes of temperature, e.g. cold (frost) and heat
- nutrient deficiencies
- insect pests, e.g. aphids, wireworms

- disease
- a sub-lethal dose of herbicide from previous applications or soil residues
- mechanical damage, i.e. tillage or slashing.

Moisture stress is one of the most common plant stresses. Translocation and respiration slow dramatically when plants are moisture stressed, restricting the movement of herbicides to their sites of action. When herbicides are applied to stressed crops and pastures, herbicide breakdown via metabolic processes can be slowed, leading to crop or pasture damage.

Weeds that have been moisture stressed may have limited leaf development but extensive root systems, developed to assist in the search for moisture. This means that the above ground plant biomass does not adequately reflect the true weed size or growth stage.

In the case of summer annual grasses the opposite is often true. For example, liverseed grass (*Urochloa panicoides*) or barnyard grass (*Echinochloa* spp.) plants might be well-tillered but only have two or three roots, which means it stresses very quickly.

Plants experiencing high temperatures, low humidity and low soil moisture conditions tend to have a thicker cuticle (the protective cover of the leaf) with more waxy deposits on the surface. This reduces absorption of foliar applied herbicides.

The timing and amount of rainfall not only determines the moisture status of the plant but also removes dust from the leaves and modifies the leaf cuticle. Recent rainfall will therefore improve herbicide absorption.

Weeds may have sufficient soil moisture available but still be stressed by high (greater than 30 °C) temperatures. This is a common cause of poor control in summer fallows.

Seasonal environmental conditions determine overall herbicide performance, and conditions on the day of spraying determine the variation around this level.

Once a weed has been stressed it will not be adequately controlled by herbicide rates that would otherwise be sufficient for unstressed weeds, even when there has been enough rainfall to make the weed appear healthy.

Additives such as ammonium sulfate, wetters and oils may help improve the control of stressed weeds by 10 to 20% but can be unpredictable. Performance enhancements are specific to some herbicides or formulations, so always check the label.

How to tell if plants are moisture stressed

Symptoms of moisture stress include wilting, rolling of leaves and a dull blue colour. Photosynthesis and respiration will decline before these symptoms are visible.

Roots can indicate if a plant is actively growing. Carefully dig out the plant and gently wash the soil from the roots. Actively growing plants will have fresh white roots. Leaves of well-hydrated plants will be 'springy'.

To determine the extent to which grass is hydrated:

- Remove the mid-vein of the leaf.
- Hold the remaining portion of the leaf horizontally between thumb and forefinger.
- Flick it down with the other hand.

A well-hydrated leaf will spring back to the horizontal position, while leaves from stressed plants will not.

Contributors

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References

Beckie HJ, Ashworth MB and Flower KC 2019. Herbicide resistance management: recent developments and trends. *Plants*, vol. 8, 161.

Diggle AJ, Neve PB and Smith FP 2003. Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. *Weed Research*, vol. 43, pp. 371–382.

Hugie JA, Bollero GA, Tranel PJ and Riechers DE 2008. Defining the rate requirements for synergism between mesotrione and atrazine in redroot pigweed (*Amaranthus retroflexus*). *Weed Science*, vol. 56, pp. 265–270.

Further reading

Ashton FM and Crafts AS 1973. *Mode of action of herbicides*. Wiley-Interscience, New York.

Cobb AH and Reade JPH 2010. *Herbicides and plant physiology* (Second edition) p. 286. Wiley-Blackwell, West Sussex, UK.

Piper T 1993. Understanding herbicides; J Dodd, RJ Martin and KM Howes (eds). *Management of agricultural weeds in Western Australia*. Kondinin Group.

Somervaille A, Betts G, Gordon B, Green V, Burgis M and Henderson R 2012. *Adjuvants – Oils, surfactants and other additives for farm chemicals* (Revised edition). Grains Research and Development Corporation, Kingston, Australian Capital Territory.

Whitehead J and Marley J 1989. Herbicides and how they work in plants. *Herbicides, people and the environment*. Workshop notes, Darling Downs Land Management Committee and Queensland Department of Primary Industries.

Tactic 2.2a Knockdown (non-selective) herbicides for fallow and pre-sowing control

Knockdown herbicides lack species selectivity and therefore kill all plants when used in sufficient quantities under suitable spraying conditions. For this reason knockdown herbicides are used to control a wide range of weeds, either in a fallow or before sowing.

To simplify weed management certain crop cultivars (e.g. Roundup Ready™ crops: see *Section 5 Agronomy 3 Herbicide tolerant crops*) have been developed to tolerate some knockdown herbicides.

Knockdown herbicides are also a key part of other weed management tactics, including:

- controlling weeds before sowing (see *Agronomy 2* and *Tactic 1.5*)
- herbicide tolerant crops (see *Agronomy 3*)
- controlling weeds in fallow (see *Agronomy 5*)
- inter-row application (see *Tactic 2.3*)
- crop-topping (see *Tactic 3.1b*)
- use of wiper methods (see *Tactic 3.1c*)
- crop desiccation (see *Tactic 3.1d*)
- pasture spray-topping (see *Tactic 3.2*)
- brown manuring and hay freezing (see *Tactic 3.4*).

Since their development knockdown herbicides have become one of the most heavily relied upon weed management tactics. Glyphosate entered the world market in the late 1970s although high pricing initially limited its use. Prior to this, paraquat was more commonly used. Developed to deal with capeweed (*Arctotheca calendula*) in southern Australian farming systems, Spray.Seed® (paraquat + diquat) also improved the control of *Erodium* species and black bindweed (*Fallopia convolvulus*).

Glyphosate dominates the world knockdown herbicide market due to its ease of use and application rate flexibility. Increasing affordability in Australia has played a large part in its increased popularity (*Figure T2.2a–2*), allowing no-till farming to become more competitive with standard cultivation systems.

Glyphosate use is likely to further increase due to:

- enterprise flexibility becoming increasingly important
- legislation aimed at curbing the off-target movement of herbicides leading to a reduction in the use of tank mixes of herbicides and the use of glyphosate at higher application rates
- increased fuel prices making cultivation more expensive
- Paraquat and Spray.Seed® regaining popularity and their use in managing glyphosate resistance.

Benefits

Key benefit #1

Knockdown herbicides are effective.

Over 95% control can be expected when knockdown herbicides are applied under suitable conditions (Wallens 1983).

Key benefit #2

Knockdown herbicides are cost-effective.

At the time of writing the cost of glyphosate for fallow and pre-sowing spraying is between $4/L and $8/L (*Figure T2.2a–2*).

Spraying is also a quicker operation than cultivation: spraying can cover up to 20 ha/hour compared with about 8 ha/hour for cultivation. This means that one person can control weeds over a much greater area in a given time. The increasing price of fuel will increase the price advantage of spraying.

Figure T2.2a–1 Summer fallow spraying Wickepin, WA
Photo: Andrew Storrie

Key benefit #3

Use of knockdown herbicides can improve the timeliness of sowing.

Spraying is usually quicker to conduct than cultivation, and this is particularly important after breaking rain. Minimum tillage paddocks can also be accessed more quickly after rain compared with conventionally cultivated paddocks.

Because spray machines can be lighter than cultivation equipment, they are less likely to cause large wheel tracks or soil structural problems associated with cultivation of moist soil. Therefore, with less delay, crops can be sown closer to their optimum sowing date into better soil moisture.

Glyphosate can also be applied by air if conditions are too wet to get machinery on to the paddocks.

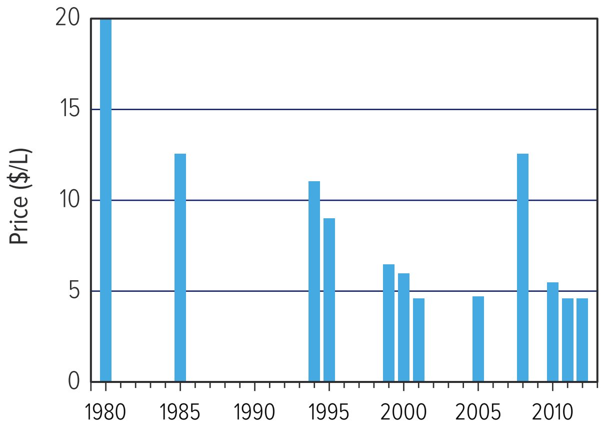

Figure T2.2a–2 The price of glyphosate (450 g/L) in Australia since its release in 1980.

Whole-farm benefits

Maintaining plant residue cover on the soil for as long as possible will:

- reduce wind and water erosion risk
- help improve soil structure
- improve plant available water content (see *Tactic 2.1 Fallow and pre-sowing cultivation*).

Practicalities

Key practicality #1

Overuse of a knockdown herbicide will select for weed populations that are resistant to that particular herbicide.

At the time of writing, there are 363 documented glyphosate-resistant populations of annual ryegrass, 76 of awnless barnyard grass, 57 of fleabane, 10 of windmill grass, three of liverseed grass and two of great brome. See the Australian Glyphosate Sustainability Working Group website www.glyphosateresistance.org.au which provides up-to-date information on glyphosate and paraquat resistance.

Non-herbicide tactics must be used in an integrated weed management plan to save the effectiveness of our herbicides.

Key practicality #2

Consider the suitability of knockdown herbicides for fallow or pre-sowing weed control by assessing environmental conditions.

There are a number of considerations when choosing between a spray and a cultivation tactic for fallow weed control (*Table T2.2a–1*).

Key practicality #3

Stressed weeds will not be adequately controlled by knockdown herbicides.

Weeds that are stressed do not readily absorb or translocate applied herbicide. As a result, only a sub-lethal dose of herbicide reaches the active sites within the plant, leading to low levels of weed control.

Figure T2.2a–3 A paddock of wild oats showing moisture stress before sowing, Tamworth, NSW. Herbicide control now will be ineffective. Note the large blue patches of the stressed plants.
Photo: Andrew Storrie

Table T2.2a–1 Fallow situations – suggestions for weed control (Somervaille and McLennan 2003).

Situation	Cultivate	Spray
Weeds small and fresh		✓
Weeds stressed	✓	
Soil too wet for machinery		✓
Weather unsuitable for spraying	✓	
Weeds grazed but have not regrown	✓	
Excessive wheel tracks after harvest	✓	
Excessive stubble in windrows/disease control	✓	
Soil conditions suitable for planting		✓
Build-up of weeds not well controlled by herbicides – too large and/or resistant	✓	
Wind erosion – paddock starting to blow	✓	

Figure T2.2a–4 Wild oats showing moisture stress prior to cropping, Tamworth, NSW. Notice that the leaves are curled and the leaf colour is blue, not green.
Photo: Andrew Storrie

Key practicality #4

Suitable meteorological conditions for spraying can be limited, especially in summer.

Applying knockdown herbicides in unsuitable conditions leads to spray failure because insufficient herbicide reaches the target.

Movement of herbicides off-target (spray drift) can contaminate neighbouring enterprises, communities and native vegetation. *Figure T2.2a–5* shows the effect of meteorological conditions on the risk of spray loss (drift) at Moree, New South Wales, during 2003. November to March had a greater than 50% risk of significant application losses due to conditions that were too hot, dry, windy or still. This means that during this period at least 12 hours each day were unsuitable for spraying. Insufficient herbicide would have reached the target and acceptable weed control would not have been achieved. In addition, issues such as off-target herbicide damage and contamination would have been problematic.

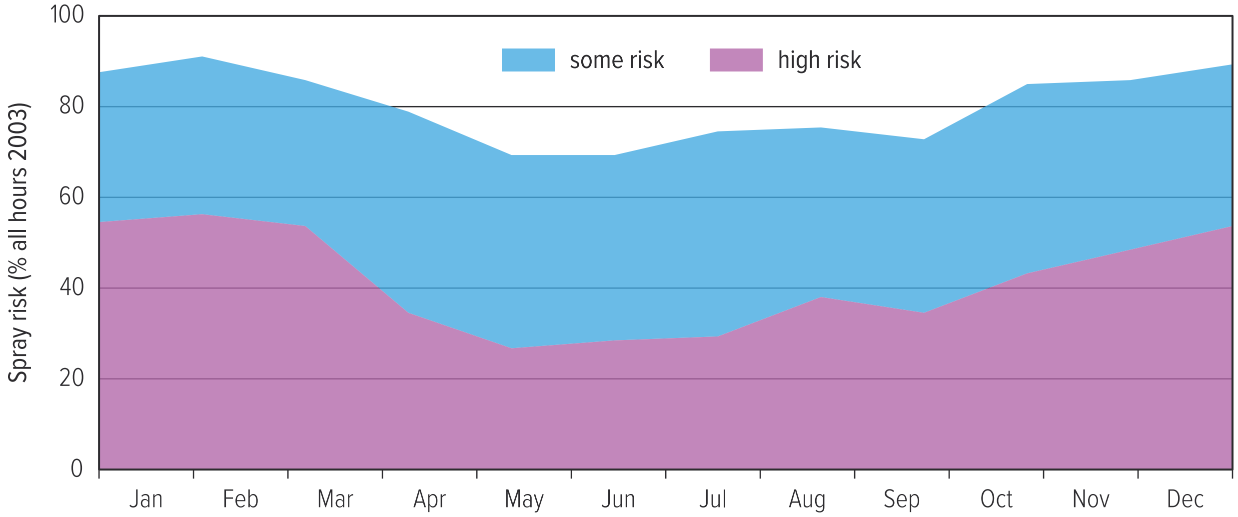

Figure T2.2a–5 Effect of meteorological conditions on the risk of spray loss over an average 24 hours at Moree, New South Wales, during 2003 (Gordon J, unpublished).

Contributor

Andrew Storrie

References

Somervaille A and McLennan B 2003. *The 2nd Fallow Weed Management Guide*. Conservation Farmers Inc.

Wallens PG 1983. Roundup® performance on common fallow weeds in northern Australia. *Proceedings of No-tillage Crop Production in Northern NSW Project Team Meeting*. Department of Agriculture, Agriculture Research Centre, Tamworth, New South Wales.

Tactic 2.2b Double knockdown or 'double knock'

'Double knock' refers to the sequential application of two different weed control tactics applied in such a way that the second tactic controls any survivors of the first tactic. Most commonly used for pre-sowing weed control, this concept can also be applied in-crop.

The double knock approach to weed management was first used in the 1960s when direct drilling was still developing. The system comprised an application of knockdown herbicide (paraquat or paraquat/diquat) followed by full disturbance sowing.

Other double knock strategies include non-selective herbicide application followed by burning or grazing. Although these combinations of tactics are still valid today, the trend towards no-till farming, with minimal disturbance sowing and often with wider crop rows, has led to the double knockdown technique.

The double knockdown technique is the sequential application of two knockdown herbicides from different MOA groups, such as glyphosate (Group M) followed by paraquat/diquat (Group L), at an interval of between one and 14 days. Used before sowing, each herbicide in the double knockdown must be applied at a rate which would be sufficient to control weeds if it was used singularly. The second herbicide is applied with the aim of controlling any survivors of the first herbicide application. Control of weeds that germinate during the interval between the two herbicide applications is an incidental benefit.

Figure T2.2b–1 Double knockdown treatment of glyphosate followed eight days later with paraquat on glyphosate resistant annual ryegrass, *Photo*: Andrew Storrie

It is important to understand that the double knockdown method is definitely not two sequential applications of the same knockdown herbicide. While this practice is used occasionally when there are a number of pre-sowing germination events, it does not include the key characteristic of minimising selection pressure for resistance.

Although double knockdown has primarily targeted annual ryegrass (*Lolium rigidum*) it is an effective tactic for use on a wide range of weed seedlings.

Benefits

Key benefit #1

Double knockdown delays or prevents glyphosate resistance development.

A 30-year modelling simulation (Neve et al. 2003) demonstrated that the double knockdown strategy of sequential applications of glyphosate and paraquat in the same year prevented resistance evolving in annual ryegrass to either herbicide (*Table T2.2b–1*). To be fully effective the technique must be applied before glyphosate resistance has had a chance to develop.

The model results indicate that the proportion of glyphosate-resistant annual ryegrass plants in the population slowly increased over time if either cultivation or an in-crop selective herbicide was used after a glyphosate application.

A more rapid move to glyphosate resistance occurred where there was no tillage at sowing or where a selective in-crop herbicide, to which resistance had already developed, followed the pre-sowing application of glyphosate or paraquat.

Thornby et al. (2008) demonstrated 30-year-run simulations using the DAFF developed glyphosate resistance evolution model on the likely development of resistance in awnless barnyard grass (*Echinochloa* spp.), the troublesome northern region summer fallow weed, in a high risk system (minimal till, no summer crop, no control of survivors). The various simulations revealed that the double knockdown technique as a 'resistance busting' tactic significantly reduced the risk of glyphosate resistance evolving. The model showed the use of the double knock every year delayed onset completely in the 30-year period. Application every second year delayed onset until the twenty-fourth year, and no application of the tactic had resistance developing 10 years earlier than the previous scenario.

Table T2.2b–1 Probabilities of glyphosate resistance evolution in annual ryegrass under four knockdown management strategies (Neve et al. 2003).

Strategy	Probability of glyphosate resistance evolution
Glyphosate every year	0.64
Alternate glyphosate and paraquat each year	0.35
Double knockdown every year	0.00
Double knockdown three years in five	0.017

Key benefit #2

Using a double knockdown or double knock strategy reduces the number of glyphosate-resistant weeds to be controlled in-crop.

Attempting to control all emergent weeds before sowing reduces the number of surviving glyphosate-resistant weeds to be controlled by selective in-crop herbicides.

Treating smaller numbers of weeds with selective in-crop herbicides also reduces the selection pressure for resistance development to these selective herbicides.

Key benefit #3

Excellent weed seedling control is obtained by using a pre-sowing double knockdown.

Although this is not a primary objective of the technique, double knockdown may improve pre-sowing weed control which is particularly important in minimum or zero tillage sowing systems.

In 19 experiments in five states over five years, Sabeeney (2006) showed that a double knockdown gave 10 to 15% better control (average 95% weed control) of a range of annual weeds than a single knockdown application (average 80% weed control). The double knockdown used was either glyphosate and bipyridyl or two applications of bipyridyl, with similar results. The single knockdown used was either glyphosate or bipyridyl alone, again with similar results. It should be noted, however, that using two herbicides from the same MOA group is not recommended because of the increased risk of developing herbicide resistance. Studies by Borger and Hashem (2007) have shown the double knockdown of glyphosate followed by a paraquat-diquat mix was more effective at controlling three- to six-leaf annual ryegrass than glyphosate alone.

Numerous double knockdown studies have been conducted in Australia since 2006, not only for managing herbicide-resistant populations, but also for fallow management of difficult to control weeds (e.g. feathertop Rhodes grass, fleabane), particularly in the northern grain region (Werth et al. 2010; Osten and Spackman 2011).

Fleabane (*Conyza* spp.) can be effectively controlled in the early rosette stage by double knockdown where paraquat alone or in-mix with diquat is applied five to seven days after glyphosate or glyphosate mixed with 2,4-D. The double knockdown tactic has also been described as the most consistent and reliable method of controlling feathertop Rhodes grass (*Chloris virgata*) across various growth stages (Osten and Spackman 2011). The only herbicides registered for fallow control of pre-tillering to early tillering feathertop Rhodes grass in eastern Australia are haloxyfop and paraquat and these must be applied as a double knockdown before sowing mung bean (minor use permit, PER12941, www.apvma.gov.au/permits/). This permit was granted based on unpublished research work from the sub-regional Grains Research and Development Corporation Grower Solutions projects.

Practicalities

Key practicality #1

Glyphosate should be applied first, followed by paraquat or paraquat/diquat.

Traditionally, the system has been viewed as requiring the translocated herbicide (glyphosate) to be applied first because it is moved to the root system by the plant. Subsequent application of the paraquat/diquat effectively destroys the plant top, while regrowth is prevented by glyphosate in the root system. Applying the contact herbicide (paraquat/diquat) first damages the leaf surface and can interfere with the ability of the weed to take up glyphosate.

When targeting glyphosate-resistant annual ryegrass, Storrie (2005) found a 10% improvement in control by using glyphosate followed by a bipyridyl compared to using a bipyridyl followed by glyphosate. Field experiments by Borger and Hashem (2007) in Western Australia showed a similar response, also to annual ryegrass.

Research conducted by Newman and Adam (2003, 2004) has shown that capeweed (*Arctotheca calendula*) does not survive a double knockdown when glyphosate is applied first. If a bipyridyl is applied first, up to 30 plants/m^2 can survive. Wild radish (*Raphanus raphanistrum*) follows a similar trend, with survival decreasing from 13 to three plants per plot, if glyphosate is used ahead of a bipyridyl (Newman and Adam 2004).

Key practicality #2

The time between applications will vary with the main target weed species.

Historically, the recommended interval between the two herbicide applications has been a minimum of four days and preferably 10 days. The primary aim of the double knockdown is to allow the second herbicide to control survivors of the first herbicide application, and a longer delay increases the likelihood that weeds germinating after the first herbicide application will be killed by the second herbicide.

Newman and Adam (2004) found that, under good growing conditions, the bipyridyl herbicide could be applied as soon as one day after the glyphosate when targeting glyphosate-susceptible annual ryegrass. However, this short timing would limit the ability of the double knockdown to control subsequent germinations.

Borger et al. (2004) concluded that an interval of at least two days was required before spraying glyphosate following an application of paraquat/diquat. Later studies by Borger and Hashem (2007) defined the effective interval to be between two and 10 days for seedling annual ryegrass.

An application of glyphosate stops glyphosate-resistant annual ryegrass growth for approximately seven days. Storrie (2005) found that the bipyridyl application could be extended to 14 days with glyphosate-resistant annual ryegrass under good conditions. Longer intervals may be required for broadleaf weeds.

Current research in the northern grain region is determining the interval between knocks for Group M followed by Group L herbicides for a range of problem summer grasses and broadleaf weeds, and for Group A followed by Group L for the grasses, particularly the troublesome *Chloris* species (windmill and feathertop Rhodes grasses). Results to date are indicating that intervals are quite specific for each weed and that the intervals may differ within the same weed for the different first knocks. These are currently being validated (Widderick M, DAFF, Queensland, pers. comm. 2012).

Key practicality #3

Identify the weed species being targeted.

In paddocks free of capeweed, *Erodium* species or black bindweed (*Fallopia convolvulus*), paraquat alone as the second knock gives the most cost-effective result. If any of these species are present paraquat/diquat must be used.

Key practicality #4

Apply the first herbicide when the weeds are most likely to be killed.

Maximum control of annual ryegrass results from applying herbicide at the three- to four-leaf stage. Annual ryegrass sprayed at the zero- to one-leaf stage can potentially regrow from seed reserves (Borger et al. 2003, 2004).

Later application, when the annual ryegrass is tillering, risks an incomplete control by the bipyridyl application. Paraquat and Spray.Seed® are contact herbicides which result in little translocation taking place within the plants. Excellent herbicide coverage, which is difficult to achieve in the case of tillering plants, is needed for success.

Key practicality #5

Double knockdown is more expensive than a single herbicide application.

A double knockdown does not need to be applied every year. Llewellyn et al. (2005) looked at the economics of introducing the double knockdown system (glyphosate followed by paraquat) in two out of three years to prevent glyphosate resistance. They found that this timing resulted in glyphosate resistance in 1.7% of populations over 30 years, which would be economic for growers in high-risk situations such as no-tillage systems.

The higher the cost of weed control after glyphosate resistance has occurred, the longer the break-even period for introducing double knockdown. A paddock risk assessment, involving history of herbicide use and density of weeds to be controlled, should be conducted before using double knockdown.

Key practicality # 6

Seasonal conditions and spraying capacity will influence the scale of on-farm implementation.

Pressure to rapidly establish crops restricts the proportion of the cropping program in which double knockdown can be practically implemented. In addition, the way in which seasons unfold can mean limited pre-sowing weed germinations and thus limited scope to use the double knockdown.

The best option is to select paddocks with the highest target weed populations as these are the highest risk for selecting resistance. It also means that a higher number of individuals will survive the first control operation, requiring follow-up control from the double knockdown.

By reviewing farm herbicide application records, it is possible to identify paddocks where there has been long-term glyphosate use. These paddocks should be targeted first with the double knockdown.

If the tactic is being used to manage difficult to control weeds such as feathertop Rhodes grass, the worst infested paddocks should be targeted first where property size may limit spraying capacity (i.e. where it is physically impossible to cover all of the country in a timely fashion). In summer, feathertop Rhodes grass develops very quickly and timely application is necessary to target pre- to early tillering plants. Also, under hot summer conditions the application window (suitable delta T conditions) for knockdown sprays narrows considerably. Together, these temporal and spatial constraints may limit the use of this very effective tactic.

Contributors

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References

Borger C, Hashem A and Wilkins N 2003. The double knockdown effect on annual ryegrass. *Proceedings of Crop Updates 2003 Weeds*, Perth, pp. 25–26.

Borger C, Hashem A and Wilkins N 2004. Double knockdown herbicides – preserving glyphosate. *Proceedings of Crop Updates 2004 Weeds*, Perth, pp. 34–35.

Borger CP and Hashem A 2007. Evaluating double knockdown technique: sequence, application interval, and annual ryegrass growth stage. *Australian Journal of Agricultural Research*, vol. 58, pp. 265–271.

Llewellyn R, Pannell D and Weersink A 2005. When does the double knockdown strategy pay? *Proceedings of Crop Updates 2005 Weeds*, Perth, pp. 17–18.

Newman P and Adam G 2003. The 'double knock' – how close can we go? *Proceedings of Crop Updates 2003 Weeds*, Perth, pp. 23–24.

Newman P and Adam G 2004. Double knockdown – one day between knocks. *Proceedings of Crop Updates 2004 Weeds*, Perth, pp. 31–33.

Osten V and Spackman G 2011. Managing feathertop Rhodes grass – the CQ experience. *Proceedings of the Grains Research Update – Cropping strategies for 2011*, Goondiwindi, Queensland, p. 93. Grains Research and Development Corporation.

Sabeeney J 2006. Syngenta Crop Protection Trials 1998–2002. Syngenta Spray.Seed® brochure.

Storrie AM 2005. Glyphosate resistant weeds – what's next if you don't make changes now. *Northern Region Crop Updates*. Grains Research and Development Corporation.

Thornby DT, Walker SR and Whish JPM 2008. Modeling to estimate glyphosate resistance risk in barnyard grass in the northern Australian grain region. *Weed management 2008 hot topics in the tropics: 16th Australian Weeds Conference*, Cairns, Queensland, (eds RD van Klinken, VA Osten, FD Panetta and JC Scanlan), pp. 513–515. Queensland Weeds Society.

Werth J, Widderick M, Osten V, Thornby D and Walker S 2008. "Double knock" as a tactic for problematic weeds. Cotton Catchment Communities Report.

Werth J, Walker S, Boucher L and Robinson G 2010. Applying the double knock technique to control *Conyza bonariensis*. *Weed Biology and Management*, vol 10, pp. 1–8.

Widderick M and McLean A 2018. Optimal intervals differ for double knock application of paraquat after glyphosate or haloxyfop for improved control of *Echinochloa colona*, *Chloris virgatra* and *Chloris truncata*. *Crop Protection*, vol. 113, pp. 1–5.

Further reading

Neve PB, Diggle AJ, Smith FP and Powles SB 2003. Simulating evolution of glyphosate resistance in *Lolium rigidum*. II, Past, present and future glyphosate use in Australian cropping. *Weed Research*, vol. 43, pp. 418–427.

Tactic 2.2c Pre-emergent herbicides

Pre-emergent herbicides control weeds at the early stages of the life cycle, between radical (root shoot) emergence from the seed and seedling leaf emergence through the soil.

Of the 19 herbicide MOA groups, 12 are classed as having pre-emergent activity.

Pre-emergent herbicides may also have post-emergent activity through leaf absorption and can be applied to newly emerging weeds. For example, metsulfuron methyl is registered for control of emerged weeds but gives residual control typical of many pre-emergent herbicides. There are also herbicide treatments that are solely applied pre-emergent (e.g. trifluralin).

Benefits

Key benefit #1

The residual activity of a pre-emergent herbicide controls the first few flushes of germinating weeds (cohorts) while the crop or pasture is too small to compete.

The earliest emerged weeds are the most competitive. Therefore, pre-emergent herbicides are ideal tools to prevent yield losses from these 'early season' weeds. The residual activity gives control of a number of cohorts rather than simply those germinating around the time of application.

Ideally, pre-emergent herbicides should be applied either just before or just after sowing the crop or pasture. This maximises the length of time that the crop will be protected by the herbicide during establishment.

Practicalities

Key practicality #1

Good planning is needed to use pre-emergent herbicides as an effective tactic.

There are four main factors to consider when using pre-emergent herbicides.

1. Weed species and density

When deciding to use a pre-emergent herbicide it is important to have a good understanding of the expected weed spectrum. Use paddock history and observations of weed species and densities from at least 12 months before application. Correct identification of the weed species present is vital.

Pre-emergent herbicides are particularly beneficial if high weed densities are expected. Post-emergent herbicides are often unreliable when applied to dense weed populations, as shading and moisture stress from crowding result in reduced control.

Pre-emergent herbicides have the advantage of controlling very small weeds, whereas post-emergent herbicides can be applied to larger, more tolerant or robust plants.

2. Crop or pasture type

The choice of crop or pasture species will determine the herbicide selection. Some crops have few effective post-emergent options. For example, weed control in grain sorghum is strongly reliant on the pre-emergent herbicides atrazine and metolachlor. In chickpeas, faba beans and lentils there are few effective broadleaf post-emergent herbicides available. In these cases it is important to have a plan of attack which is likely to include the use of a pre-emergent herbicide.

Crop competitiveness should also be considered. Chickpeas, lupins and lentils are poor competitors with weeds and rely on pre-emergent herbicides to gain a competitive advantage.

In the northern grain region, approximately 70% of growers use pre-emergence herbicides in both sorghum and chickpea crops but only 20% use pre-emergents in wheat, and double the number (20%) use this herbicide type in summer fallow compared to uses in winter fallow (10%t) (Osten et al. 2007).

3. Soil condition

Soil preparation is a critical first step in the effective use of pre-emergent herbicides. The soil is the storage medium by which pre-emergent herbicides are transferred to weeds.

Soil surfaces that are cloddy or covered in stubble may need some pre-treatment such as light cultivation or burning to prevent 'shading' during application.

Too much black ash from burnt stubble may inactivate the herbicide, and therefore must be dissipated with a light cultivation or rain before herbicide application.

Less soluble herbicides such as simazine need to be mixed with the topsoil for best results. This process, called incorporation, mixes or cultivates the top 3 to 5 cm of soil for uniform distribution of the herbicide in the weed root zone.

Herbicides such as the sulfonylureas and imidazolinones may not need mechanical incorporation as they move into the topsoil with water (rain or irrigation). Some herbicides need to be incorporated to prevent losses from photodegradation (e.g. atrazine) or volatilisation (e.g. trifluralin).

4. Rotation of crop or pasture species

All pre-emergent herbicides persist in the soil to some degree. Consequently, herbicides may carry over into the next cropping period. The time between spraying and safely sowing a specific crop or pasture without residual herbicide effects (the plant-back period) can be as long as 36 months, depending on herbicide, environmental conditions and soil type.

Key practicality #2

Soil characteristics and environmental conditions at the time of application play an important role in the availability, activity and persistence of pre-emergent herbicides.

The factors that affect pre-emergent herbicide activity and persistence are complex. The following nine interacting factors influence the fate of herbicides in the soil:

1. soil texture
2. soil pH
3. organic matter
4. previous herbicide use
5. soil moisture
6. initial application rate
7. soil temperature
8. volatilisation
9. photodegradation.

1. Soil texture

The proportion of clay, silt and sand determines soil texture. Clay particles bind many herbicides to their surfaces, making them less available to plant roots and shoots. Lighter textured soils, such as sandy loams, have lower clay content, making more herbicide available for plant uptake. These soils require lower rates of herbicides than heavy clay soils, which require relatively high rates of herbicide to give the same level of control. Research in Queensland (Walker and Starasts 1996) has shown that different soil types and soil pH affect control of turnip weed (*Rapistrum rugosum*), (*Figure T2.2c–2*).

Soil texture may also affect herbicide persistence. Sandy soils are prone to herbicides being leached away from weed root zones after rain or irrigation. The herbicide may persist below the crop root zone and move towards the surface with the wetting front later in the season, causing crop damage.

Figure T2.2c–1 Effect of simazine residues used in a lupin crop on the following wheat crop.
Photo: Andrew Storrie

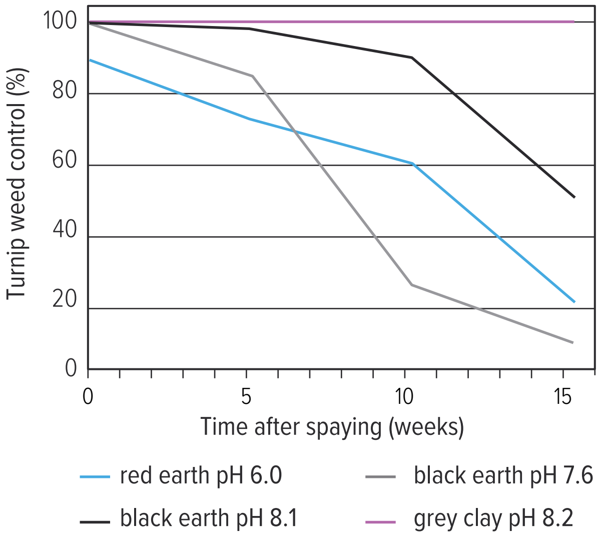


Figure T2.2c–2 Variation in turnip weed control levels with chlorsulfuron is highly dependent on soil type and soil pH (Walker and Starasts 1996).

2. Soil pH

Soil pH plays an important role in the longevity of soil active herbicides. Triazine and sulfonylurea herbicides persist longer in alkaline soils and break down faster in acidic soils (Noy 1996; Walker and Robinson 1996; Walker and Starasts 1996) (*Figure T2.2c–3*), whereas the imidazolinones break down faster in alkaline soils. Plant-back periods for many herbicides vary depending on soil pH.

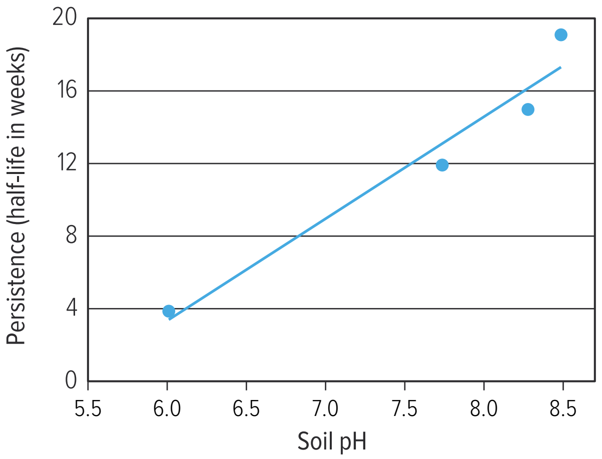


Figure T2.2c–3 Effect of soil pH on the persistence of chlorsulfuron in Queensland soils (Walker and Starasts 1996).

3. Organic matter

Just as clay particles can render herbicides unavailable for plants, organic matter can act in a similar way. Binding of herbicides is caused by the attraction between negative ionic charges on the organic colloids in organic matter and positively charged herbicide particles. The bound herbicides are then either released with the breakdown of the organic matter or degraded by micro-organisms on the colloid. Soils high in organic matter also contain more micro-organisms, increasing the herbicide degradation rate. Most Australian soils have low organic matter levels; however, the high use of organic amendments (e.g. poultry manure, biosolids) may cause rapid increases in the soil organic matter.

Retained stubble may also affect the soil–herbicide contact by limiting the amount of herbicide reaching the soil; however, research has shown that most herbicides will wash off crop residue with 5 mm of rain (Shaner 2013). This interception of herbicide by crop residue increases the time for herbicide loss through volatilisation and breakdown by ultraviolet light. Trifluralin binds strongly to crop residues and is lost through volatilisation.

4. Previous herbicide use

Microbes also break down herbicide in the soil. Soils with a history of use of a particular herbicide are expected to have a higher microbial activity and to break down faster compared to soils with no history of use. Specific microbes that break down active ingredients build up after more frequent use of pre-emergent herbicides (e.g. atrazine, propyzamide) (Rattray et al. 2007) and Group I herbicides such as 2,4-D.

5. Soil moisture

Figure T2.2c–5 provides a diagrammatic representation of the effect of dry soil conditions on the uptake of herbicide through the roots. In the left-hand diagram herbicide molecules are bound to the soil particle in the surrounding thin film. An aqueous bridge is required between the soil particle and the root for the herbicide molecules to move towards the root for uptake (as seen in the right-hand diagram).

In contrast, moist soil conditions can speed up herbicide breakdown, shortening the time interval in which the herbicide is available. Moisture levels at or close to field capacity increase microbial activity and thus increase the chemical degradation rate. Also, some herbicides are degraded by hydrolysis, where water and the active ingredient react to create two new compounds. Triazines and sulfonylurea herbicides are frequently degraded by hydrolysis and break down faster in moist soils than in dry soils.

6. Initial application rate

The half-life of a herbicide is the time taken for half of the herbicide to degrade. The herbicide breakdown rate is independent of the initial quantity applied. For example, if the half-life of a herbicide is assumed to be 6 months and 1 kg/ha is applied, 500 g/ha will be available after 6 months. If 2 kg/ha is applied then 1 kg/ha will remain after the same time. Therefore, the greater the quantity of herbicide applied and the higher the application rate, the greater the quantity that will remain at any particular time.

The Grazon® Extra label reflects the increase in plant-back period for increasing rates. Other labels also infer this rate effect. For example, trifluralin should be used at a lower rate if applied just before sowing, whereas a higher rate can be used if applied before planting rain. Most pre-emergent herbicide labels do not state a shorter plant-back period for lower rates.

7. Soil temperature

Many studies have shown that higher soil temperatures result in faster breakdown of pre-emergent herbicides. The rate of most chemical reactions speeds up with increasing temperatures. Microbial activity also increases to specific levels at higher temperatures, dependent on the micro-organisms present. Walker and Starasts (1996) showed that, compared to southern Australia, the higher temperatures experienced in southern and central Queensland led to more rapid breakdown of sulfonylurea herbicides (*Figure T2.2c–4*). Re-cropping experiments in central and southern Queensland showed that temperature had the greatest influence on sulfonylurea herbicide (metsulfuron methyl, chlorsulfuron and triasulfuron) dissipation and that only small quantities of rain (approximately 80 mm) over the summer were required to degrade the herbicides to non-injurious levels (Osten and Walker 1998).

8. Volatilisation

Herbicides such as triallate, trifluralin and pendimethalin are volatile and must be incorporated to remain active. The herbicide vapour is trapped between soil particles and aggregates after incorporation, preventing volatilisation.

9. Photodegradation

Many herbicides (e.g. atrazine) are subject to degradation by the action of ultraviolet light. They rely on mechanical incorporation or movement with water to prevent inactivation.

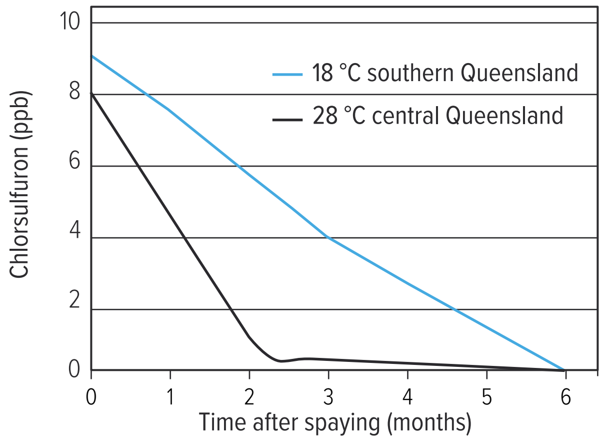
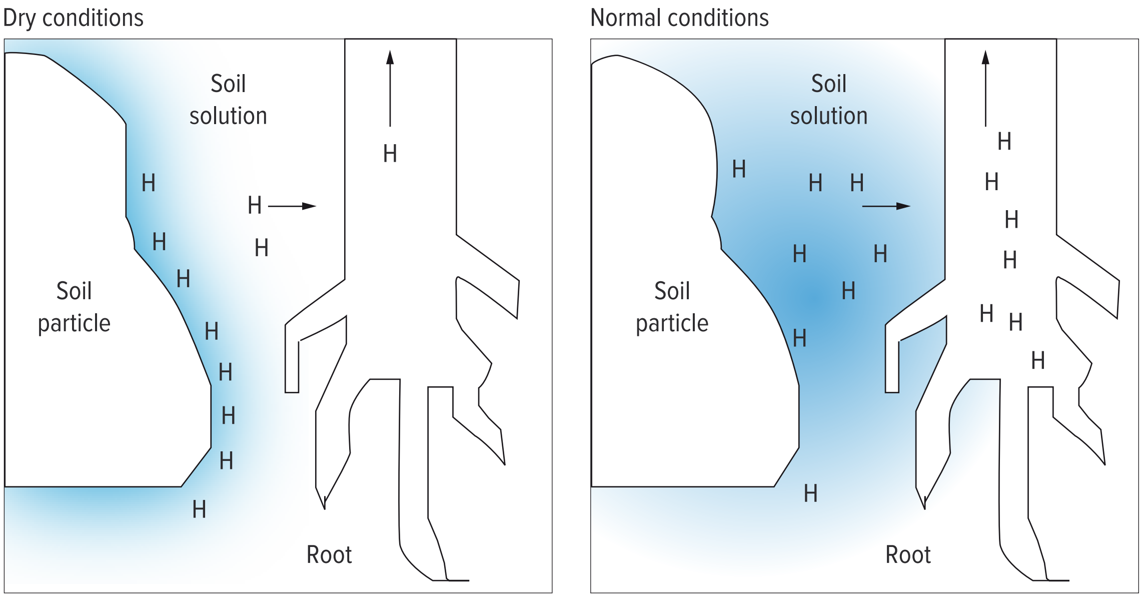


Figure T2.2c–4 Effect of soil temperature on persistence of chlorsulfuron in Queensland (Walker and Starasts 1996).



Note: H = herbicide.

Figure T2.2c–5 Diagrammatic representation of the effect of soil moisture conditions on uptake of herbicide through the roots, contrasting dry soil conditions and normal soil conditions (Cameron 2005).

Key practicality #3

Both the positive and negative aspects of using pre-emergent herbicides should be considered in the planning phase (*Table T2.2c–1*).

Table T2.2c–1 Positive and negative aspects of using pre-emergent herbicides.

Positive	Negative
Relatively inexpensive	Unpredictable efficacy, strongly dependent on soil moisture
Optimises crop yield through control of early weed germinations	Because weeds are not yet visible, must have paddock histories and knowledge of previous weeds and weed seedbank
Different modes of action to most post-emergent herbicides	Plant-back periods limit crop rotation
Timing of operation – generally have a wide window of opportunity for application options which can be used to prevent or manage herbicide resistance	Crop damage if sown too shallow or excessive quantities of herbicide move into root zone
Best option for some crops (e.g. sorghum and pulse crops are reliant on good pre-emergent control)	Seedbed preparation – soil may need cultivation and herbicide may need incorporation, which can lead to erosion, soil structural decline and loss of sowing moisture
Effective on some weeds that are hard to control with post-emergent herbicides (e.g. wireweed and black bindweed)	Not suitable when dense plant residues or cloddy soils are present
Extended period of control of multiple cohorts (6–8 weeks); good for weeds with multiple germination times	Varying soil types and soil moisture across paddock can be reflected in variable results

Contributors

Tony Cook, Vikki Osten and Andrew Storrie

References

Congreve M, and Cameron J (eds) 2015. *Soil behaviour of pre-emergent herbicides in Australian farming systems. A reference manual for agronomic advisors*. GRDC publication, Australia.

Noy DM 1996. Persistence of sulfonylureas on alkaline soils in south-eastern Australia and the potential damage to subsequent crops and pastures. *Where in the world is weed science going?: 11th Australian Weeds Conference*, Melbourne, Victoria, (ed RCH Shepherd), pp. 42–44. Weed Science Society of Victoria.

Osten VA and Walker SR 1998. Recropping intervals for the sulfonylurea herbicides are short in the semi-arid subtropics of Australia. *Australian Journal of Experimental Agriculture*, vol. 38, pp. 71–76.

Osten VA, Walker SR, Storrie A, Widderick M, Moylan P, Robinson GR and Galea K 2007. Survey of weed flora and management practices relative to cropping practices in the north-eastern grain region of Australia. *Australian Journal of Experimental Agriculture*, vol. 47, pp. 57–70.

Rattray DJ, Standley J, Silburn DM, Freebairn DM and Spann KP 2007. Atrazine degradation and transport in runoff on a Black Vertosol. *Soil Research*, vol. 45, pp. 598–606.

Somerville GJ, Powles SB, Walsh MJ and Renton M 2016. 2017. Why was resistance to shorter-acting pre-emergence herbicides slower to evolve? *Pest Management Science*, vol. 73, pp. 844-851.

Shaner D 2013. Interactions of herbicides with crop residue. *Proceedings of Northern Crop Updates*. Grains Research and Development Corporation, Goondiwindi, Queensland.

Walker SR and Robinson GR 1996. Chlorsulfuron residues are not accumulating in the soils of southern Queensland. *Australian Journal of Experimental Agriculture*, vol. 36, pp. 223–228.

Walker S and Starasts A 1996. Soil pH and temperature influence herbicide breakdown in Queensland soils. *South Queensland Farmer*, vol. 2, pp. 6–7.

Further reading

Hollaway K, Noy D and Wilhelm N 2002. Persistence of ALS inhibiting (Group B) herbicides in alkaline soils of south-eastern Australia. *Weeds 'threats now and forever': 13th Australian Weeds Conference*, Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 329–332, Plant Protection Society of WA.

Popov VH, Cornish PS, Sultana K and Morris EC 2005. Atrazine degradation in soils: the role of microbial communities, atrazine application rate and soil carbon. *Australian Journal of Soil Research*, vol. 43, pp. 861–871.

Walker SR, Barnes JE, Osten VA, Churchett JD and McCosker M 2000. Crop responses to sulfonylurea residues in soils of the subtropical grain region of Australia. *Australian Journal of Agricultural Research*, vol. 51, pp. 587–596.

Tactic 2.2d Selective post-emergent herbicides

Selective post-emergent herbicides control weeds that have emerged since crop or pasture establishment and can be applied with little damage over the top of a crop or pasture.

The first selective post-emergents to be developed were the Group I MOA herbicides and the first 'modern' herbicide, 2,4-D, became commercially available around 1945. Western industrialised agriculture changed with the release of Group A and B herbicides in the late 1970s.

Selective post-emergent herbicides belong to herbicide MOA Groups A (e.g. diclofop), B (e.g. metsulfuron), C (e.g. diuron), F (e.g. diflufenican), G (e.g. carfentrazone), I (e.g. 2,4-D, dicamba, picloram), J (e.g. flupropanate), R (e.g. asulam) and Z (e.g. flamprop). Some predominantly pre-emergent herbicides also have registrations for some selective post-emergence activity, e.g. dithiopyr (Group D) and chlorpropham (Group E).

There have been no new MOA groups released for nearly 25 years, and it is unlikely that any additional groups will be released in the foreseeable future.

Benefits

Key benefit #1

Post-emergent herbicides give high levels of target weed control with the additional benefit of improved crop or pasture yield.

Selective post-emergent herbicides give high levels of control (often greater than 98%) when applied under recommended conditions. When used early in crop development selective post-emergents also result in optimum yield and significant economic returns.

Post-emergent herbicides are often more reliable than pre-emergent herbicides. This is particularly true under low rainfall conditions, as pre-emergent herbicides rely on moist soil conditions to achieve high levels of weed control.

Early removal of grass weeds (e.g. annual ryegrass and wild oats) reduces competition with the crop for resources. McNamara (1976) found that the later the time at which wild oats (*Avena* spp.) were removed from a wheat crop, the higher the resultant yield loss (*Figure T2.2d–1*). Crop yield benefited most dramatically when wild oats were removed from the paddock in the earlier stages (two to three leaves) of crop development. Delaying control of wild oats until the flag leaf stage of the wheat crop was found to be not much more effective than a zero weed control treatment.

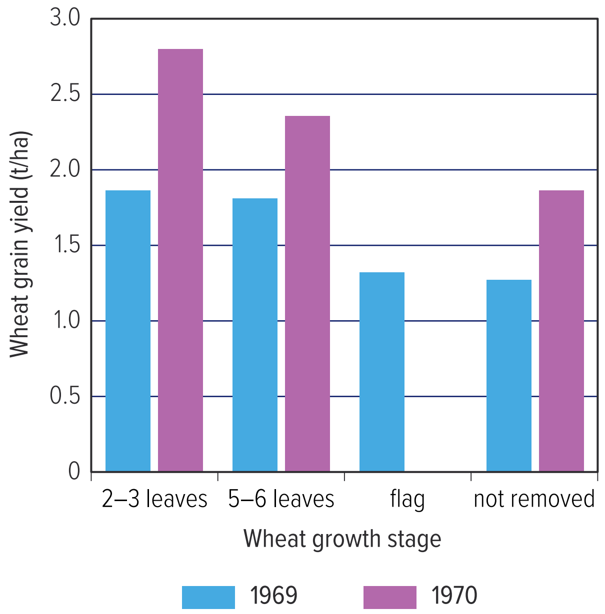


Figure T2.2d–1 Effect of time of removal of wild oats (using selective post-emergent herbicide) on wheat (cv Gamut) yield over two years at Tamworth, northern New South Wales (McNamara 1976).

Figure T2.2d–2 Post emergent herbicides being sprayed on a wheat crop, Cummins, SA.
Photo: Andrew Storrie

Key benefit #2

Observations made just before application allow fine-tuning of herbicide selection to match target weeds present in the paddock.

Unlike pre-emergent herbicides, post-emergent herbicides are applied after the weeds have emerged. This allows flexibility in choosing the best herbicide, or combination of herbicides, to control the particular suite of weeds in the crop and identification of the most appropriate application rate. It is important that the weeds are identified correctly to ensure that the correct herbicide is selected.

Key benefit #3

Application timing can be flexible to suit weed size, crop growth stage and environmental conditions.

Dry conditions following sowing often delay weed emergence. Post-emergent herbicides can be applied after the majority of weeds have emerged, at a time when they are most susceptible to the herbicide being applied.

Many post-emergent herbicides (e.g. bromoxynil and metsulfuron on wheat) have a long application-timing window due to a wide margin of crop safety, allowing flexibility in farm management.

Key benefit #4

Some post-emergent herbicides have pre-emergent activity on subsequent weed germinations.

Depending on the application rate, some post-emergent herbicides have some pre-emergent or residual activity on susceptible weeds, thus extending the period of weed control. This is particularly the case with some Group B MOA herbicides (e.g. metsulfuron methyl) and Group I MOA herbicides such as 2,4-D and dicamba.

Often this is related to the application rate: the higher the rate, the longer the residual effect. Additionally, soil moisture, organic matter, clay content, temperature, pH and microbial activity can greatly influence the longevity or availability of these herbicides in the soil.

Practicalities

Key practicality #1

Use careful consideration when selecting the best post-emergent herbicide to use in any one situation.

When choosing a selective post-emergent herbicide for a particular situation, consider the following factors:

- target weed species and growth stage
- herbicide resistance status of target weeds
- crop safety (variety, environmental conditions, effect of previously applied herbicide on crop)
- grazing and harvest withholding periods and plant-back periods (minimum recropping intervals after application)
- cost
- spray drift risk
- mix partners
- crop rotation and the effect of residual herbicides.

Unfortunately, herbicide cost often becomes the second consideration after target species to be controlled, but the cheaper treatments can be associated with poor control, unsuitable residues and crop damage.

For example, for post-emergent control of black bindweed (*Fallopia convolvulus*) in wheat, the most effective herbicides are bromoxynil, fluroxypyr and Tordon® 242. However, these will cost around $15/ha for an effective rate. Many growers consider this too expensive and will use chlorsulfuron or metsulfuron + MCPA costing about $9/ha, but these mixes give only 50 to 70% control of black bindweed.

Key practicality #2

Applying post-emergent herbicides to stressed crops and weeds can result in reduced levels of weed control and increased crop damage.

Environmental conditions before spraying influence the absorption ability of foliar herbicides due to the effects they have on leaf structure (Gerber et al. 1983). Hot and dry conditions increase the waxiness of leaves, thereby reducing herbicide absorption. Plants exposed to any kind of stress will have lower rates of translocation and the herbicide will take more time to reach sites of action.

Crops that are normally tolerant can be damaged when stressed due to waterlogging, frost or dry conditions because they cannot produce sufficient levels of the enzymes that normally break down the herbicide into harmless compounds.

Key practicality #3

Crop competition is important for effective weed control using selective post-emergent herbicides.

Good crop competition improves the efficacy of post-emergent herbicides. Marley and Robinson (1990) found that barley was more competitive than wheat against black bindweed and turnip weed (*Rapistrum rugosum*) and that higher crop populations improved the effectiveness of herbicides against these species (*Figure T2.2d–3*).

In a study by Walker et al. (1998) on the effect of crop type and herbicide rate on paradoxa grass (*Phalaris paradoxa*) seedset, it was shown that barley was more competitive than wheat at all herbicide rates (*Figure T2.2d–4*).

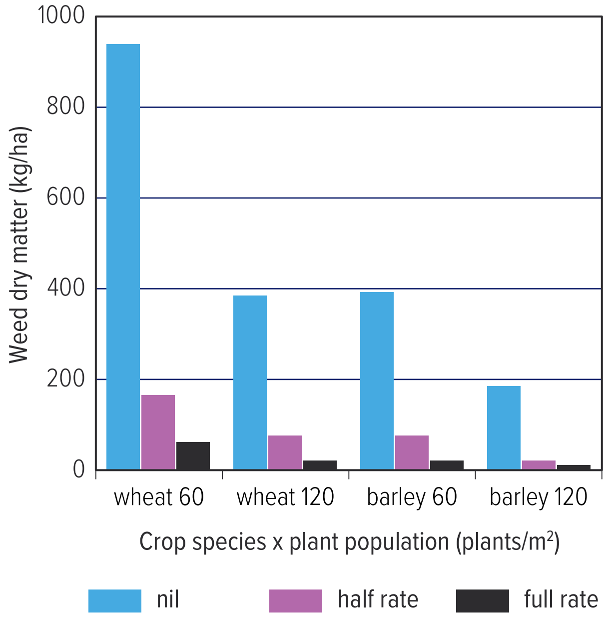


Figure T2.2d–3 Effect of wheat and barley population and herbicide rate on the dry matter production of turnip weed and black bindweed at crop anthesis (Marley and Robinson 1990).

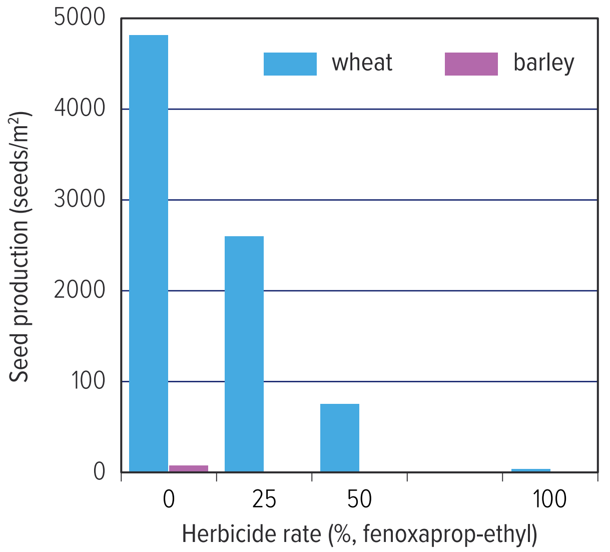


Figure T2.2d–4 Effect of crop type and herbicide rate on paradoxa grass seed production (Walker et al. 1998).

Key practicality #4

The technique used for applying selective post-emergent herbicides must be suited to the situation in order to optimise control.

When using selective post-emergent herbicides it is important to use the correct application technique, paying particular attention to:

- equipment (nozzles, pressure, droplet size, mixing in the tank, boom height, ground speed) to maximise the efficiency of herbicide application to the target
- meteorological conditions. Suitable conditions are indicated by Delta T <8 °C when air movement is neither excessively windy nor still (Delta T is an indication of evaporation rate and droplet lifetime and is calculated by subtracting the wet bulb temperature from the dry bulb temperature).

Spraying should be done when temperatures are less than 28 °C. *Figure T2.2d–5* shows the effect of temperature on spray coverage. Only 60% of the applied herbicide reaches the target when the air temperature is 32 °C (Hughes 2004).

See 'Further reading' for more detailed information.

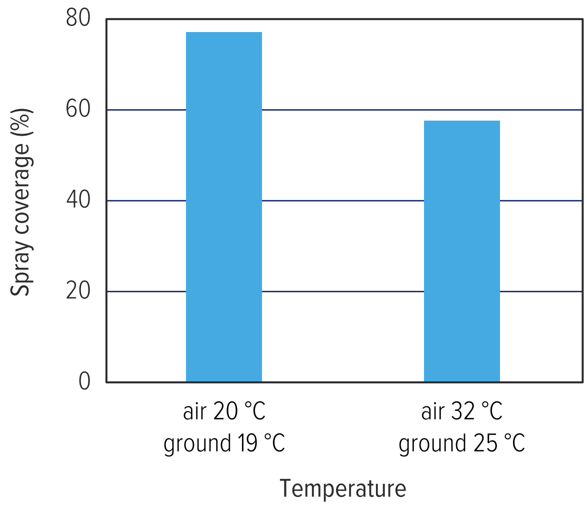


Figure T2.2d–5 Effect of air temperature on spray coverage (Hughes 2004).

Key practicality #5

Always use the correct adjuvant to ensure effective weed control.

Use the adjuvant recommended on the herbicide label to get the best performance from the herbicide being applied. Because plants have different leaf surfaces, an adjuvant may be needed to assist with herbicide uptake and leaf coverage. Adjuvants can also increase performance lowered by pH, hard water, compatibility, rainfastness or drift. Hazen 2000 and Somervaille et al. 2012, listed under 'Further reading' provide more detailed information on adjuvants.

Work conducted by Storrie and Cook (2004) on the control of lucerne for fallow commencement showed significant differences between adjuvants on the efficacy of 2,4-D amine (*Figure T2.2d–6*). One adjuvant reduced weed control while others gave varying levels of weed control greater than using 2,4-D amine alone (i.e. nil treatment). The rate of 2,4-D applied was half that recommended for the control of lucerne.

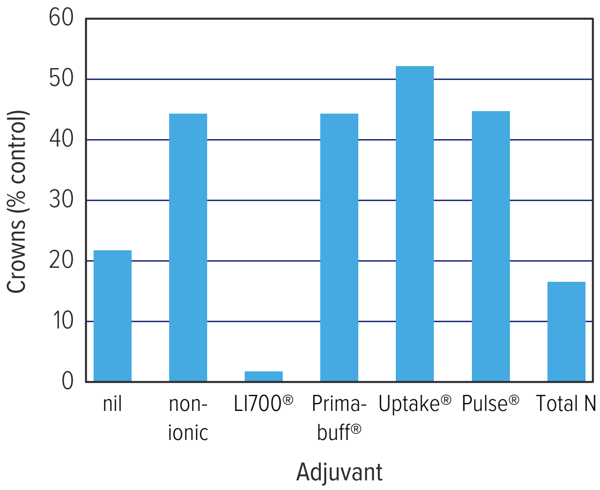


Figure T2.2d–6 Effect of different adjuvants on the control of lucerne by a sublethal rate of 2,4 D d.m.a. (Storrie and Cook 2004).

Figure T2.2d–7 Upper surface of capeweed showing trichomes.

Photo: Andrew Storrie

Figure T2.2d–8 Lower surface of capeweed showing trichomes.

Photo: Andrew Storrie

Figure T2.2d–9 Droplet of rainwater left compared with rainwater with 0.1% non-ionic surfactant on a waxy leaf (Nasturtium) showing the need for effective adjuvants on plants with waxy cuticles.

Photo: Andrew Storrie

Key practicality #6

Selective post-emergent herbicides applied early and used as a stand-alone tactic have little impact on weed seedbanks.

Early post-emergent herbicide application aims to maximise yield by removing weed competition in crop establishment stages. Any weed that germinates after, or survives, this application will set seed that will return to the seedbank, thus maintaining weed seedbank numbers and ensuring continuation of the weed problem.

Work through the 1990s by Cook (1998) and others showed that by preventing seedset of wild oats, the seedbank and therefore the problem can be run down to very low levels in three to five years.

As shown in *Table T2.2d–1*, stopping the seedset each year with post-emergent herbicides and a selective spray-topping leads to a 96% decline in the seedbank over five years, compared to using post-emergent herbicides alone, which resulted in only a 40% decrease in wild oat seedbank numbers.

In this experiment initial seedbank numbers were high (approximately 1,600 seeds/m^2). The 'post-emergent herbicide alone' treatment would have reduced the number of seeds to 960/m^2, an unsatisfactorily high density, and seedbank decline would have stabilised at this point. By contrast, the 'post-emergent and selective spray-topping' treatment reduced seedbank numbers to 64 seeds/m^2, with a strong indication for continued seedbank decline after the experiment had been completed.

Table T2.2d–1 Effect of annual applications of different herbicide treatments on wild oat seedbank numbers after five years (Cook 1998).

Herbicide treatment	Percentage change in wild oat numbers over five years
Pre-emergent alone	+15
Post-emergent alone	−40
Post-emergent + selective spray topping	−96

Notes: Pre-emergent – Avadex® BW @ 2.1 L/ha; Post-emergent – Puma® S (fenoxaprop) @ 500 mL/ha; Selective spray-topping – Mataven® L @ 3 L/ha

Key practicality #7

Choose the most suitable herbicide formulation for each particular situation.

The correct herbicide formulation needs to be chosen to take into account efficacy, compatibility and drift. For example, although 2,4-D ester is compatible with most other herbicides and is very efficacious, it should not be used near susceptible crops during summer. In Queensland, use of 2,4-D ester formulations requires a special permit since most broadacre cropping areas sit within defined hazardous zones (Biosecurity Queensland, DAFF).

Weak acid herbicides (e.g. glyphosate) are affected by hard water containing high levels of soluble salts such as calcium and magnesium. If better quality water is not available for use, an ester or suspension concentrate formulation should be substituted.

Key practicality #8

Selective post-emergent herbicide effectiveness is influenced by a range of plant and environmental factors.

Inactivation of herbicides can occur due to:

- leaf and cuticle structure
- dust particles
- rainfall
- dew.

Key practicality #9

Match herbicide mode-of-action (MOA) to its use.

It is important to match the herbicide MOA to its intended use. For example, when considering weed size, if weeds are large a herbicide that is poorly translocated (e.g. a bipyridyl) or only upwardly translocated (e.g. atrazine) will be a poor choice. Glyphosate, a fully systemic herbicide, is a better choice for larger weeds.

Droplet coverage and water quality are also important considerations when choosing a herbicide.

Figure T2.2d–10 Spraying post-emergent herbicides on lupins, Ouyen, Victoria.
Photo: Andrew Storrie

Key practicality #10

Avoid spray drift

It is important to reduce spray drift potential to protect human health, the environment, and other off-target damage. Spray quality, boom height, spraying speed and tank mix can all impact drift potential. Careful planning can help manage other factors that spray operators must consider such as weather conditions, spray timing and sensitive crops in the surrounding area. GRDC and the Australian Pesticides and Veterinary Medicines Authority (APVMA) have comprehensive resources for addressing spray drift management

Contributors

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References

Congreve M 2017. Understanding post-emergent graminicides. *Workshop manual*. GRDC, Australia.

Cook AS 1998. Reducing seed production using late post-emergence applications of selective herbicides to manage wild oats (*Avena* spp.) populations. *Master of Rural Science thesis*, University of New England, New South Wales.

Gerber HR, Nyffeler A and Green DH 1983. The influence of rainfall, temperature, humidity and light on soil and foliage-applied herbicides. *Aspects of Applied Biology*, vol. 4, pp. 1–14.

Gordon B 2012. Implications for nozzle selection and spray quality from recent trial results. *Summer fallow spraying fact sheet*. Grains Research and Development Corporation, Canberra, ACT.

Hughes P 2004. Spray right – reduce drift. *Extension note*. Queensland Department of Primary Industries and Fisheries.

McNamara DW 1976. Wild oat density and the duration of wild oat competition as it influences wheat growth and yield. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 16, pp. 403–406.

Marley JM and Robinson GR 1990. Strategies for Broadleaf Weed Control in Wheat. *Final report*. Barley Research Committee for Queensland.

Storrie AM and Cook AS 2004. Lucerne – a perennial weed problem now solved. *Proceedings of 4th International Weed Science Congress*, Durban, South Africa, June 2004. (Poster).

Walker SR, Robinson GR and Medd RW 1998. Management of wild oats and paradoxa grass with reduced dependence on herbicides. *Proceedings of the 9th Australian Agronomy Conference*, Wagga Wagga, New South Wales, pp. 572–574.

GRDC Spray water quality fact sheet 2019. Ed. Bill Gordon, Graham Betts, April 2019

Madafiglio G, Medd R and Cornish P 1999. Selective spray-topping, a new technique for controlling broadleaf weeds in cereals. *Weed management into the 21st Century : do we know where we're going?: 12th Australian Weeds Conference*, Hobart, Tasmania (eds AC Bishop, M Boersma and CD Barnes), pp. 269–272, Tasmanian Weed Society.

Robinson T 2011. Growers given a spray. *Farming Ahead*, vol. 238, pp. 46–47.

Somervaille A, Betts G, Gordon B, Green V, Burgis M and Henderson R 2012. *Adjuvants – Oils, surfactants and other additives for farm chemicals*. Revised 2012 edition. Grains Research and Development Corporation, Kingston, Australian Capital Territory.

Tepper G 2012. *Weather essentials for pesticide application*. Grains Research and Development Corporation, Kingston, Australian Capital Territory.

Tepper G and Gordon B 2012. Surface temperature inversions and spraying. *Fact Sheet*. Grains Research & Development Corporation, Kingston, Australian Capital Territory.

Wolf TM, Harrison SK, Hall FR and Cooper J 2000. Optimising post-emergence herbicide deposition and efficacy through application variables in no-till systems. *Weed Science*, vol 48, pp. 761–768.

Further reading

GRDC

Spray application manual - https://grdc.com.au/spray-application-manual

Fact sheets

- Maintaining efficacy with larger droplets - New 2,4-D application requirements
- Pulse width modulation sprayers (correct operation)
- Spray water quality
- Spraying efficiency

APVMA

Spray drift management website
https://apvma.gov.au/node/10796

APVMA permit website: https://portal.apvma.gov.au/permits.

Hazen JL 2000. Adjuvants: Technology, classification and chemistry. *Weed Technology*, vol. 14, pp. 773–784.

General

Kondinin Group 2012. Nozzles: Agriculture's tiny achievers – What's new in nozzle technology (Bill Gordon); Nozzle efficacy trials show performance (Bill Gordon); Clean nozzles for superior spray (Josh Glumelli). *Research Report No. 29*, June 2012. Kondinin Group, Western Australia.

GRDC; GrowNotes. Spray Application Manual 2017. Ed. Bill Gordon, February 2017.

Tactic 2.3 Weed control in wide-row cropping

In northern NSW and Queensland wide-row cropping has been used for some years as a way to improve yield reliability in grain sorghum production. Wide rows are also used in wheat and chickpea cropping in central Queensland to improve stubble handling and moisture seeking abilities of sowing operations (Reid et al. 2004).

Glossary

Wide rows – crop rows which are 50 cm and wider

Inter-row – the strip of soil between the crop rows

Crop-row – the strip of soil taken up by the crop

Shielded spraying – the practice in which shields are used to protect the crop rows while weeds in the inter-row area are sprayed with a non-selective herbicide (see *Tactic 2.3a Inter-row shielded spraying and crop-row band spraying*)

Band spraying – the practice in which a given area (band) of selective herbicide is applied to weeds in either the crop row or inter-row (see *Tactic 2.3a Inter-row shielded spraying and crop-row band spraying*) only

Inter-row cultivation – the practice in which weeds in the inter-row space are controlled using tillage equipment (see *Tactic 2.3b Inter-row cultivation*).

Wide-row cropping has also been widely adopted in Western Australia as a strategy to overcome herbicide-resistant wild radish (*Raphanus raphanistrum*) and, to a lesser extent, annual ryegrass (*Lolium rigidum*).

In response to escalating herbicide resistance and to maintain cropping programs, growers and researchers are developing shielded spraying tactics for wide-row winter crops. This tactic uses non-selective (knockdown) herbicides to control weeds in the inter-row space of the crop. In some circumstances inter-row cultivation may be applicable.

Inter-row cultivation, band spraying and, to a lesser extent, shielded spraying are not new techniques. The innovation is to use them in winter growing broadacre crops.

Pulse crops have been the initial driver and subsequent emphasis for much of the wide-row research aimed at herbicide resistance management across Australia. The wide-row planting configuration has a distinct advantage, particularly when using non-selective herbicides for inter-row weed control. Using the tactic in only one part of the crop rotation avoids excessive use of the knockdown herbicide, thus reducing the risk of herbicide resistance development.

Research has indicated that weeds (e.g. annual ryegrass) in the crop-row space can be problematic even when the inter-row weeds have been controlled. Depending on the weeds present and their herbicide resistance status, selective herbicides can be band sprayed over the rows, targeting the crop-row weeds. Overseas research is currently addressing innovative mechanical treatment of crop-row weeds through the development of 'intelligent' weeders that use advanced sensing and robotics (Van der Weide et al. 2008).

A recent comprehensive review of weed management in wide-row cropping systems (Peltzer et al. 2009) identified some potential risks in Australian farming systems with continual herbicide use and tillage on the inter-row zone. These risks include herbicide resistance, species and/or dominance shifts, crop damage, increased costs, yield reductions and more expensive weed management technology.

Figure T2.3–1 Inter-row shielded spraying in sorghum

Benefits

Key benefit #1

Increasing row spacing allows improved weed control while maintaining or improving crop yield.

Weed management benefits, particularly for herbicide-resistant weeds, outweigh the minor risk of crop yield loss when using wide-row cropping. Research to evaluate the impact of increasing row spacing in pulses and other winter crops in the absence of weeds has been conducted across Australia. Reduction in yield was found to be negligible. Despite these widespread research results, wide-row cropping had not yet been widely adopted in the farming community up to the late 1990s, particularly in the low to medium rainfall areas (Gill and Holmes 1997). However, summer crops such as sorghum, sunflower, cotton, mung bean and soy bean have been grown on rows at least 1 m wide or in skip-row configurations. Wide row spacings have become more common as the adoption of conservation tillage has increased (Peltzer et al. 2009).

As shown in *Table T2.3–1*, the yield of two chickpea cultivars in central western NSW was not affected when row space was increased from 17 cm to 65 cm (Fettell 1998). This experiment also investigated the effect of sowing rate on row spacing and yield. Fettell found that there was no difference in yield with different sowing rates (recommended sowing rate and 30% above and below recommended) and also no interaction between sowing rate and row spacing on yield. Sowing rate could therefore be ruled out as a factor affecting yield.

Table T2.3–1 Impact of row spacing on the yield of two chickpea varieties at Condobolin, NSW (Fettell 1998).

Row spacing (cm)	Yield (t/ha)	
	Amethyst	Kaniva
17.5	1.2	0.9
26	1.4	1.2
35	1.2	1.0
50	1.4	1.2
65	1.1	0.9

Widderick (2002) investigated the effect of plant population and row spacing on the dry matter production of sowthistle (*Sonchus* spp.) and found that at a narrow row spacing of 25 cm dry matter production was minimal. As row spacing was doubled to 50 cm sowthistle dry matter production increased. As the density of wheat was increased in the wide rows sowthistle dry matter production decreased (*Figure T2.3–2*).

Felton et al. 2004 studied the impact of row spacing, in the absence of weeds, over a three-year period in wheat, canola, faba bean and chickpea at Tamworth, NSW. In that environment, increasing the row spacing from 32 cm to 64 cm had very little effect on crop yield (*Table T2.3–2*).

Figure T2.3–2 The effect of plant population and row spacing on the dry matter production of sowthistle (Widderick 2002).

In a similar study at Mullewa, Western Australia, Riethmuller and McLeod (2001) showed that there was no impact on the yield of chickpea (cultivar Sona) by increasing the row spacing from 19 cm to 76 cm. Similarly, work at Wagga Wagga, NSW (Lemerle et al. 2002), showed a relatively small impact of wider rows on field pea yield (cultivar Excell) despite higher annual ryegrass numbers in July at the narrow row spacing (*Table T2.3–3*).

Table T2.3–2 The effect of crop row spacing on grain yield (t/ha) at Tamworth, New South Wales, over 3 years (Felton et al 2004).

Crop	Grain yield (t/ha)					
	2001		2002		2003	
Row spacing (cm)	32	64	32	64	32	64
Wheat	3.6	3.6	2.8	2.2	4.4	4.0
Canola	1.9	2.0	1.1	1.1	2.3	2.5
Chickpea	3.0	3.2	2.2	2.1	4.1	3.9
Faba bean	2.3	2.8	1.6	1.9	4.5	4.2

Table T2.3–3 Effect of two row spacings on annual ryegrass density and field pea (cv Excell) yield at Wagga Wagga, NSW (Lemerle et al. 2002).

Row spacing (cm)	Annual ryegrass in July (plants/m²)	Field pea yield (t/ha)
23	98	2.5
46	57	2.3

In Western Australia Jarvis (1992) found an average lupin yield increase of 3.6% in wide rows (36 cm) compared to standard rows (18 cm) across a range of environments.

Key benefit #2

Cropping in wide rows enables the use of shielded inter-row herbicide application, crop-row band spraying and inter-row cultivation for in-crop weed control.

Selecting the most appropriate tactic allows cropping rotations to continue, even where resistance to some herbicide MOAs has already evolved. *Tactic 2.3a* in the following section has more information and data relevant to this key benefit.

Whole-farm benefits

Additional benefits from using wide rows include the following:

- Wide-row cropping enables increased quantities of crop residues to be retained, thus reducing the potential for erosion and improving soil characteristics.
- Wide-row cropping enables easier sowing into retained crop residues.
- There is an option to use smaller tractors with less tynes per sowing width, thus reducing costs.
- Wide rows can reduce crop foliar fungal disease incidence by allowing better airflow within the crop canopy.
- Wide rows work well with tramlining and controlled traffic farming, adding benefits associated with reduced soil compaction and more accurate and timely application of inputs.
- Wide-row cropping provides opportunities for precision fertiliser placement such as side dressing.

Practicalities

Key practicality #1

Reduced competition from the crop can result in lower yield potential if weeds are not controlled.

Crop competitive ability will reduce as row spacing increases and crop density falls. Minkey et al. (2000) reported that in wheat, in the absence of selective herbicide, the total number of annual ryegrass seed-heads was reduced as row spaces were narrowed and crop density increased. Therefore, at increased row spacing the need for weed control by herbicide or mechanical means is also increased.

Due to slow canopy closure of the crop, weed management timing and effectiveness becomes critical to prevent yield loss and reduce the impact of weeds.

The competitiveness of wide-row sorghum and sunflower also reduces as row spacing widens, resulting in increased weed growth and seed production. In the absence of weed control in low weed densities, sunflowers grown on 1 m row spacing can have 11% yield loss (Osten et al. 2006).

Key practicality #2

A change to wide rows will require modifications to sowing equipment, a complete change in equipment or use of a contractor.

Although excellent specialised row-planting equipment is available, wide rows may be sown using modified air-seeders and combines.

In central Queensland, many growers also made the move to wide-row winter crops to reduce the capital outlay on zero till planting equipment. It was deemed more cost-effective to modify existing summer crop planters (with 1 or 1.5 m row set-ups) to sow winter crops on 0.5 m rows than to purchase separate planting equipment for the winter opportunities (Reid et al. 2004).

Key practicality #3

Precision farming technologies fit well with wide rows for weed management.

Technologies such as GPS guidance and controlled traffic farming easily fit with wide-row cropping and weed management.

Contributors

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References

Felton W, Haigh B and Harden S 2004. Comparing weed competition in chickpea, fababean, canola and wheat. *Weed management - balancing people, planet, profit: 14th Australian Weeds Conference*, Wagga Wagga, New South Wales, (eds BM Sindel and SB Johnson), pp. 304–307, Weed Society of NSW.

Fettell N 1998. Pulse crops for central western NSW. *Central West Farming Systems Research Compendium*, pp. 16–18.

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Jarvis RJ 1992. Lupin row spacing. *Technote No. 2/92*. Western Australian Department of Agriculture.

Lemerle D, Sutherland S, Koetz E and Smith A 2002. Suppressing weeds in conservation farming. *Weeds 'threats now and forever': 13th Australian Weeds Conference*, Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 705–708, Plant Protection Society of WA.

Minkey D, Hashem A, Riethmuller G and Harries M 2000. Effect of seeding density, row spacing and trifluralin on the competitive ability of annual ryegrass in a minimum tillage system. *Proceedings of Crop Updates 2000*. Department of Agriculture, Western Australia.

Osten V, Wu H, Walker S, Wright G and Shields A 2006. Weeds and summer crop row spacings studies in Queensland. *Managing weeds in a changing climate: 15th Australian Weeds Conference*, Adelaide, South Australia,. (eds C. Preston, J. Watts and N. Crossman), pp. 347–350, Weed Management Society of South Australia.

Peltzer SC, Hashem A, Osten VA, Gupta ML, Diggle AJ, Riethmuller GP, Douglas A, Moore JM and Koetz EA 2009. Weed management in wide-row cropping systems: a review of current practices and risks for Australian farming systems. *Crop and Pasture Science*, vol. 60, pp. 395-406.

Reid D, Aguis P, Buck S, Collins R, Conway M, Keys P, Kuskie J, Spackman G and Sullivan A 2004. *Effect of row spacing and plant population on wheat production in central Queensland*. Queensland Department of Primary Industries and Fisheries, Brisbane.

Riethmuller G and McLeod W 2001. Effect of row spacing and orientation on growth and seed yield. *Proceedings of Crop Updates 2001 (Pulse research and industry development), Western Australia*, pp. 38–40.

Van der Weide RY, Bleeker PO, Achten VT, Lotz LA, Fogelberg F and Melander B 2008. Innovative mechanical weed control in crop rows. *Weed Research*, vol. 48, pp. 215–224.

Widderick MJ 2002. Ecology and management of the weed common sowthistle (*Sonchus oleraceus* L.). *PhD thesis*, University of New England, New South Wales.

Further reading

Martin P, Scott B, Edwards J, Haskins B and Smith J 2010. Row spacing in cereal and broadleaf crops. *Mallee Sustainable Farming 2009 Research Compendium*, pp. 147–152.

Tactic 2.3a Inter-row shielded spraying and crop-row band spraying

The trend towards wide-row planting for a range of crops risks greater reliance on herbicide control to balance declining crop competition. This in turn poses serious problems for herbicide-resistant weed development and management. Work with resistant weed populations (Storrie, unpublished) has shown that inter-row spraying with lower risk herbicides is a useful tool for managing resistant or hard-to-kill weeds. However, this practice increases the herbicide resistance risk to those herbicides being used and needs to be carefully managed.

Despite farmers seeing benefits in inter-row spraying using shields with knockdown herbicides and trialling a range of techniques, its use at time of writing is limited to glyphosate in cotton and paraquat in row crops.

Benefits

Key benefit #1

Shielded spraying allows inter-row application of non-selective herbicides in-crop, which can increase crop yield.

Using non-selective herbicides in-crop has the potential to control weeds that are difficult to manage with selective herbicides, while minimising spray costs.

In Western Australia research investigating methods to control a range of weeds, particularly in the pulse phase of a rotation, identified inter-row spraying as a potentially effective option. Hashem et al. (2004) showed that paraquat + diquat used in the inter-row area of narrow-leaf lupins sown in 55 cm wide rows effectively controlled two weeds, blue lupin (*Lupinus cosentinii*) and wild radish (*Raphanus raphanistrum*) (*Table T2.3a–1*). Inter-row spraying of the lupin crop at the 7-leaf growth stage with a bipyridyl herbicide at a rate of 2 L/ha gave the best lupin yield and a high level of control for both broadleaf weed species.

Key benefit #2

Band spraying reduces the risk of herbicide resistance development by limiting the application of higher risk selective herbicides over the crop row.

By limiting the use of higher resistance risk herbicides to the crop-row band, only 30 to 50% of the field is being treated, placing less selection pressure on the whole weed population. The remaining portion of the paddock (inter-row) is treated with either a lower risk (knockdown) herbicide or by inter-row cultivation.

Crop-row weed control is important, particularly in reducing weed seedbank additions. Band spraying over the crop row allows selective herbicides to control weeds that the shielded sprayer or inter-row cultivation techniques cannot reach. Hashem et al. (2008a) found a 70% yield increase in wide-row lupins when the crop row was band sprayed with a residual herbicide to control ryegrass. In addition, band spraying effectively reduces the total amount of herbicide used on a per hectare basis. This in turn reduces costs and minimises the potential for herbicide carryover, as well as reducing the risks of potential off-site movement (because less is available to move).

Osten and Lotz (2008) demonstrated similar responses in wide-row sorghum and chickpea crops in the northern grain region. Crop yields were unaffected and weed control was not compromised when residual herbicides were banded (50 cm) over the crop row with either tillage or non-selective herbicide applied to the inter-row (75 cm swath) by a shielded sprayer.

In similar but later studies in central Queensland, Osten and Cattell (2011) showed that WeedSeeker® technology could be safely used in-crop when fitted to hooded or shielded booms. In these studies residual herbicides were banded over the sorghum or chickpea rows while non-selective herbicides were applied via shields with and without WeedSeeker® fitted. High levels of weed control were achieved across all treatments and crop yields were unaffected. On a unit area basis, residual herbicide use was reduced by 50% while the amount of non-selective herbicide applied was reduced by up to 90% with WeedSeeker® but this was dependent on weed density.

Practicalities

Key practicality #1

Timing of shielded spraying is important.

It is important to spray small weeds in order to maximise control.

Shielded spraying also needs to occur before the crop canopy begins to close in, to avoid physical damage from the passage of the shields.

Key practicality #2

Care must be taken with the set-up and operation of shielded sprayers to minimise spray drift. All shields leak spray drift to some extent.

The set-up and operation of shielded sprayers is as important as the design of the shield (Rochecouste and Burgis 2003).

Small amounts of a translocated herbicide such as glyphosate can damage most crops. Cotton growers using glyphosate through shields in 2001 and 2002 reported yield losses of up to 30%.

Any drift from paraquat onto row crops can cause damage, but also can leave unacceptable levels of residues that will remain until harvest

Drift from shields is decreased by reducing shield height to less than 5 cm, by using coarse droplets (the British Crop Protection Council [BCPC] developed an international classification system using a set of reference nozzles for comparison with manufacturers' nozzles) and by travelling at lower speeds (Nicholls et al. 2003).

Table T2.3a–1 Effect of controlling blue lupin and wild radish in narrow-leaf lupins in Western Australia with Spray.Seed® at 1 L/ha and 2 L/ha at two application times (Hashem et al. 2004).

Lupin growth stage	Spray.Seed® (L/ha)	Blue lupin (% control)	Wild radish (% control)	Lupin yield (t/ha)
Untreated control	–	0	0	0.90
7-leaf	1	60	24	1.48
7-leaf	2	93	88	2.29
Flowering	1	83	93	1.88
Flowering	2	83	93	1.50

Contributors

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References

Hashem A, Blackwell P and Collins M 2004. Excellent weed control in wide row-lupins. *Crop Updates 2004*, Western Australian Department of Agriculture.

Hashem A, Fulwood R and Roberts C 2008a. Effect of alternative Group K herbicides on the control of on-row annual ryegrass in wide-row lupins. *Agribusiness Crop Updates 2008*, pp. 48–50. Department of Agriculture and Food Western Australia and Grains Research and Development Corporation, Perth, Australia.

Hashem A, Storrie A, Gupta M and Barker J 2008b. *Managing wide-row systems to minimise glyphosate resistance in chickpeas*. Cooperative Research Centre for Australian Weed Management, Adelaide, Australia.

Nicholls J, Dorr G, Woods N, Burgis M and Rochecouste J 2003. Shields ain't shields. *Cotton Research & Development Corporation-funded shielded sprayer study*. Conservation Farmers Inc.

Osten V and Lotz G 2008. The Irvin boom – adapting proven sugar cane industry weed management technology for dryland broadacre agriculture. *Weed management 2008 hot topics in the tropics: 16th Australian Weeds Conference*, Cairns, Queensland, (eds RD van Klinken, VA Osten, FD Panetta and JC Scanlan), pp. 223–225. Weed Society of Queensland.

Osten V and Cattell A 2011. WeedSeeker technology can be effectively used in wide-row crops in dryland broadacre farming systems. *Proceeedings of the 23rd Asian-Pacific Weed Science Conference* (CD Rom), Cairns, Queensland. Asian-Pacific Weed Science Society.

Rochecouste J and Burgis M 2003. Shielded sprayers. *The Conservation Farmer*, vol. 4, no. 2, pp. 137–146.

Tactic 2.3b Inter-row cultivation

Benefits

Key benefit #1

Inter-row cultivation provides an opportunity to control weeds without herbicides.

Inter-row cultivation was used in grain sorghum crops in the Northern Territory in the 1950s (Phillips and Norman 1962). They found that with 18 inch and 36 inch row spacings, one inter-row cultivation benefited yield whereas two cultivations removed too much soil moisture.

Research conducted in northern NSW in the 1970s (Holland and McNamara 1982) indicated that inter-row cultivation reduced weed growth in dryland sorghum to about half that of the unweeded controls.

Buhler et al. (1995) reported weed control using inter-row cultivation in the range of 50 to 75% to be common in the USA, and many North American growers find inter-row cultivation highly effective in wide-row summer crops.

Research in the USA also found that inter-row cultivation used in combination with residual herbicides can reduce the quantity of herbicide required for high levels of control (Buhler et al. 1995; Forcella 2000). Despite this, there is some uncertainty regarding the level of effective weed control resulting from inter-row cultivation (Forcella 2000).

Figure T2.3b–1 Inter-row cultivation can be effective for controlling small and stressed weeds.
Source: Vikki Osten

Practicalities

Key practicality #1

Inter-row cultivation timing is critical to ensure maximum levels of weed control with minimal damage to the crop.

Best weed control is obtained when the majority of the target species population has emerged and the weeds are small. In Minnesota, USA, Forcella (2000) found that to obtain maximum control of three *Setaria* species by cultivation it was necessary to wait for 60% emergence.

The Australian cotton industry recommends that inter-row cultivation is carried out when the soil is drying out. This timing, kills more weeds and minimises any damage from tractor compaction and soil smearing from the tillage implements (Roberts and Charles 2002).

Studies in Western Australia with inter-row tillage in narrow-leaf lupin showed crop stand losses to range from 39 to 55% depending on the timing and type of tillage employed (Hashem et al. 2008).

In sorghum experiments in central Queensland (Osten and Lotz 2008), inter-row tillage with sweep tynes set 100 mm from the crop rows and conducted at crop mid-tillering stage provided 91 to 100% weed control with only slight crop injury levels of 0.1 to 2% , and in three of four experiments the tillage caused less damage than shielded spraying with paraquat.

Key practicality #2

Weed control is reduced if the soil is too wet or weed densities are too high.

With any cultivation, weeds will successfully transplant if the soil is too wet. Soil structure can also be damaged when cultivating soil that is too wet.

Inter-row tillage is often not as effective as herbicides for both weed control and crop yield maintenance under high weed densities (Amador-Ramirez et al. 2001). Collins and Roche (2002) also showed failure of inter-row tillage to control dense (5,000 plants/m^2) annual ryegrass in Western Australian grown narrow-leaf lupins.

Key practicality #3

Heavy stubble cover may preclude inter-row cultivation.

Where retained stubble is dense, it may not be physically possible to carry out inter-row cultivation.

Key practicality #4

Inter-row cultivation does not control weeds in the crop row, so an additional tactic must be used for the crop-row weeds.

Some cultivation implements move sufficient soil from the inter-row to the crop row to smother some weeds, but this is only effective either on very small weed seedlings or if the crop is tall enough to avoid being covered. In many situations band spraying is required for crop-row weed control.

Holland and McNamara (1982) found that inter-row cultivation combined with a band spray of pre-emergent atrazine over the crop row was as effective in weed control as, and used less chemical than, an overall spray of pre-emergent atrazine.

Key practicality #5

Inter-row cultivation cannot be used in conjunction with ground covering stubble mulch techniques.

Mulching the soil surface has been shown to have benefits in retaining soil moisture and suppressing weeds.

Inter-row cultivation reduces the opportunity to maintain the mulch, and therefore is not a complementary tactic.

In the central Queensland sorghum experiments described previously, while the inter-row tillage was effective and safe to the crop, it did reduce the standing carry-over wheat stubble by 85% (i.e. shifted it out of the treated area) and the 15% that remained was no longer standing (Osten and Lotz 2008).

Key practicality #6

Inter-row cultivation can stimulate emergence of some weed species.

Cultivation is known to stimulate fresh germination of weeds. An understanding of the likely impact of cultivation on the weed species in the paddock is essential. This allows a management plan to be put in place to control the expected weeds that do germinate.

Peltzer et al. (2007) showed a mid-season inter-row tillage operation in wide-row lupins stimulated an emergence of wild radish producing weed numbers 50% greater than the control treatment.

Contributors

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References

Amador-Ramirez MD, Wilson RG and Martin AR 2001. Weed control and dry bean (*Phaseolus vulgaris*) response to in-row cultivation, rotary hoeing and herbicides. *Weed Technology*, vol. 15, pp. 429–436.

Buhler DD, Doll JD, Proost RT and Visocky MR 1995. Integrated mechanical weeding with reduced herbicide use in conservation tillage corn production systems. *Agronomy Journal*, vol. 87, pp. 507–512.

Collins M and Roche J 2002. Weed control in lupins using a new spray shield and other row crop techniques. *Weeds 'threats now and forever': 13th Australian Weeds Conference*, Perth, Western Australia,. (eds H Spafford Jacob, J Dodds and JH Moore), pp.484–487, Plant Protection Society of Western Australia.

Forcella F 2000. Rotary hoeing substitutes for two-thirds rate of soil-applied herbicide. *Weed Technology*, vol. 14, pp. 298–303.

Hashem A, Douglas A, Pathan S and Peltzer S 2008. Control and seed production of annual ryegrass in wide-row lupins in the WA wheatbelt. *Weed management 2008 hot topics in the tropics: 16th Australian Weeds Conference*, Cairns, Queensland, (eds R van Klinken, V Osten and D Panetta), pp. 480–482, Weed Society of Queensland.

Holland JF and McNamara DW 1982. Weed control and row-spacing in dryland sorghum in northern New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 22, pp. 310–316.

Osten V and Lotz G 2008. The Irvin boom – adapting proven sugar cane industry weed management technology for dryland broadacre agriculture. Weed management 2008 hot topics in the tropics: *16th Australian Weeds Conference*, Cairns, Queensland, (eds R van Klinken, V Osten and D Panetta), pp. 223–225. Weed Society of Queensland.

Peltzer S, Pathan S and Mason PT 2007. Timing of weed removal in wide-row lupins. *Crop Updates 2007*, Perth, pp. 72–74. Department of Agriculture and Food, Western Australia.

Phillips LJ and Norman MJT 1962. The influence of inter-row and intra-row cultivation on the yield of grain sorghum at Katherine, N.T. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 2, pp. 204–208.

Johnson SB, Charles GW, Roberts GN and Taylor IN 2002. Weed Identification and Information Guide. WEEDpak, a guide for integrated management of weeds in cotton. Australian Cotton Cooperative Research Centre, Narrabri, pp. B2.1–B2.11. https://cottoninfo.com.au/publications/weedpak

Tactic 2.4 Spot spraying, chipping, hand roguing and wiper technologies

Where new weed infestations occur in low numbers eradication may be possible. In such situations more intensive tactics to remove weeds can be used in addition to ongoing management tactics which aim to minimise weed impact. The term 'wiper technologies' refers to the many versions of wipers available (e.g. wick wipers, rope wipers, carpet wipers, weed wipers).

Benefits

Key benefit #1

Vigilance and attention to detail can be the difference between eradication and a prolonged and costly problem.

Targeted control will ensure that all target plants are removed along with any seed or plant parts that allow future propagation. Key steps include the following:

- Correctly identify the plant.
- Understand the plant's biology – when does it actively grow, is it annual or perennial, and how and when does it reproduce?
- Identify which control tactics are best suited to the plant and at what growth stages these should be implemented.

Practicalities

Key practicality #1

Instigate accurate future monitoring by marking isolated infestations.

Monitoring is a key part of weed management and is essential if eradication is to be attempted.

Use of a physical marker (e.g. steel post) or a GPS will ensure that the correct area can be regularly checked and additional weeds removed prior to setting seed.

Key practicality #2

Isolate the infested area to reduce the risk of further spread.

Fences to exclude livestock or markers so that the area can be avoided when carrying out paddock operations (such as cultivation, sowing or harvest) will avoid spreading the weed within the paddock and to other areas of the farm.

Key practicality #3

Controlling new weed infestations and low density weed populations requires only simple measures.

A number of simple measures may be used:

'Roguing' refers to hand pulling or chipping of weeds before flowering or seedset. It is also used in seed crops to reduce the chance of spreading weeds in the seed and when other options of controlling the weed are limited. If roguing is carried out after seed is physiologically mature, both the plants and their seeds should be contained and carefully disposed of. Roguing is an effective method of eradicating a new infestation in annual crops, despite being labour intensive and expensive.

'Spot spraying' is a quicker alternative to hand roguing and can be used to sterilise weed seed. Spot spraying usually involves applying a non-selective herbicide to individual weeds using a sprayer in a back-pack or mounted on an all-terrain vehicle. The sprayer should have a single nozzle on a wand attached to a flexible hose. A boom sprayer fitted with weed detector units may also be used for applying non-selective herbicides to low density infestations in fallows.

'Wick wiping' with a hand-held rope-wick wiper is an alternative to spot spraying when herbicide drift on to sensitive adjacent plants is a possibility. It is particularly useful if the weed is taller than the crop canopy (see *Tactic 3.1c Wiper technology*).

Key practicality #4

Timing of control is important to avoid seedset.

Ensure that weed management is extremely thorough while weed numbers are low. Timing control measures according to weed development will avoid seedset. Remember, seedset from a single year can easily result in many years and dollars spent on weed control measures.

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Tactic 2.5 Weed detector sprayers

Weed detector sprayers are low volume spot spraying technology for the control of scattered weeds in crop fallows. The 'weed detector-activated' sprayer consists of detector units mounted to a boom which detect weed presence using infra-red reflectance. When each individual unit passes over a weed it activates a solenoid which in turn switches on an individual even-fan nozzle, spraying the weed.

There are provisions, when targeting weeds larger than 10 cm in diameter, to use higher herbicide rates per hectare compared with normal 'broadcast' boom spraying. Despite this, the technology is currently reducing the per hectare fallow spray application rates by 80 to 95% depending on the density of the fallow weeds.

Figure T2.5–1 WeedSeeker® spraying large sowthistle in a fallow, northern NSW.
Photo: Crop Optics

Benefits

Key benefit #1

Only 10 to 15% of the field is being treated, reducing fallow management costs and encouraging higher levels of weed control.

Up to 95% reductions in the area sprayed are possible depending on weed density. This reduces the total amount of herbicide being used and encourages better weed control in fallows due to reduced costs or higher rate of herbicide applied per plant.

Key benefit #2

A range of herbicide mode-of-action (MOA) groups can be used to combat herbicide resistance.

This technology can use a range of herbicide MOAs, making it an effective tool in herbicide resistance management programs. At the time of writing seventeen weed species have been identified as having populations resistant to glyphosate (MOA Group M), the most widely used fallow herbicide. Weed detector sprayers enable cost effective control of scattered (low density) weeds in fallows.

Figure T2.5–2 WEEDit weed detector sprayer applying herbicide to large spear thistle in a Victorian fallow.
Photo: WEEDit

Key benefit #3

Using a weed detector sprayer reduces the risk of herbicide drift.

Herbicide drift risk is reduced as the nozzles activate for short periods and a coarse spray quality is used. This reduced risk assumes a dual (conventional) spray line is not being used in conjunction with the weed detector sprayer.

Key benefit #4

Using a weed detector sprayer enables spraying in the evening.

Since many weed detector technologies emit an infra-red signal and collect the reflectance off weeds and other material, the units can operate at night. This may allow greater opportunities to undertake more time consuming activities such as double knocking that requires two applications of herbicide. The second knock often requires the use of a bipyridil herbicide (MOA Group L) on patchy survivors from the first spray, and this group of herbicides tends to be more effective if sprayed late afternoon or evening.

Practicalities

Key practicality #1

Weeds must be large enough to be detected.

Weeds must be larger than 5 cm in diameter (in wheat stubble) to be reliably detected at recommended travel speeds.

Key practicality #2

Travel speeds are limited.

Due to time required for the solenoids to switch on the nozzles, sprayer ground speeds should be limited to approximately 16 kph. The maximum recommended speed is 20 kph to maintain sufficient spray coverage of the target weeds.

Key practicality #3

Strong winds can reduce coverage and control.

Winds greater than 15 kph can move the spray away from the target weeds, reducing the effective dose applied. Strong winds can be a more significant problem for weed detector sprayers compared with normal broadcast spraying. There is unlikely to be spray from adjacent nozzles moving across with the wind and covering the target weeds, because pairs of nozzles directly above the weed switch on and off when a weed is detected.

Contributors

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Further reading

Australian Pesticides and Veterinary Medicines Authority www.apvma.gov.au/permits/search.php

Blackshaw R E, Molnar L J and Lindwall C W 1998. Merits of a weed-sensing sprayer to control weeds in conservation fallow and cropping systems. *Weed Science*, vol. 46, pp. 120–126.

Crop Optics Pty Ltd http://www.cropoptics.com.au

Weed-it https://www.weed-it.com/

Tactic 2.6 **Biological control**

Biological control (or 'biocontrol') for weed management uses the weed's natural enemies (biological control agents). These natural enemies include herbivores such as insects, but also include sheep (see *Tactic 3.5 Grazing – actively managing weeds in pastures*) where there is direct consumption of the weed. They also include micro-organisms such as bacteria, fungi and viruses which can cause disease, change weed vigour and competitiveness relative to the crop and decay the weed seed in the seedbank. Other plants which can be included under biological control are those which release substances that suppress weed growth (known as 'allelopathy').

There are three basic types of biological control strategies: 'classical', 'inundative' and 'conservation'.

Classical biological control

Classical biological control, the most widely known approach, intentionally introduces an exotic (non-native) biological control agent.

- Low numbers of the exotic organism are introduced which then spread through reproduction.
- The aim is for permanent establishment, where the organisms are released for long-term control without additional releases.
- Natural enemies of the host weed are sought in the plant's region of origin.
- Potential control agents are tested to ensure they attack only the target weed, before importation and clearance through quarantine.
- The most successful example of classical biocontrol in Australia is the cactoblastis moth to control prickly pear (*Opuntia* spp.). The moth was introduced in 1926 and within six years had destroyed much of the infestation that covered 23 million hectares of land in Queensland and NSW.

Inundative biological control

Inundative biological control overwhelms weeds with massive numbers of a naturalised pathogen that is already found in low numbers.

- Biological control agents are mass produced and then released in big numbers to produce an epidemic against the weed.
- The agent is not expected to reproduce or persist in the environment.
- Agents used for inundative releases, especially micro-organisms, are also commonly called biopesticides or bioherbicides. A commonly used biopesticide in Australia is the bacteria, *Bacillus thuringiensis* (*Bt*), marketed as Dipel® and used to control caterpillars in vegetables.
- An example of a bioherbicide is the formulation of the fungal pathogen *Colletotrichum gloeosporoides* (Collego®) to control northern jointvetch (*Aeschynomene virginica*) in rice and soybeans in the USA. No bioherbicides have been released in Australia.
- A potential bioherbicide was investigated in Australia using deleterious rhizobacteria (DRB). DRB are non-parasitic bacteria that are associated with plant roots (in the rhizosphere or area just around the roots) and can inhibit or reduce the growth of specific plants (or the weed). This reduction in growth gives the crop the competitive edge. In the USA, one DRB strain (isolated from winter wheat roots) reduced the growth of downy brome and increased yields of winter wheat by up to 35% (Kennedy et al. 1991). In Australia, DRB strains were investigated for their ability to reduce annual ryegrass (*Lolium rigidum*) but the study failed to find strains that consistently reduced growth and was abandoned.

Conservation biological control

Conservation biological control, the most readily available biocontrol practice and distinguishable from other strategies in that natural enemies are not released, modifies the environment or existing practices to protect and enhance natural enemies.

- Managing both the crop and the weed can favour the presence of naturally occurring biological control agents that attack or reduce the weed.
- *Tactic 1.2 Encouraging insect predation of seed* provides an example of conservation biocontrol. Ants have been shown to remove large quantities of weed seed over summer. The ants can be 'conserved' by reducing the use of broad spectrum insecticides and minimising tillage.
- Another example is allelopathy, whereby crops are planted that release chemicals to suppress the germination and/or growth of other plants including weeds. Many crops including rice and wheat release chemicals that can suppress other plants. Wu et al. (2001) reported that residue extracts from a range of wheat varieties suppressed root growth of annual ryegrass by over 60%. This may have implications where retained stubble could be used to suppress weeds. Allelopathy can also work in reverse where the weed suppresses the growth of the crop. For example, degraded silver grass (*Vulpia* spp.) residues can reduce crop establishment and growth, and toxins released by green wild radish (*Raphanus raphanistrum*) pods can substantially reduce the viability of crop seed in storage.

Benefits

Key benefit #1

The effectiveness of biological control can be increased when used in conjunction with other methods.

Biological control is most effective as one element in an integrated weed management approach in combination with herbicides, grazing and cultivation. Biological control rarely controls the weed completely but can reduce its vigour. Optimising the crop's competitive ability, for example, at the same time can further reduce weed growth. This is particularly pertinent for the conservation biological control strategy.

Figure T2.6–1 Patersons curse leaf showing blisters containing *Dialectica scaleria* caterpillars.
Photo: Andrew Storrie

Figure T2.6–2 Patersons curse shoot showing blisters containing *Dialectica scaleria* caterpillars.
Photo: Andrew Storrie

Key benefit #2

Biocontrol agents, particularly bioherbicides, have an advantage over chemical herbicides in situations where the latter may be ineffective (e.g. due to herbicide resistance) or inappropriate (e.g. near sensitive wetlands or in organic agriculture).

Practicalities

Key practicality #1

The biology of the weed influences how well a classical biocontrol agent will work.

Short-lived annual weeds of cropping are less suitable targets than longer-lived weeds of pasture or native vegetation. For a classical control agent to work in cropping, it must survive hot and dry summers and/or periods of non-cropping then multiply rapidly at the beginning of the season in order to sufficiently reduce the weed. Usually the presence of the biocontrol agent is dependent on the presence of the weed, which is unlikely for annual cropping species.

Key practicality #2

Success is dependent on the existence of suitable agents and their degree of host specificity.

Usually it is difficult to find safe biological control agents for weeds that are closely related to crops (e.g. wild oats and cultivated oats, or wild radish and canola).

Key practicality #3

Bioherbicide technology is limited by the need for a large-scale market to make the product viable and by environmental constraints.

In most cases the Australian market is too small to warrant bioherbicide development. Other limitations are that bioherbicides are usually less tolerant than chemicals to the extremes of temperature and humidity commonly found in storage and transport conditions. Bioherbicides can also be more sensitive than chemicals to unfavourable environmental conditions during application (e.g. the low humidity in Australian cropping conditions can prevent the bioherbicide from persisting). There is also the possibility of the weed becoming resistant to the bioherbicide.

Contributors

Sally Peltzer and Aaron Maxwell

References

Kennedy AC, Elliott LF, Young FL and Douglas CI 1991. Rhizobacteria suppressive to the weed downy brome. *Soil Science Society of America*, vol. 55, pp. 722–727.

McFadyen REC 1998. Biological control of weeds. *Annual Review of Entomology*, vol. 43, pp. 369–393.

Wu H, Pratley JE, Lemerle D and Haig T 2001. Wheat allelopathic potential against a herbicide-resistant biotype of annual ryegrass. *Proceedings of the 10th Australian Agronomy Conference*, January 2001, Hobart, Tasmania.

Further reading

Harley KLS and Forno IW 1992. *Biological Control of Weeds: A Handbook for Practitioners and Students*. Inkata Press, Melbourne, Australia.

Julien M and White G 1997. Biological Control of Weeds: Theory and Practical Application. Australian Centre for International Agricultural Research Centre, *Monograph Series 49*: p.192.

Julien MH and Griffiths MW 1998. *Biological Control of Weeds. A World Catalogue of Agents and their Target Weeds*. Fourth edition. CAB International, Wallingford, U.K, p. 223.

Online reading

CSIRO research on biological control of temperate and tropical weeds in Australia. https://research.csiro.au/weed-biocontrol/

Agrifutures Biocontrol of Weeds https://www.agrifutures.com.au/partnerships/rural-rd-for-profit-program/weeds-biocontrol/

Tactic Group 3 **Stop weed seedset**

Seedset control tactics include spray-topping with selective herbicides, crop-topping with non-selective herbicides, wick wiping, windrowing and crop desiccation, and techniques such as hand roguing, spot spraying, green and brown manuring, hay and/or silage production and grazing.

Tactic Group 3 (TG3) tactics can be loosely termed 'seed kill' tactics because each aims to reduce weed seed production. The goals are to reduce the weed seedbank, obtain future benefits from depleted weed populations and reduce grain contamination.

In-crop seedset control advice

- Before sowing decide if seedset control has a role in the paddock in question.
- Choose crop and variety to suit timing of the seedset control tactic selected (i.e. short-season cultivars).
- Choose a competitive crop and variety to improve efficacy of the tactic.
- Choose the most suitable seedset control tactic for the situation and business.
- Check for herbicide(s) registered for seedset control in the crop and target weed(s).
- Look at past records of crops and herbicides used in rotation and assess herbicide resistance risk.
- Monitor in-crop weeds and assess the feasibility of seedset control.
- Strategically time tactic implementation. The technique will be less effective before or after the optimal window and may cause unacceptable crop damage.
- Be prepared: the timing window to obtain maximum effect is short. If using contractors ensure that they can be there at the critical time.
- Seek advice if unsure about any aspect of the seedset control tactic being used.
- Always read and follow the herbicide label.
- Always check and adhere to harvest and grazing withholding periods.
- Seedset control is not a remedy for rampant weed problems. Pursue other options and use seedset control in conjunction with tactics from other tactic groups.
- Seedset control should not be solely relied upon to manage herbicide resistance. It is part of an integrated approach to herbicide resistance management.
- Do not apply herbicides from the same mode-of-action group more than once in the same season.
- Do not apply unregistered or non-permitted herbicides.

Weed seedset management is most applicable to weeds that are expensive to control and/or resistant to herbicides and when weed densities are low. Seedset control tactics are particularly effective when weed populations have already been reduced to low levels through fallowing, pasture or other specific crop rotation or weed management practices.

Tactic 3.1 **In-crop weed management for seedset control**

In-crop management of weed seedset is used to minimise the replenishment of seedbanks and/or reduce grain contamination. This is achieved by intercepting the seed production of weeds that have escaped, survived or emerged after application of weed management tactics (see *Tactic Group 1* and *2*) earlier in the cropping season.

Controlling weed seedset contrasts with early in-crop weed management tactics (*TG1* and *TG2*), which aim to maintain or maximise crop yield by reducing weed competition. Generally, there is no grain yield benefit from seedset control tactics, as most competition from weeds occurs earlier during the vegetative stages of the crop. For this reason TG3 tactics should always be used with tactics from other Tactic Groups.

Benefits

Key benefit #1

Using in-crop weed seedset control tactics can dramatically reduce future expenditure on weed management.

Weed control is beneficial in the short term because the weed problem is removed. Long-term benefits arise when the weed is prevented from setting seed as there are no increases to the seedbank and, as a consequence, fewer weeds in the future. Annual ryegrass (*Lolium rigidum*), for example, has a relatively short-lived seedbank, so if seed production is prevented in the spring there will be fewer weed seeds to germinate in the subsequent crop (Gill and Holmes 1997).

Research has shown that one wild radish (*Raphanus raphanistrum*) seed/m^2 is enough to replenish the seedbank and incur ongoing economic losses. For wild oat (*Avena* spp.) which does not have the dormancy characteristics of wild radish, six seeds/m^2 will replenish the seedbank and incur economic losses (Murphy et al. 2000).

Managing weed populations with a long-term approach has shown economic benefits of up to $50/ha/year for major weeds such as wild oat and wild radish (Jones and Medd 1997, 2000). Non-adoption of weed seedset control into an integrated weed management program will incur a high risk of seedbank population increase (Jones and Medd 2005) and lead to future economic costs.

For low-density seedbanks (up to 100 seeds/m^2) there is a future cost of approximately $1.50 or $0.63 respectively for each new wild oat or wild radish seed added to the seedbank (Jones et al. 2002). The cost of adding more seeds of either species to the seedbank diminishes to negligible levels with high-density seedbanks as the damage from existing weed populations is already significant.

Key benefit #2

In-crop seedset control reduces weed seed contamination levels in grain samples at harvest.

Weed seedset control can help in meeting grain receival standards. For example, zero or low seed tolerances apply to several weeds and certain crop seed contaminants, as well as ergot of annual ryegrass (see relevant grain receival standards for targeted market). In such instances hand roguing of paddocks or using other seedset management options before harvest may help avoid or minimise delivery rejection, downgrading or dockage penalties or the need to clean seed before delivery.

Practicalities

Key practicality #1

Plan weed seed set management in advance.

Weed seed set management needs to be planned as it is most successful when crop or variety choice is made with the specific aim of implementing a particular tactic for a known weed problem. Forward planning of this kind will maximise weed seed kill, with minimal reduction in crop performance.

Spot spraying and hand roguing are feasible for scattered weed patches, very low weed densities or new incursions. On the other hand, selective spray-topping works best on densities of weeds up to 50 plants/m^2. Above this density, or where herbicide resistance problems are encountered, crop salvaging options should be considered. Crop-topping, windrowing and desiccation are mostly applicable to pulse and oilseed crops where the crop matures early enough to harvest and prevent weed seedset before seed becomes viable.

Annual ryegrass, wild oat and brassica weeds (especially wild radish) have been the targets of research into weed seedset management techniques. However, registered herbicides are only available for crop-topping of annual ryegrass in pulses and selective spray-topping of brassica weeds in cereals. Harvest and grazing withholding periods must be observed.

Contributors

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References

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Jones RE and Medd RW 1997. Economic analysis of integrated management of wild oats involving fallow, herbicide and crop rotational options. *Australian Journal of Experimental Agriculture*, vol. 37, pp. 683–691.

Jones RE and Medd RW 2000. Economic thresholds and the case for longer term approaches to population management of weeds. *Weed Technology*, vol. 14, pp. 337–350.

Jones RE and Medd RW 2005. A methodology for evaluating risk and efficacy of weed management technologies. *Weed Science*, vol. 53, pp. 505–514.

Jones RE, Cacho OJ and Medd RW 2002. What are the future benefits of a change in the weed seedbank? *Weeds 'threats now and forever': 13th Australian Weeds Conference*, Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 732–735, Plant Protection Society of WA.

Murphy C, Craddock T and Peltzer S 2000. Weed seeds – breaking the bank. *Advice Sheet for southern region*. Grains Research and Development Corporation.

Tactic 3.1a Spray-topping with selective herbicides

Selective spray-topping applies a post-emergent selective herbicide to weeds at reproductive growth stages to prevent seedset of certain weeds. The technique is aimed at weed seedbank management (i.e. reducing additions to the weed seedbank) but with minimal impact on the crop.

Selective spray-topping is suited to a crop situation and largely targets broadleaf weeds (especially brassica weeds). The tactic should not be confused with pasture spray-topping which occurs in a pasture phase, involves heavy grazing, uses a non-selective herbicide and largely targets grass weeds (see *Tactic 3.2 Pasture spray-topping*).

The strategy can be used to control 'escapes', as a late post-emergent salvage treatment or for managing herbicide resistance.

The rapid spread of Group B resistance in brassica weeds and Group A and Z resistance in wild oat (*Avena* spp.) has significantly reduced the potential to apply this tactic.

Benefits

Key benefit #1

Correctly executed selective spray-topping will result in a 90% reduction in weed seedset in herbicide-susceptible populations.

A range of herbicides can produce high levels of seedset control in a number of brassica weeds. *Table T3.1a–1* shows the effects of selective spray-topping on seedset of wild radish (*Raphanus raphanistrum*) and turnip weed (*Rapistrum rugosum*).

Practicalities

Key practicality #1

Know the herbicide resistance status of weeds before using selective spray-topping.

Herbicide resistance testing has shown significant levels (25 to 33%) of cross resistance from clodinafop and fenoxaprop (Group A 'fop') herbicides to Group Z. The development of multiple resistance in wild oat will severely limit the use of this technique (see *Section 3: Herbicide resistance*). At least 50 cases of resistance to flamprop-M-methyl (Group Z) have been identified in Australia (Broster 2012; Boutsalis pers. comm. 2012). Flamprop-M-methyl resistance has been recorded in wild oat in Canada and the United Kingdom since 1994 (Heap 2013). These weed populations are also resistant to Group A and Group B ('imi') herbicides.

Widespread Group B resistance in brassica weeds will limit the effectiveness of this group of herbicides for selective spray-topping.

Table T3.1a–1 Seedset of herbicide-susceptible wild radish and turnip weed after the application of selective spray-topping herbicide at flowering (Madafiglio et al. 1999).

Herbicide	Reduction in seedset (%)	
	Wild radish	Turnip weed
Logran®	100	99
Logran®+ MCPA	100	100
Broadstrike®	96	83
MCPA amine	95	86
2,4-D amine	96	91
Untreated weed density (plants/m^2)	36	<1
Seedset in untreated (seeds/m^2)	7,736	254

Note: Check chemical selected is registered for this purpose in appropriate state.

Figure T3.1a–1 Typical effect of Mataven® 90 on wild oats when applied as a selective spray top application.
Photo: Andrew Storrie

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References

Broster JC 2012. *2012 Herbicide Resistance Testing Service Report*. Charles Sturt University, New South Wales.

Cook AS 1998. Reducing seed production using late post-emergence applications of selective herbicides to manage wild oat (Avena spp.) populations. *Master of Rural Science thesis*, University of New England.

Cook AS, Storrie AM and Medd RW 1999. Selective spray-topping: field testing of a new technique for reducing wild oat seed production. *Weed management into the 21st Century : do we know where we're going?: 12th Australian Weeds Conference*, Hobart, Tasmania, (eds AC Bishop, M Boersma and CD Barnes), pp. 53–56, Tasmanian Weed Society.

Heap I 2013. International survey of herbicide resistant weeds. Herbicide Resistance Action Committee and the North American Herbicide Resistance Action Committee. www.weedscience.org

Madafiglio G, Medd R and Cornish P 1999. Selective spray-topping: a new technique for controlling broadleaf weeds in cereals. *Weed management into the 21st Century : do we know where we're going?: 12th Australian Weeds Conference*, Hobart, Tasmania, (eds AC Bishop, M Boersma and CD Barnes), pp. 269–272, Tasmanian Weed Society.

Medd RW, McMillan MG and Cook AS 1992. Spray-topping of wild oats (*Avena* spp.) in wheat with selective herbicides. *Plant Protection Quarterly*, vol. 7, pp. 62–65.

Medd RW, Nicol HI and Cook AS 1995. Seed kill and its role in weed management systems: a case study of seed production, seed banks and population growth of *Avena* species (wild oats). *Challenges for weed science in a changing Europe: 9th European Weed Research Society Symposium*, Budapest, Hungary, vol. 2, pp. 627–632, European Weed Research Society.

Tactic 3.1b Crop-topping with non-selective herbicides

Crop-topping applies a non-selective herbicide (e.g. glyphosate or paraquat) before harvest when the target weed is at flowering or early grain fill. Crop-topping aims to minimise production of viable weed seed while also minimising yield loss. The selectivity of the crop-topping process is dependent on a sufficient gap in physiological maturity between crop and weed.

Currently, non-selective herbicide crop-topping registrations are limited to use in pulse crops and predominantly target annual ryegrass (*Table T3.1b–1*).

Alternative pre-harvest non-selective herbicide applications for crop desiccation are outlined in *Tactic 3.1d Crop desiccation and windrowing*.

Benefits

Key benefit #1

Crop-topping can reduce annual ryegrass weed seedset, reducing additions to the seedbank.

A well-timed application of a non-selective herbicide can significantly reduce the seedset of annual ryegrass (*Lolium rigidum*) and other weeds. A reduction of more than 90% of seedset in annual ryegrass can be achieved if the herbicides are applied at the correct stage of development (Gill and Holmes 1997; Newman 2003).

Balancing annual ryegrass control with potential crop yield loss is important, so in-paddock control results are commonly in the range of 75 to 80%.

Key benefit #2

Reductions in seedset achieved by crop-topping can be increased if used in conjunction with selective herbicide treatments.

In South Australia applying a pre-emergent herbicide (see *Tactic 2.2c Pre-emergent herbicides*) in combination with crop-topping reduced annual ryegrass seedset by 99% of the untreated control, compared with a 71% reduction when crop-topping was used alone (Matthews et al. 1996).

Combining controls from different tactic groups is important. In this case the crop-topping was used to control annual ryegrass that had escaped the use of pre-emergent herbicide.

Whole-farm benefits

Crop-topping can deliver a number of benefits in addition to reducing weed seedset, including:

- improved harvest due to even maturity of crops (particularly pulses)
- improved harvest, grain quality and storage by desiccating late weed growth in seasons with late rain.

Table T3.1b–1 Product registrations for pre-harvest weed control and desiccation from GRDC Factsheet: Pre-harvest herbicide use, October 2017. Always check product labels (NOTE: Paraquat/diquat products, for example Spray.Seed®, are not registered for pre-harvest weed control or desiccation).

Crop	Paraquat	Diquat	Glyphosate	Sharpen®
Wheat	Paraquat is not registered for: • in-crop spray topping; • pre-harvest crop desiccation; pre-harvest weed control. These use patterns are unregistered. DO NOT USE PARAQUAT PRODUCTS FOR THESE USE PATTERNS	Winter cereals – pre-harvest weed control (all states): Spray as soon as the crop is mature and ready for harvesting. Under wet spring conditions crops can periodically become infested with weeds which seriously interfere with harvest operations. Diquat will control these weeds allowing for efficient harvest. WHP: NOT required when used as directed.	Not all glyphosate formulations are registered for this use Apply to mature crop from late dough stage (28 per cent moisture) onwards. The higher rate will be required when crops are heavy and leaf shading effects may occur. DO NOT use on crops intended for seed or sprouting. Where wheat is grown in rotation with any herbicide-tolerant crop, management should be consistent with implementation of any management plan for herbicide-tolerant crops. WHP: DO NOT harvest within 7 days of application. Certain glyphosate formulations can now be applied at higher-use label rates in wheat with a 5-day harvest withholding period.	DO NOT apply before growth stage Z71 (watery ripe where first grains have reached half their final size) and DO NOT apply after growth Z83 (early dough). In order to guarantee good coverage it is recommended to apply at minimum 100 L/ ha volume. ALWAYS apply with 1% v/v Hasten® Spray Adjuvant or high quality methylated seed oil (MSO). WHP: NOT required when used as directed.
Barley	Paraquat is not registered for: in-crop spray topping; pre-harvest crop desiccation; pre-harvest weed control. These use patterns are unregistered. DO NOT USE PARAQUAT PRODUCTS FOR THESE USE PATTERNS	Winter cereals – pre-harvest weed control (all states): Spray as soon as the crop is mature and ready for harvesting. Under wet spring conditions crops can periodically become infested with weeds which seriously interfere with harvest operations. Diquat will control these weeds allowing for efficient harvest. WHP: NOT required when used as directed.	Glyphosate is not registered[#] for use in malt barley for: • in-crop spray topping; • pre-harvest crop desiccation; • pre-harvest weed control. These use patterns are unregistered. DO NOT USE GLYPHOSATE PRODUCTS FOR THESE USE PATTERNS	DO NOT apply before growth stage Z71 (watery ripe where first grains have reached half their final size) and DO NOT apply after growth Z83 (early dough). In order to guarantee good coverage, it is recommended to apply at minimum 100 L/ ha volume. ALWAYS apply with 1% v/v Hasten® Spray Adjuvant or high quality methylated seed oil (MSO). WHP: NOT required when used as directed.

[#] An APVMA minor use permit (PER 82594) is in place until 30 April 2020 that permits pre-harvest use of Weedmaster® DST® and Weedmaster® Argo® glyphosate formulations on feed barley crops. No glyphosate products are approved for use on malt barley crops.

[1] Diquat only; [2] Not glyphosate; [3] Paraquat only; [4] Glyphosate only; [5] glyphosate and diquat only

WHP = withholding period; v/v = volume per volume

Disclaimer: The information contained in this table has been compiled as a guide only. Registrations can and do change regularly. All users of herbicide products must read the label of the product they are using and follow the directions printed on that label.

Crop	Paraquat	Diquat	Glyphosate	Sharpen®
Canola	Paraquat is not registered for: • in-crop spray topping; • pre-harvest crop desiccation; • under-the-cutter-bar spraying during swathing or windrowing activities; • pre-harvest weed control; • spraying over the top of swaths or windrows These use patterns are unregistered. **DO NOT USE PARAQUAT PRODUCTS FOR THESE USE PATTERNS**	Pre-harvest crop desiccation (all states): Spray when 70 per cent of the pods are yellow and the seeds are browny or bluish and pliable. Canola ripens unevenly and is prone to pod shatter and seed loss. Direct harvest 4–7 days after spraying. **WHP: DO NOT harvest for at least 4 days after application.**	Certain glyphosate formulations are registered for pre-harvest use in canola. Apply to mature standing crop from early senescence (minimum of 20% seed colour change to a dark brown/black colour from within the crop) prior to windrowing or direct harvest. Use the higher label rate when crops or weeds are dense and/or where faster desiccation is required. DO NOT use on crops intended for seed Withholding periods may apply. Refer to the label. DO NOT overspray windrows DO NOT apply to standing crops and again at the time of windrowing Refer to the complete label and critical comments section.	**Sharpen® is highly damaging to canola and is not registered for any use patterns. DO NOT USE.**

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WHP = withholding period; v/v = volume per volume

Disclaimer: The information contained in this table has been compiled as a guide only. Registrations can and do change regularly. All users of herbicide products must read the label of the product they are using and follow the directions printed on that label.

Crop	Paraquat	Diquat	Glyphosate	Sharpen®
Chickpeas Faba beans Field peas Lentils Pigeon peas[1] Lupins[2] Vetch[3] Adzuki beans[4] Cowpeas[4] Mungbeans[5] Soybeans	Spray-topping to reduce seed set – annual ryegrass. Chickpeas/Faba beans/ Field peas/Lentils/ Lupins/ Vetch: Spray the crop when the ryegrass is at the optimum stage, that is when the last ryegrass seed heads at the bottom of the plant have emerged and the majority are at or just past flowering (with anthers present or glumes open) but before haying off is evident – usually October to November. Use of the higher registered rate in these crops is usually more reliable and gives a greater reduction in seed set. Reduction in crop yield may occur especially if the crop is less advanced relative to the ryegrass, that is if crops have a majority of green immature pods. The higher rate may also increase any yield reduction. In practice crop losses in excess of 25% may occur. WHP: DO NOT harvest for 7 days after application.	Pre-harvest crop desiccation (all states): Dry beans/Dry peas/ Pigeon peas/Lentils/ Chickpeas/Faba beans/ Lupins: Spray as soon as the crop has reached full maturity. Helps overcome slow and uneven ripening and weed problems at harvest. Soybean: Spray when 80% of the pods are yellow/brown and the seeds are ripe – yellow and pliable. Mungbeans: Apply when 80% to 90% of pods are black or brown. WHP: NOT required for dry beans, dry peas, mungbeans when used as directed. Lentils/Chickpeas/ Faba beans: DO NOT harvest for 2 days after application. Pigeon peas, Soybeans: DO NOT harvest for 4 days after application.	Not all glyphosate formulations are registered for these uses. Field peas/Faba beans: Pre-harvest application to reduce viable seed set of annual ryegrass. Adzuki beans*/Chickpeas*/ Cowpeas*/Faba beans*/Field peas*/Lentils*/Mungbeans*/ Soybeans*: Pre-harvest application to desiccate a crop as a harvest aid and weed control – annual weeds. Chickpeas*: Glyphosate + metsulfuron tank mix for pre-harvest application as harvest aid and weed control – annual weeds (selected formulations only – check individual labels). WHP: DO NOT harvest within 7 days of application. Refer to label for specific timings. *Application to crops intended for seed production or for sprouting may reduce germination percentage to commercially unacceptable levels.	Desiccation timing: Faba bean: Hilum black in the pods at the top of the canopy (30–80% of pods ripe and dark) Field pea: 30% seed moisture or when lower 75% of pods are brown with firm seeds and leathery pods Chickpea: 80–85 % of pods within crop have turned yellow-brown Lentil: just after crop starts to yellow (or senesce) Narrow leaf lupin: at 80% leaf drop. Apply to direct harvested lupins only. Application prior to windrowing will result in severe loss of grain yield. Early applications other than described above may result in grain yield penalties. In order to guarantee good coverage, it is recommended to apply at minimum 100 L/ ha volume. May have a negative effect on lentil germination. Do not use on lentil crops for seed production. ALWAYS apply Sharpen® with 1% v/v Hasten® spray adjuvant or high quality methylated seed oil (MSO). WHP: DO NOT harvest for 7 days after application.

[#] An APVMA minor use permit (PER 82594) is in place until 30 April 2020 that permits pre-harvest use of Weedmaster® DST® and Weedmaster® Argo® glyphosate formulations on feed barley crops. No glyphosate products are approved for use on malt barley crops.

[1] Diquat only; [2] Not glyphosate; [3] Paraquat only; [4] Glyphosate only; [5] glyphosate and diquat only

WHP = withholding period; v/v = volume per volume

Disclaimer: The information contained in this table has been compiled as a guide only. Registrations can and do change regularly. All users of herbicide products must read the label of the product they are using and follow the directions printed on that label.

Practicalities

Key practicality #1

The ideal time for crop-topping is when the annual ryegrass is just past flowering and the pulse crop is as mature as possible.

Plan crop-topping at the start of the season so that suitable crop species and variety can be carefully selected to minimise yield loss. The tactic works best with early maturing pulse varieties.

The best weed control will be achieved if crop-topping takes place when the weed is flowering and/or at the soft dough stage of seed development (*Table T3.1b–2*).

Table T3.1b–2 Crop-topping results from a range of farmers' paddocks tested in 2001, Geraldton, Western Australia (Newman 2003).

Lupins (% leaf drop)	Annual ryegrass development stage	Germination test annual ryegrass control (%)
90	Late flower/milky dough	90–95
90–100	Milky to soft dough	96
90–100	Firm dough	52
100	Hard	7

Figure T3.1b–1 Germination of field peas can be affected by application of glyphosate at maturity. The earlier the application the higher the likelihood of seed damage.
Photo: Eric Armstrong

Unfortunately, the window of physiological difference between crop and weed is not always as wide as required, and yield losses may occur or weed control may not be as effective as desired. Crop-topping applied before crop maturity can significantly reduce crop grain yield and quality. A physiologically mature crop (or later stage) will not be damaged by crop-topping.

Table T3.1b–3 shows the impact on yield and grain size of desi chickpeas treated with a range of herbicides when the crop was at the last flowering stage and at maturity (when pods had changed colour).

Key practicality #2

Crop-topping should not be performed on crops where the grain is intended for use as seed or for sprouting.

When the crop is sprayed before physiological maturity, grain viability is likely to be reduced. For this reason, glyphosate is not registered for use on seed crops or on pulse crops intended for the sprouting market. Use diquat on seed crops and, if crop-topping occurs before the crop seed is mature, find an alternative seed source.

Key practicality #3

Crop-topping for wild radish and other brassica weed control in current pulse varieties is not recommended because of the closely matched rate of development of weed and crop.

The ideal time to apply non-selective herbicides to reduce wild radish (*Raphanus raphanistrum*) seedset is when the wild radish is at the early flowering and pod development stage. The pod is still very thin and the seed has not reached the embryo stage. The pod will be squashy and watery when pressed between thumb and finger (Cheam et al. 2004).

For crop-topping to be effective at reducing wild radish seedset, the weed must be treated before embryo development. If crop-topping is delayed in order to preserve lupin yield, the weeds will have sufficient time to reach the embryo development stage and thus become more tolerant of the herbicide treatment.

In the experiment results summarised in *Table T3.1b–4*, 92% of the wild radish present in the crop had already reached the embryo stage before the lupins had achieved sufficient physiological development to be sprayed without significant yield loss. The delay caused by waiting for physiological maturity of the lupin before spraying is reflected in the poor wild radish seedset reduction seen after the 50% lupin leaf-fall stage.

Table T3.1b–3 Effect of herbicide on desi chickpea yield and grain size at two crop-topping application times, North Star, New South Wales, 1996 (Storrie and Cook 2000).

Crop maturity	Herbicide	Rate (L/ha)	Yield (% of untreated)	% of total grain with diameter >6 mm	Comment
Chickpeas at last flower	Glyphosate 450	1	98	46	Yield loss, significantly smaller grains
	Basta®	2	83[a]	41[b]	
	Spray.Seed®	2	90[a]	36[b]	
Physiological maturity, 90% pods changed colour	Glyphosate 450	1	105	51	Yield stable, grain size unaffected
	Basta®	2	103	47	
	Spray.Seed®	2	101	54	

[a] >10% yield reduction; [b] significantly less than untreated

Note: Information presented in this table includes results from non-registered herbicide uses. However, the presentation of this research data does not imply a recommendation for non-registered herbicide use. All herbicide use should be in accordance with the directions printed on the herbicide product label.

Table T3.1b–4 Reduction in wild radish seedset (%) and grain yield losses of lupin cv Belara (%) compared with untreated control following crop-topping of lupins at various maturity stages, Western Australia (adapted from Cheam et al. 2004).

Herbicide	Lupin growth stage – measured as leaf-fall							
	Zero lupin leaf-fall		50% lupin leaf-fall		80% lupin leaf-fall		100% lupin leaf-fall	
	Yield loss	Seedset	Yield loss	Seedset	Yield loss	Seedset	Yield loss	Seedset
Paraquat (250 g/L) at 800 mL/ha	65	100	7	13	4	16	0	17
Glyphosate (450 g/L) at 1 L/ha	100	100	15	32	12	20	1	26

Note: There are currently no non-selective herbicide registrations for crop-topping wild radish in pulse crops.

Different herbicide treatments are also contrasted in *Table T3.1b–4*. Applying glyphosate early (at the zero lupin leaf-fall stage) resulted in a complete kill of the crop. However, the lupins managed to partially recover from the early (zero lupin leaf-fall) Gramoxone® treatment. Evidence from the later spray timings also indicated that glyphosate has a more damaging effect on lupins than Gramoxone®.

Desirable weed seedset reduction is only achievable in lupins with significant crop yield loss. Work by Storrie et al. (2006) in northern NSW showed similar trends for crop-topping turnip weed (*Rapistrum rugosum*) and wild mustard (*Sinapis arvensis*) in chickpeas.

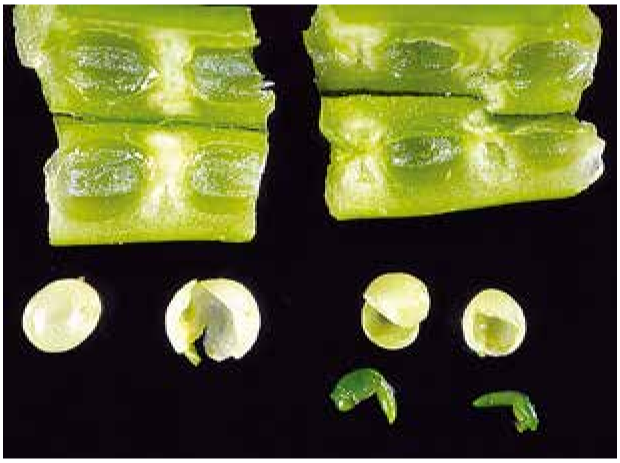

Figure T3.1b–2 Dissected wild radish pod showing pre-embryo stage (left) and embryo stage (right). *Photo*: Peter Maloney

Key practicality #4

Crop-topping timing is crucial to reduce risk of residues impacting market access

Application of herbicides close to harvest increases the possibility of detectable herbicide residues being present in harvested grain. Maximum residue limits (MRLs) vary according to herbicide, crop and market. Compliance with Australian MRLs does not guarantee the grain will meet an importing country's MRL. It is important to know the destination of your grain and to check both domestic and importing countries' MRLs to determine what herbicides are permitted on that crop. Breaches of MRLs can lead to rejected grain both domestically and by the importing country. Late season herbicide use must strictly comply with the registered label to ensure Australian MRLs are not breached. Growers should seek advice from their grain buyers before using late applications of herbicides. This is very important for seed that is intended for sprouting.

Contributors

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References

Cheam A, Lee S and Peirce J 2004. How effective are crop-topping and blanket wiping in reducing wild radish seed-set? *Proceedings of Crop Updates 2004*. Perth. Department of Agriculture and Food WA and Grains Research and Development Corporation.

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Matthews JM, Llewellyn R, Powles S and Reeves T 1996. Integrated weed management for the control of herbicide resistant ryegrass. *Proceedings of the 8th Australian Agronomy Conference*, Toowoomba.

Newman P 2003. Crop-topping lupins for ryegrass control. *e-weed* 2003, vol, 4, no. 16,pp. 67–70.

Storrie AM and Cook AS 2000. Late Weed Control in Chickpeas. *GRDC project DAN 262 NR Final report*. Grains Research and Development Corporation.

Storrie AM, Moylan PD and Cook T 2006. Seed set control of charlock and turnip weed in chickpeas. *Proceedings of Symposium Wild Radish and other cruciferous weeds*. Department of Agriculture and Food, Western Australia, 2006.

Further reading

Hashem A, Dhammu H, Stewart V, Rayner B and Collins M 2000. Can blanket wiping and crop topping prevent the seed set of resistant wild radish and mustard? *Proceedings of Crop Updates 2000*. Department of Agriculture Western Australia.

Llewellyn R and Walsh M 2003. Target weed weaknesses to win resistance war. *Farming Ahead*, no. 140, pp. 44–45.

Mayfield A 1995. Controlling Escape Ryegrass in Legume Crops. *Final report: AMC 1*. Grains Research and Development Corporation.

Mayfield A 1998. Crop-topping in pulses with paraquat and glyphosate for control of annual ryegrass. *Proceedings of Crop Protection Technical Symposium – Highlights of weed research and development in Western Australia for weed science programs*, Western Australia.

Tactic 3.1c Wiper technology

Wick wiping, blanket wiping, carpet wiping, and rope wicking are all forms of weed wiping technology that aim to reduce weed seedset by using a range of devices to wipe low volumes of concentrated herbicide on to weeds that have emerged above the crop.

Figure T3.1c–1 Blanket wipers use a sheet (blanket) moistened with herbicide to apply to weeds above the crop.
Photo: Andrew Storrie

Benefits

Key benefit #1

Weed wiping is selective due to the application method rather than the herbicide used.

The technique allows the use of a non-selective herbicide such as glyphosate at the late post-emergent stage to control seedset of weeds growing above the crop canopy. The use of paraquat in weed wiping technology has just been approved for use overseas, but at the time of writing its use was not approved in Australia.

Weed wiping is most effective on individual plants or small populations of weeds growing 20 to 30 cm above the height of the crop. Larger infestations result in more contact between weeds and crop, causing transfer of herbicide which can lead to crop damage and yield penalties.

Weed wiping is used extensively in lentils (a short stature crop) to control the seedset of hard-to-manage muskweed (*Myagrum perfoliatum*).

Rayner and Peirce (1996) found that 1- and 2-leaf cape tulip (*Moraea flaccida* and *M. miniata*) could be controlled in pastures with no damage to the subterranean clover (*Table T3.1c–1*).

Key benefit #2

Weed wiping is an effective method of reducing seedset in weeds which have not been controlled by tactics used earlier in the growing season.

Weeds that have survived other tactics used earlier in the season can be targeted with weed wiping if the weeds are not dense and rise above the crop canopy. Effective seedset reduction can be achieved (*Table T3.1c–2*).

Practicalities

Key practicality #1

Care is needed to ensure that excess herbicide does not drip on to the crop and cause damage.

Hashem and Devenish (2001) showed that up to 48% crop yield loss is possible if there is insufficient height difference between the crop and the target weeds, or if the herbicide drips on to the susceptible crop.

Keys to successful application include:

- Controlling herbicide flow to avoid dripping on to the crop.
- Stabilising broadacre weed wipers to avoid contact with the crop canopy.
- Targeting areas of low weed density. Dense patches of weeds tend to be knocked into the crop, causing transfer of herbicide from the treated weeds to the crop.
- Wiping in two different directions for optimal herbicide application.
- Applying only to target weeds which rise more than 25 cm above the crop canopy.
- Consulting product labels for application rates. At the time of writing only some formulations of glyphosate have been registered for use through a weed wiper.

The Cooperative Research Centre for Australian Weed Management conducted research into the use of translocated herbicides and synergistic mixtures of non-selective herbicides for use in weed wiping, aimed at controlling seedset and minimising crop damage (Storrie et al. 2006).

Failure to observe caution with the technology may still reduce seedset but there can be detrimental effects on the crop.

Table T3.1c–1 Control of 1- and 2- leaf cape tulip one year after using a wiper in a subterranean clover pasture (Rayner and Peirce 1996).

Treatment	Rate per ha	% reduction 1-leaf	% reduction 2-leaf
Metsulfuron	0.5 g	88 [bcd]	52 [b]
Metsulfuron	5 g	97 [d]	94 [cd]
Metsulfuron + glyphosate (450 g/L)	5 g + 250 mL	89 [cd]	90 [cd]
Metsulfuron + glyphosate (450 g/L)	5 g + 500 mL	89 [cd]	94 [cd]
Untreated		0 [a]	0 [a]

Values followed by the same letter do not differ significantly (P<0.05).

Table T3.1c–2 Seedset reduction of wild mustard and wild radish using blanket wiping in chickpeas and barley (Hashem and Devenish 2001).

Situation	Target weed	Herbicide	Seed-set reduction
Chickpeas at flowering [a]	Wild mustard	Glyphosate or 2,4-D amine + chlorsulfuron	74–91%
Barley [b]	Wild radish	2,4-D amine + chlorsulfuron	98%

[a] In this experiment there was insufficient height difference between target weed and crop.

[b] The treatment in barley resulted in an 89% reduction in wild radish emergence in the following crop.

Key practicality #2

Timing of weed wiping is the key.

The best time to use weed wiping is when the target weed is most vulnerable. For muskweed, wiping at flowering to early pod fill stages will achieve the greatest reduction in seedset (Stuchbery 2002; *Table T3.1c–3*). The degree of weed control decreases after the weed reaches mid pod fill.

The best control of wild radish (*Raphanus raphanistrum*) in lupins and chickpeas is achieved when the weed is at early to mid flowering and has soft squashy pods (Cheam et al. 2004).

Research at Wagga Wagga showed glyphosate was more effective than paraquat in killing wild radish (98% compared with 94%) at the pre-embryo stage of the seed. Paraquat only controlled 12% of wild radish seed production compared with glyphosate which gave 33% control at the post-embryo seed stage (McGillion and Koetz 2005).

The seedset of annual ryegrass (*Lolium rigidum*) is greatly reduced when weed wiping occurs at or before flowering (Stuchbery 2002).

Key practicality #3

A special applicator is required for weed wiping.

Weed wipers apply herbicides at a concentrated rate, usually between 1 L of chemical to 2 L of water down to 1 L of chemical to 40 L of water.

Weed wipers have developed significantly since the early days of the single rope, gravity-fed models of the late 1970s to early 1980s. Currently there are models with multiple ropes, carpets, sponges, revolving cylinders and pressurised supply. At least one manufacturer has a system that senses the wetness of the pad and automatically switches on the pump to maintain pad wetness.

A grower group in the Victorian Wimmera region has designed and developed a broadacre wick wiper which can apply concentrated chemicals while travelling at up to 18 kph. This allows areas as large as 400 ha to be wiped in one day. Individual farmers are modifying existing booms with the addition of a line of porous hose which is a quick and inexpensive solution for problem weeds such as muskweed in lentils.

Table T3.1c–3 Seed production and seed viability of muskweed in eight commercial paddocks following glyphosate application with a weed wiper (Stuchbery 2002).

Paddock #	Growth stage of muskweed	Seeds per plant		Germination %	Comments
		Total	Viable		
1	Flowering – early pod fill	134	0	0	Small pods, 50% seed shrivelled
2	Flowering – early pod fill	292	3	1	Small pods, 50% seed shrivelled
3	Flowering – very early pod fill	43	9	22	Low seed number, seed plump but green
4	Mid pod fill	326	33	10	Plump and shrivelled seeds
5	Mid pod fill	335	47	14	Plump and shrivelled seeds
6	Late pod fill	265	56	21	Plump seeds
7	Late pod fill	439	97	22	Large pods, green and plump
8	Late pod fill	489	176	36	Mixture of seed types

Experiments on turnip weed (*Rapistrum rugosum*) in northern NSW with a Weed Swiper™ produced good control on wild mustard (*Sinapis arvensis*) and turnip weed. Chlorsulfuron applied at the pre-embryo stage (soft squashy pods) reduced turnip weed pod set by 95% (Storrie et al. 2006). Glyphosate applied at the same timing reduced pod set by 60%. Late applications (post-embryo) of glyphosate and 2,4-D achieved 50% pod reduction. Chlorsulfuron was ineffective at the later stage. In experiments involving wild mustard, chlorsulfuron and glyphosate reduced pod set by 80%. While some crop damage and yield loss occurred, especially when the crop to weed height differential was less than 20 cm, weed wiping in chickpeas with glyphosate only produced 2 to 8% yield losses.

Including weed wiper technology as part of an integrated weed management plan for wild mustard and turnip weed has seen numbers remain low and slowed the development of herbicide resistance, particularly to Group B herbicides (Cheam et al. 2008).

Contributors

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References

Cheam A, Lee S and Peirce J 2004. How effective are crop-topping and blanket wiping in reducing wild radish seed set? *Proceedings of Crop Updates, 2004 Perth*. Department of Agriculture Western Australia.

Cheam AH, Storrie AM, Koetz EA, Holding DJ, Bowcher AJ and Barker JA 2008. Managing wild radish and other brassicaceous weeds in Australian cropping Systems. Cooperative Research Centre for Australian Weed Management, Adelaide, Australia.

Hashem A and Devenish K 2001. Blanket wiping prevents radish seed production. *e-weed* 14. Department of Agriculture, Western Australia.

McGillion T, Koetz E 2005. Hit radish early to control seed set. *Farming Ahead*, no. 163, August 2005.

Rayner B J and Peirce J R 1996. Weed control in Western Australia using blanket wipers. *Where in the world is weed science going?: 11th Australian Weeds Conference*, Melbourne, Victoria, (ed RCH Shepherd), pp. 66-68, Weeds Society of Victoria.

Storrie A, Moylan P and Cook T 2006. Seed set control of charlock and turnip weed in chickpeas. *Proceedings of the Wild Radish and other Cruciferous Weeds Symposium*, South Perth, 2006.

Stuchbery J 2002. Weed wiping impresses in field trials. *Australian Grain*, vol. 12, p. 41.

Further reading

Rayner B 2005. Blanket wipers for tall weed control. *Farmnote 75/2005*. Department of Agriculture and Food, Western Australia

Tactic 3.1d Crop desiccation and windrowing

Crop desiccation and windrowing (also called swathing) are harvest aids which ignore the growth stage of any weeds present, so they are not true weed seedset control tactics. However, in certain conditions windrowing and crop desiccation can provide significant weed management benefits.

The tactics are defined as the termination of crop growth by physical (windrowing) or chemical (desiccation) means at physiological maturity or a later stage.

Benefits

Key benefit #1

Windrowing used in conjunction with other tactics can greatly enhance weed control results.

In conjunction with trash burning and the collection of residue at harvest, windrowing can minimise the addition of weed seeds to the seedbank (see *Tactic 1.1 Burning residues* and *Tactic 4.1 Weed seed control at harvest*).

Weed seeds that would otherwise be shed before harvest are cut and concentrated into windrows. Seed remaining in the weed seed-heads in the windrow are likely to be processed by the header, with the option of being removed in a seed collection system. Seeds that drop out of the seed-heads will generally fall through the windrow to the ground but will remain concentrated in a narrow band.

Figure T3.1d–1 Raking stubble (following crop windrowing and harvesting without spreaders) concentrates the stubble into a narrower windrow which gives a hotter burn that kills more seeds. *Photo*: Warwick Holding

Key benefit #2

There is a chance that crop desiccation or windrowing will reduce weed seedset.

Used on an early maturing crop and variety, desiccation can reduce the seedset of many weeds, including annual ryegrass (*Lolium rigidum*), without reducing crop yield or quality.

Because crop desiccation is timed according to crop maturity, it will only be effective as a weed management tool if its use coincides with the period when weed seed development is sensitive to the chemical used. Crop desiccation or windrowing can reduce the quantity of seed produced by later germinating weeds.

Table T3.1d–1 shows that windrowing can be an effective means of reducing wild radish seedset (*Raphanus raphanistrum*), particularly if the crop matures before completion of weed seed development. The earlier maturity of the barley and canola, compared with wheat and lupin, resulted in greater reduction of pod numbers. In the poorly competitive lupins, windrowing greatly reduced wild radish seed production compared with the control treatment, which was not windrowed.

Key benefit #3

Windrowing or desiccation can help manage late germinating weeds.

Spring rain promotes the germination of a range of weeds that become a problem in summer fallow. Desiccation or windrowing of winter crops removes a potential harvest nuisance and a summer fallow problem.

Whole-farm benefits

Windrowing and desiccation can:

- assist harvest schedule
- encourage even ripening of crops
- increase harvest speed and efficiency
- minimise yield loss from shattering or lodging
- enhance seed quality
- overcome harvest problems caused by late winter or early summer weed growth
- minimise weather damage during harvest by increasing the speed of drying, while protecting the crop in the windrow
- improve the yield of following crops by halting water use by the current crop. Crops can continue to use soil water when past physiological maturity.

Practicalities

Key practicality #1

Timing is the key to maximum yield and quality.

Yield and quality will be optimised at crop physiological maturity (*Table T3.1d–2*).

Table T3.1d–1 Wild radish seed production levels in wheat, lupin, barley and canola crops as influenced by windrowing at crop maturity, Goomalling, Western Australia (Walsh 2001).

Treatment	Wild radish (seeds/m²)				Wild radish seed and pod reduction (%)			
	Wheat	Lupin	Barley	Canola	Wheat	Lupin	Barley	Canola
Control	5,565	10,220	4,873	7,974				
Windrowing	4,787	4,901	1,849	2,932	14	52	62	63

Table T3.1d–2 Optimum timing for windrowing of different crops (compiled from Metz 2004).

Crop	When to windrow
Canola	At 45 to 60% seed colour change in cool weather. Hot weather can increase shattering losses.
Barley	From 30% moisture or lower. It is better to windrow early in varieties susceptible to head loss and lodging.
Wheat	1 to 2 days prior to harvest, to reduce grain moisture content.
Lupins	When cotyledons from the primary spike pods are yellow and the cotyledons from the tertiary branch pods are yellowish-green and past the firm dough stage.
Faba beans	When the hilum on the seed has just turned black and the pods are still leathery to touch.
Field peas / vetches	When the seeds from the least mature pods are firm and moisture cannot be squeezed from the pod with pinched fingers.

Key practicality #2

Weed and crop regrowth (post-windrowing) must be controlled to stop seedset.

Apply a non-selective herbicide to manage any regrowth and seedset in-crop or in weeds following windrowing or desiccation.

Some windrowing machines have been adapted by mounting a spray line behind the windrowing front. A non-selective herbicide is sprayed prior to the windrow being laid back on to the paddock surface. This can be an effective way of preventing regrowth and controlling seedset in tillers below the windrow height. Note that only herbicides that are registered as desiccants for the crop in question can be used due to grain minimum residue level (MRL) issues. Observe harvest withholding periods.

Key practicality #3

Weeds and tillers below cutting height will not be incorporated into the windrow.

There is a practical limitation to the lowest height at which crops can be cut. Any weeds that grow below this height will escape this management tactic.

Key practicality #4

Check herbicide labels.

Crop desiccation is registered in a limited number of crops. Weed control guides produced by state departments of agriculture and primary industries contain tables outlining registrations for desiccation. Always check herbicide labels, follow the directions on the label and adhere to harvest and grazing withholding periods.

Key practicality #5

Windrowing in hot weather can increase losses due to shattering.

Hot weather can cause the rapid desiccation of standing crops and windrowing of such crops can lead to significant shattering losses.

Contributors

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References

Metz N 2004. Swathing, a Harvest Management Tool for Western Australia. Co-operative Bulk Handling Ltd and Fitzgerald Biosphere Group Inc.

Walsh M 2001. Crop-topping to reduce wild radish seed production. *Proceedings of the Mingenew Irwin Group Crop Updates*, March 2001.

Further reading

Armstrong E, Carpenter D and Matthews P 1999. Desiccation and harvest of field peas. *Pulse Point 5* (2nd ed.) New South Wales Department of Primary Industries.

Carpenter D 2000. Windrowing lupins. *Pulse Point 10*. New South Wales Department of Primary Industries.

Matthews P and Carpenter D 1999. Windrowing faba beans. *Pulse Point 9*. New South Wales Department of Primary Industries.

Tactic 3.2 **Pasture spray-topping**

The composition of a medium-term ('phase') pasture dominated by annual legumes and grasses (a three- to five-year pasture phase between crop phases in a rotation) changes over time. A pasture may be legume dominant in year 1 but often by year 3, without intervention, it will be dominated by annual weeds, often a result of low intensity set stocking. In some regions (and paddocks) the dominant annual weeds are broadleaf, but predominantly they are annual grasses.

Typical grass species that build up in pastures include ryegrass (*Lolium* spp.), silver grass and other vulpia grasses (*Vulpia* spp.), barley grass (*Hordeum* spp.) and brome grass (*Bromus* spp). It is worth noting that before the advent of widespread herbicide resistance problems, annual ryegrass (*L. rigidum*) was often sown as a component of pastures throughout the Western Australian wheatbelt.

Problems caused by annual grass weed build-up in the pasture include:

- a build-up of weed seeds in the seedbank (often herbicide resistant types) that will pose a threat to future crops
- reduced nitrogen availability from pasture legume input as weeds use the nitrogen reserves
- a build-up of cereal root diseases
- an increased risk of eye and hide injury, meat contamination in sheep and increased vegetable faults in wool.

One of the tactics for reducing annual grasses and retaining desirable species in pastures is pasture spray-topping (see *Tactic 3.1a Spray-topping with selective herbicides* to understand the difference between the terms 'pasture spray-topping' and simply 'spray-topping'). This involves applying a non-selective herbicide at a critical time (flowering) followed by heavy grazing, to target weed seedset.

Pasture spray-topping is possible because annual grasses become more sensitive to non-selective knockdown herbicides during flowering. This increased sensitivity allows low herbicide rates to be used to prevent the formation of viable grass seeds, with limited or no effect on desirable pasture species.

'Mechanical topping' refers to slashing or mowing activities late in the season to prevent development of viable weed seeds. It can be used as an alternative to pasture spray-topping, especially if weeds are resistant to knockdown herbicides. Mechanical pasture topping is slower and more expensive than pasture spray-topping (*Table T3.2–1*) and there is greater likelihood of the plants regrowing to produce seed.

Integrating multiple methods of seedset control in pastures may be useful if the problem is resistance to knockdown herbicides.

Targeted grazing can be very effective as a mechanical pasture topping tactic provided that sufficient numbers of dry sheep are available (see *Tactic 3.5 Grazing – actively managing weeds in pastures*).

Figure T3.2–1 Strip of pasture dominated by barley grass and capeweed spray-topped (right) and untreated (left).
Photo: Sally Peltzer

Table T3.2–1 Pasture spray-topping compared with mechanical management and targeted grazing for seedset control in pastures.

Tactic	Advantages	Disadvantages
Pasture spray-topping with paraquat or glyphosate	• Quick • Economical • Pasture can be grazed afterwards (check withholding period) • Efficacy on target weed can be ≥90%	• Desirable species can be affected (glyphosate can be more of a problem than paraquat) if timing is poor
Mechanical topping (see Note 1)	• Non-selective • Can be used on organic farms • Used in conjunction with grazing	• Time-consuming • Plants often regrow, especially if rain falls soon after cutting • Can have profound effect on species balance
Targeted grazing (see Note 2)	• Non-chemical option for organic farms • Small positive income stream from wool production	• Large numbers of dry (see Note 2) sheep needed • Difficult to treat large areas • Stock may increase density of some species (e.g. vulpia) • Can have profound effect on species balance

Note 1: Non-herbicide methods can be highly effective in changing the species balance in annual pasture (see *Table T3.3–2*). While mechanical topping and grazing may not be as time efficient as pasture spray-topping, they are viable alternatives where herbicide use is not possible or desirable.

Note 2: The grazing technique required to alter pasture grass composition generally involves placing a lot of stress on the sheep involved, and excessively stressed ewes and lambs will exhibit reduced performance. Unless sufficient grazing pressure is applied, sheep will ignore the targeted grasses.

Figure T3.2–2 Anthers (yellow pollen sacs) about to emerge from the ryegrass flowers. An ideal time to spray-top with paraquat.
Photo: Andrew Storrie

Benefits

Key benefit #1

Strategically timed pasture spray-topping significantly reduces the production of viable weed seed in pastures.

Pasture spray-topping of annual ryegrass has resulted in a 30 to 80% decrease in seed production (Gill and Holmes 1997). The variation between spray-top experiments is due to a number of factors, including the development stage of annual ryegrass, grazing pressure and rain after treatment. There have been reports of an 85% decline in annual ryegrass density after spray-topping (Gill and Holmes 1997).

Dowling (1997) collated data for several experiments that showed large decreases in grass species following pasture spray-topping (*Table T3.2–2*).

Variations between experiments can often be explained by differences in application timing . In addition, some *Vulpia* species never extend their heads fully from the boot (Dowling 2005, pers. comm.), which may partly explain some of the low control of *Vulpia* species in the above data. Leys et al. (1991) investigated the effect of pasture spray-topping application time with paraquat and glyphosate on the regeneration of vulpia. Their results showed that for both herbicides application timing was critical for the level of regeneration of vulpia obtained. Pasture spray-topping at heading and flowering (anthesis) was more effective at reducing vulpia than pasture spray-topping at grain fill (*Figure T3.2–3*).

Table T3.2–2 Effect of pasture spray-topping in the previous spring on percentage reduction of seedling numbers in the following autumn compared with untreated control (Dowling 1987).

Grass species % control				Source of data
Lolium spp.	*Hordeum* spp.	*Bromus* spp.	*Vulpia* spp.	
94	98	94	98	Blowes et al. 1984
–	88	87	69	Departments of Agriculture (Victoria and Western Australia)
–	85	85	85	England 1986
96	77	97	97	Dowling (unpublished data)

Research in Western Australia (Stewart and Mann 1988) has shown that the number of viable seeds or tillers of barley grass is low when spray-topping is conducted before anthesis is complete. Once anthesis ends, pasture spray-topping in barley grass is not as effective for seedset control (*Figure T3.2–4*).

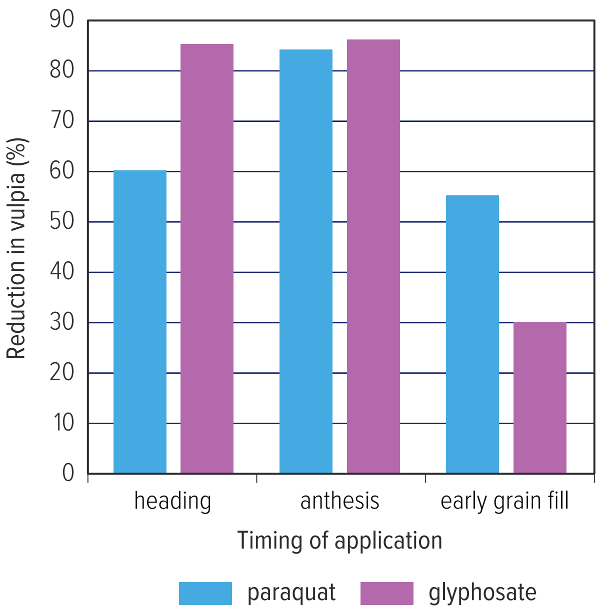

Figure T3.2–3 The effect on growth stage of vulpia at time of pasture spray-topping with paraquat 250 g/L and glyphosate 450 g/L on the regeneration of vulpia: average of three replicates by two years by two rates (Leys et al. 1991).

Key benefit #2

Both paraquat and glyphosate can be used for pasture spray-topping.

The availability of both paraquat and glyphosate for pasture spray-topping allows for flexibility in mode-of-action rotation, particularly in situations where either herbicide has been used regularly in past seasons or where resistance to a selective herbicide has developed in the target weed.

Key benefit #3

Pasture spray-topping is a cost-effective tactic to reduce weed seedset and the weed seedbank.

Pasture spray-topping uses one third to half the rate of knockdown herbicide compared with a fallow application herbicide rate. This makes pasture spray-topping a low cost operation compared with mowing, fallow and winter cleaning.

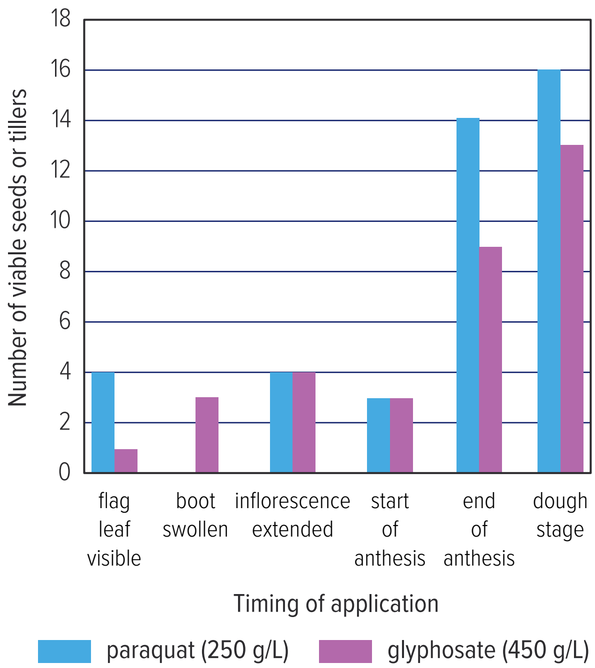

Figure T3.2–4 The effect of pasture spray-topping on barley grass seedset control using paraquat and glyphosate (Stewart and Mann 1988).

Whole-farm benefits

Additional benefits gained from pasture spray-topping include the following:

- The proportion of legume in the pasture is increased, resulting in improved feed value of the pasture and increased livestock production from grazing.
- Well-planned pasture spray-topping can be used to set up pastures for high-quality forage conservation (hay or silage) in the following spring.
- Pasture spray-topping is ideally used in the season before fallow initiation, reducing grass weeds and the risk of cereal disease carryover into the next winter crop.
- Pasture spray-topping can be effective against grass seed injuries to lambs' eyes and skin and damage to carcasses.

Practicalities

Key practicality #1

The timing of herbicide application is critical to the success of pasture spray-topping.

Pasture spray-topping must be timed according to the growth stage of the target grass weed. This period extends from when the seed-heads are fully emerged from the boot until the seeds reach the dough stage.

Timing varies slightly between glyphosate and paraquat. In general, the application window for both herbicides begins when all the seed-heads have been extended from the boot. However, the application window for glyphosate ends at the milky dough stage, whereas the window for paraquat application ends a little later, when the most mature seed-heads begin to hay off.

Seed-heads that are still partly enclosed by the upper (or 'flag') leaf may not be 'topped' and viable seed is likely to develop. The seed-heads of some grasses (e.g. *Vulpia* spp.) never fully emerge from the flag leaf.

As a result, the level of seedset control obtained from pasture spray-topping these species may be less than for those species where the majority of seed-heads fully emerge.

An example of the control given in a broad-leaf weed by pasture spray-topping is shown in *Figure T3.2–5*, which illustrates control of saffron thistle (*Carthamus lanatus*) by pasture spray-topping at four different growth stages.

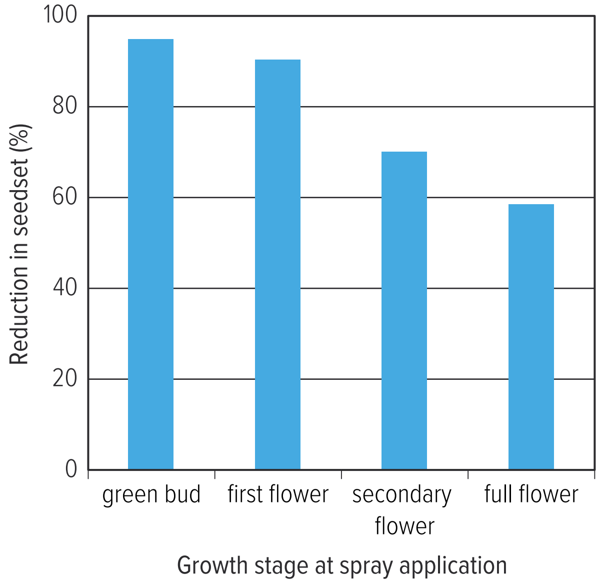

Figure T3.2–5 Reduction in saffron thistle seedset, after pasture spray-topping, at various growth stages. Pasture spray-topping used paraquat 250 g/L at 400 mL/ha and BS1000 at 60 mL/100 L (Watson 1990).

Key practicality #2

Pasture spray-topping is not an alternative to fallow spraying.

Pasture spray-topping aims to alter pasture composition by suppressing seedset in a targeted grass weed, while fallow spraying aims to kill all species present, thus initiating the fallow period.

The application window for pasture spray-topping is much narrower than for fallow spraying. Fallow spraying can be carried out much earlier than pasture spray-topping, although the latest time to successfully use either technique is similar. Furthermore, the herbicide application rates for fallowing are much higher than that for pasture spray-topping as the aim is to kill all plants outright.

Key practicality #3

Pasture spray-topping as a lone tactic cannot control a wide range of grass species simultaneously.

The success of pasture spray-topping depends on the application of herbicide at flowering. It therefore cannot be successfully used to control seedset in more than one species with one application unless the sensitive growth stage of both species occurs simultaneously. Alternatively, more than one application can be made to target different growth stages but this greatly increases the cost of the pasture spray-topping technique.

Key practicality #4

Grass weed levels determine the management 'fit' of pasture spray-topping in a pasture phase.

Grass weed density increases in response to increasing nitrogen. Typically a legume dominant pasture will be invaded by grass weeds in the second or third year of the pasture phase, depending on a range of factors such as grazing management and soil fertility.

Pasture spray-topping can be used to manipulate grass weed density to extend the pasture phase an extra year or two.

Key practicality #5

Winter cleaning or fallow spraying may be a better option to finalise the pasture phase before cropping commences.

In the final year of a perennial and/or subclover-based pasture phase the pasture should be winter cleaned if a cereal crop is to follow, or fallow sprayed if canola or another non-cereal crop is to be sown.

Winter cleaning uses non-selective or certain selective herbicides for the complete control of all annual weeds during their vegetative stage in winter. Pasture spray-topping, on the other hand, targets seedset in spring and uses lower herbicide rates than winter cleaning or fallow.

Table T3.2–3 presents management options to follow pasture spray-topping.

Key practicality #6

Spray-topping can reduce seedset in annual pasture legumes if the legume pasture development stage coincides with the development stage of the target annual grass.

There is some discussion about the effect of pasture spray-topping on the desirable pasture species, particularly subclover and medics. Evidence suggests that using paraquat for pasture spray-topping is less damaging to the legume component of pastures than using glyphosate (Milne 1990). Blowes et al. (1984) reported that when glyphosate was used for pasture spray-topping, some reductions in legume seedset were expected even though the legumes were much more tolerant to glyphosate than grasses at the time.

Other work has shown that repeated use of pasture spray-topping may be detrimental to the seedbank of desirable legumes (e.g. subclover and medic), requiring pasture to be resown (Ferris 1998).

Where pasture legume seedbank numbers are low (e.g. in newly sown pastures) pasture spray-topping should be used with caution. Pasture legume seedset plays a critical role in maximising early competition with weeds and pasture dry matter production during the following autumn.

Key practicality #7

Weeds already resistant to glyphosate or paraquat will not be controlled by pasture spray-topping with these herbicides.

Despite the fact that pasture spray-topping is targeting a different plant growth stage (i.e. flowering and seedset), a plant already resistant to that herbicide mode-of-action will show little or no effect.

Table T3.2–3 Management options in the year following pasture spray-topping.

Year 1	Year 2 options	Advantages	Disadvantages
Spray-topping	Fallow spraying	Ideal preparation for canola or other non-cereal crops sown in year 3. Stock can graze sprayed forage. Quick and economical.	May not be early enough to control cereal diseases such as take-all.
	Winter cleaning (pasture manipulation)	High levels of take-all suppression likely. A good technique when targeting high yield and grain quality wheat in year after pasture.	Only feasible if legume content is high. Pasture needs to be managed carefully before spraying. All herbicide options will suppress annual legume dry matter production.
	Fodder conservation	Hay or silage production will further reduce weed content of pasture. Best for managing resistant weeds.	Only feasible if the conserved fodder can be used economically (tends to preclude large areas).

Contributors

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References

Blowes WM, Jones SM, England PJ and Fraser PK 1984. Pasture topping using Roundup® – a review. *Proceedings of the 7th Australian Weeds Conference*, vol. 1, pp. 351–354, Weed Society of Western Australia for the Council of Australian Weed Science Societies.

Dowling P 1987. Herbicide manipulation for pasture rejuvenation – permanent pastures. *Proceedings of Riverina Outlook Conference*.

England P 1986. Pasture topping with Roundup® herbicide. *Proceedings of Conference on Recent Advances in Weed and Crop Residue Management*. Southern Conservation Farming Group, Occasional Publication no. 2, pp. 104–105.

Ferris DG 1998. Subterranean clover seed bank responses to pasture management. *Proceedings of the 9th Australian Agronomy Conference*, Wagga Wagga, New South Wales.

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Leys AR, Cullis BR and Plater B 1991. Effect of spraytopping applications of paraquat and glyphosate on the nutritive value and regeneration of vulpia (*Vulpia bromoides* (L.) S.F. Gray). *Australian Journal of Agricultural Research*, vol. 42, pp. 1405–1415.

Milne B 1990. Spray topping – the effect on subterranean clover seed reserves. *1990 Weed Research & Demonstration Results*, Orange Agricultural Research and Veterinary Centre, New South Wales Agriculture.

Pannell DJ, Stewart V, Bennett A, Monjardino M, Schmidt C and Powles SB 2004. RIM: a bio-economic model for integrated weed management of *Lolium rigidum* in Western Australia. *Agricultural Systems*, vol. 79, pp. 305–325.

Stewart P and Mann L 1988. Pasture manipulation and spray-topping for barley grass control in medic pasture (Trial number 87KA53). *Division of Plant Industries Experimental Summaries 1988*. Weed Science Branch, Western Australian Department of Agriculture.

Watson R 1990. Saffron thistle and its control in grazing country. New South Wales Agriculture and Fisheries.

Further reading

Anon 2013. NSW DPI Gross Margin Budgets. https://www.dpi.nsw.gov.au/agriculture/budgets/winter-crops

Bowcher AJ 2002. Competition between temperate perennial pasture species and annual weeds: effect of pasture management on population dynamics and resource use. *PhD thesis*, Charles Sturt University, New South Wales.

Tactic 3.3 **Silage and hay – crops and pastures**

Silage and haymaking can be used to manage weeds by:

- reducing the quantity of viable seedset by target weeds
- removing viable weed seeds so that they are not added to the soil seedbank.

Benefits

Key benefit #1

Hay and silage are options that can be used in crops and pastures where excessive numbers of weeds have survived a previous tactic.

Hay and silage each offer the chance to significantly reduce the return of weed seeds to the seedbank. Research has demonstrated that pasture hay production in spring can decrease annual ryegrass (*Lolium rigidum*) density by 84% in the following wheat crop (Gill and Holmes 1997).

Silage followed by application of paraquat can also successfully reduce annual ryegrass seed-head numbers by 95% (from approximately 900 seed heads/m^2 to 40 seedlings/m^2) in the following season (Roy 2005).

Both hay and silage tactics are most valuable to growers when the weeds, crop and/or pasture are nutritious.

Wild oat (*Avena* spp.) and annual ryegrass are excellent fodder species and can be included in either silage or hay for domestic markets, provided annual ryegrass toxicity (see *Section 2 Profiles of common cropping weeds – Weed 1 Annual ryegrass*) is not present. On the other hand, the spikelets on barley grass (*Hordeum* spp.), brome grass (*Bromus* spp.) and vulpia (*Vulpia* spp.), when close to maturity, make them unsuitable for hay or silage.

Figure T3.3–1 Paddock showing hay cutting (left) and brown manuring (right) – two options to stop weed seed set.
Photo: Alex Douglas

Practicalities

Key practicality #1

Consider the balance of using hay or silage as a weed management tactic with other farm enterprises.

Hay and silage production are better suited to farms with a livestock enterprise, as the product can be used on-farm. However, there is a limit to the area of pasture or crop that can be cut for hay or silage simply because too much of either can create a problem of over-supply.

Because the portability of hay is much better than that of silage, hay is preferred when the product must be transported to a market.

Key practicality #2

Time the hay or silage tactic in accordance with the physiological development of the target weed.

Timing the cut and regrowth management is critical for hay and silage production to be successful as weed control tactics. Cutting too late means that mature weed seed is likely to have already been shed, adding to the weed seedbank in the paddock. In the case of hay production, a high proportion of seeds may also remain viable within the hay, becoming a vector for the spread of weed seeds.

Seedset management must be timed according to stage of weed physiological maturity. Hay must be cut when weeds are flowering and before any embryos have developed in the seeds.

The timing of silage production (cut earlier than hay) usually means there are no viable seeds present. Although we assume the ensiled seeds are no longer viable, this has yet to be proven for many common Australian weeds. A Canadian study (Blackshaw and Rode 1991) identified low levels of viability in ensiled broad-leaf weeds. They showed that 3% of black bindweed (*Fallopia convolvulus*) seed remained viable following ensiling, compared with no viable wild oat seeds.

A pasture experiment conducted by Bowcher (2002) demonstrated that, although appropriate timing of cutting is important to reduce target weed seed production, the control regrowth after cutting is critical to reduce weed seed entering the soil seedbank (*Table T3.3–1*). After an early October cut, annual species such as Paterson's curse (*Echium plantagineum*), annual ryegrass and subclover (*Trifolium subterraneum*) were able to regrow. With sufficient growing season remaining, this regrowth set seed and contributed to seedling numbers in the following year (*Table T3.3–1*).

Table T3.3–1 Effect of cutting times on weed seed production (seeds/m^2) of a mixed annual grass/subclover/perennial grass pasture with no regrowth control (adapted from Bowcher 2002).

Time of cut	Annual weed seed production					
	Annual ryegrass		Vulpia		Paterson's curse	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Early October	980	830	1,000	56	970	880
Late October	95	7	210	30	300	90
Early November	240	2,900	2,250	13,650	7	220
Late November	990	6,880	11,990	29,900	210	2,150

Therefore it is essential when using hay or silage for weed management to plan for post-cutting control of regrowth by knockdown herbicide or heavy grazing. If the spring turns dry it may not be required.

Key practicality #3

Carefully consider the options for marketing or using the product on-farm.

Introduced hay or silage has the potential to transport weed seeds. Feed out in dedicated areas to allow for monitoring and control of any germinated weeds. Hay in particular has the potential to contain high proportions of viable weed seed if it has been cut when weeds have already set seed.

A study of weed seeds in hay bales conducted during the 1980 and 1981 drought (Thomas et al. 1984) found that almost all the sampled bales in the Yass, Young and Gundagai districts of NSW contained viable seeds of prohibited or restricted weeds. There were 233 different seed types identified in the 38 bales sampled, and the number of seed types and seeds per bale varied considerably. The study detected one to 30 types of seed per bale, with an average of 21. The number of seeds per bale ranged from 104 to 364, 000, with an average of 68, 700. The hay had been imported from other areas ofNSW, Victoria and South Australia.

Contamination also determines marketing options. Certain weeds such as doublegee (*Emex* spp.) are prohibited in oaten hay exports to Japan, which must be 95 to 97% pure oats (Carpenter 1999).

Figure T3.3–2 The effect of cutting a portion of a crop and making silage (left) compared with harvesting grain (right) on ARG seedling numbers the following autumn.
Photo: Warwick Holding

Key practicality #4

Understand the biological traits of the target weed to improve efficacy of the tactic.

Individual species' responses to cutting, in terms of subsequent regrowth and seed production, will be determined by the maturation stage of the weed at the time of defoliation. Understanding species differences allows for more suitable timing and can thereby improve the effectiveness of the hay or silage tactic (see *Section 2: Profiles of common cropping weeds*).

A study in southern NSW showed that early November was the most effective time to cut annual ryegrass and Paterson's curse (Kaiser et al. 2004). This timing was too late to effectively manage vulpia as it had matured earlier than the annual ryegrass and Paterson's curse, and had produced and shed vast quantities of viable seed before the defoliation occurred (*Table T3.3–2*). In contrast to annual ryegrass and Paterson's curse, it was an early October cut that greatly reduced vulpia seed production and vulpia content in the following year.

Figure T3.3–3 The impact of cutting and baling pasture infested with Paterson's curse can be seen two years later. Here only the left side of the paddock was cut for hay. Photo was taken in spring two years later.
Photo: Warwick Holding

The key is to identify the target weed species and to strike a balance between the problem weeds and other species which contribute to the pasture mix. The experiment results presented in *Table T3.3–2* show that the optimum stage for seedset control of annual grass weeds was when the majority (e.g. 75%) of the most advanced seed-heads were between post-flowering and very early seed fill. For Paterson's curse the optimum cutting time was when the majority of the earliest flowers (lowest on the stem) had started to form green seeds on the most advanced flowering heads. However, the introduction of follow-up controls such as heavy grazing or a knockdown herbicide would negate this issue.

Key practicality #5

Regrowth can produce enough seed to keep the seedbank topped up.

Regrowth monitoring is important because late cutting of hay may not reduce seedbank numbers. Roy (2005) showed that where paraquat was not used to control regrowth, and hay was cut two to three weeks after the silage production, there was an increase in annual ryegrass numbers from 900 seed-heads/m^2 to 1,200 seedlings/m^2 the following year, whereas silage followed by paraquat produced 42 seedlings the next year.

Figure T3.3–4 Regrowth of weeds following silage or hay-cutting must be controlled to prevent seed set.
Photo: Andrew Storrie

A knockdown herbicide or intensive grazing used after an early cut is a reliable way of controlling weed regrowth.

Cutting silage to target forage quality is often too early for weed management. Regrowth will occur and require subsequent additional management.

Table T3.3–3 summarises the issues to be considered when deciding whether to cut for silage or hay.

Table T3.3–2 Effect of grazing by wethers (10 DSE*/ha) and cutting times on species composition of a mixed annual grass/subclover/perennial grass pasture the third spring (year 3) after cutting or grazing in each of the two previous springs (Kaiser et al. 2004).

Species	Initial pasture composition (%)	Grazing only	Grazed then cut in spring (no control of regrowth)			
			Early Oct (silage)	Late Oct (late silage or early hay)	Early Nov (hay [a])	Late Nov (late hay)
			(Percentage of species in pasture in year 3)			
Phalaris and cocksfoot	16	15	18	14	14	17
Subclover	316	18	37	12	16	20
Naturalised clovers	4	<1	4.5	<1	4	7
Annual ryegrass	25	18	28	53	10	9
Vulpia (e.g. silver grass)	16	26	2	10	53	41
Great brome	1	14	2	<1	1	4
Barley grass	<1	5	<1	0	<1	<1
Paterson's curse	4	<1	7	4	1	2
Other broad-leaf weeds	2	3	1	6	<1	<1

* DSE = dry sheep equivalents

[a] Wagga Wagga district practice

Figure T3.3–5 ARG regrowth following hay-cutting must be controlled to prevent seed set.
Source: Andrew Storrie

Table T3.3–3 Considerations when choosing between hay and silage as a weed management tactic.

Issue	Hay	Silage
Prevention of viable seed addition to the weed seedbank in the paddock	Similarly effective, assuming no target weed seed production has occurred before the cut and regrowth is controlled to prevent further weed seed production	
Potential for weed seeds to be spread to other areas during feed out	Moderate to high	Low if ensiled properly
Potential for weed regrowth	Depends on growth stage of weed at time of cut	
Feasibility	Depends on the scale of the operation, livestock enterprises within the business, distance to end-use point and demand for the product	

Contributors

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References

Blackshaw RE and Rode LM 1991. Effect of ensiling and rumen digestion by cattle in weed seed viability. *Weed Science*, vol. 39, pp. 104–108.

Bowcher AJ 2002. Competition between temperate perennial pasture species and annual weeds: effect of pasture management on population dynamics and resource use. *PhD thesis*, Charles Sturt University, New South Wales.

Bowcher A and Holding D 2004. Cultural weed management: Paterson's curse. *Fact sheet*. Cooperative Research Centre for Australian Weed Management.

Carpenter J 1999. Quality oaten hay for export to Japan – a guide for growers. *Farmnote 39/95*. Department of Agriculture, Western Australia.

Gill GS and Holmes JE 1997. Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. *Pesticide Science*, vol. 51, pp. 352–358.

Kaiser AG, Doonan BM and Bowcher AJ 2004. Silage as a pasture management tool; A Kaiser, J Piltz, H Burns and N Griffiths (eds). *Successful Silage*. New South Wales Department of Primary Industries and Dairy Australia, pp. 57–72.

Roy B 2005. IWM as a tool to prevent herbicide resistance becoming an impediment to sustainable cropping. *Technical Report No. ACR4*. Grains Research and Development Corporation.

Thomas AG, Gill AM, Moore PH and Forcella F 1984. Drought feeding and the dispersal of weeds. *Journal of the Australian Institute of Agricultural Science*, vol. 50,pp. 103–107.

Tactic 3.4 **Manuring, mulching and hay freezing**

Crops and pastures can be returned to the soil to reduce weed seedbanks, improve soil fertility and maintain soil organic matter. This can be done by burial, mulching or chemical desiccation.

Green manuring incorporates green plant residue into the soil with a cultivation implement. Most commonly conducted with an offset disc plough, cultivation aims to kill weeds and control seedset while building soil organic matter and nitrogen status. Green manuring has a very long history of managing weeds and building soil fertility in systems where herbicides are either not an option or not available, such as organic farming systems.

Brown manuring is simply a no-till version of green manuring, using a non-selective herbicide to desiccate the crop (and weeds) at flowering instead of using cultivation. The plant residues are left standing. This may also be a preferred option on lighter soils prone to erosion. Before spraying, the crop or pasture can be 'opened up' by grazing, followed by a recovery period, to enable better coverage with the herbicide. This might preclude the need for a double knock to control any regrowth. The standing residues can be grazed post-spraying after appropriate withholding periods have been observed.

Lupins are preferred for manuring in the northern Western Australian wheatbelt, while field peas are preferred in the south. Biomass production is the key to successful manuring. In Western Australia there is a trend towards manuring weeds such as wild radish (*Raphanus raphanistrum*) when there is an early break to the season due to their high biomass. Manuring peas and lupins would cost $70 to $100/ha more than a fallow (Fosbery pers. comm. 2012).

In southern NSW there is renewed interest in brown manuring over fallow because a manure crop competes with weeds, requires less knockdown herbicides and improves accumulation of soil nitrogen and maintenance of soil cover (Patterson 2012). *Table T3.4–1* contrasts the weed management outcomes of green and brown manuring.

Mulching is similar to brown manuring but involves mowing or slashing the crop or pasture and leaving the residue laying on the soil surface. This enables more soil contact with the crop residue and might help reduce soil moisture loss through evaporation. Residues may break down more rapidly as plant pieces are likely to be smaller than in brown manuring.

Hay freezing is similar to brown manuring with the additional aim of creating standing hay. In this case herbicide is applied earlier than if the crop was to be mown for conventional haymaking. Hay freezing is a more reliable tactic for controlling weed seedset than conventional haymaking, with the added advantage that existing boom sprays are used rather than specialised haymaking equipment. The protein content and digestibility of standing hay are similar to those of conventionally baled hay.

Figure T3.4–1 Aerial photo of section of a crop that has been brown manured to control herbicide resistant ryegrass and wild oats.
Photo: Warwick Holding

Benefits

Key benefit #1

Manuring, mulching and/or hay freezing (all with regrowth control) reduce viable weed seedset, thereby controlling high weed numbers and managing herbicide-resistant weeds.

Manuring or hay freezing can greatly reduce seedset of all plants treated, including desirable pasture legumes. Pasture regeneration will be substantially reduced in the following year, depending on the size of the seedbank and the extent of seed dormancy, although it is unlikely you would use this tactic if wanting to go back to pasture the following year.

One of the advantages of hay freezing is that weed seedset reduction is much more reliable than with hay production, as the grower is tempted to maximise hay yield and cut later, allowing some weed seeds to be set. Hay bales also need to be removed from the paddock before spraying of regrowth can occur. In addition, specialised haymaking equipment is not required and existing farm equipment (e.g. a boom spray) can be used. This can be a useful tactic to use when changing from one pasture species to another, or when moving from a pasture to a cropping phase.

Table T3.4–1 Contrasting green and brown manuring.

Weed management outcome	Green manuring	Brown manuring
Effectiveness in preventing seed return to paddock	Depends on weed regrowth. A secondary cultivation or heavy grazing is often needed to ensure complete success.	Tall, dense or tangled herbage may interfere with herbicide coverage and a double knock treatment is advised to control survivors. This may not be necessary if the paddock is grazed to open up the sward before spraying.
Ability of viable seeds to germinate	Burial can induce dormancy in many species. Ideally, the manuring occurs before seeds are mature, so this should apply only to existing seeds in the seedbank.	Herbicides at recommended rates generally have little effect on the ability of viable seeds to germinate. The sward should be sprayed before weeds set viable seed. Existing seeds will be left on the soil surface.

Because a number of legumes are relatively competitive with annual ryegrass (*Lolium rigidum*), green manuring of high-density plantings of legumes (e.g. arrowleaf, Persian and berseem annual clovers) can reduce seedset and subsequent weed germination in the following season (*Table T3.4–2*). The 'no tactic' treatment in the table indicates that field peas are a more competitive crop than lupins.

Table T3.4–2 Annual ryegrass germination (plants/m^2) in autumn following green manuring, silage or hay production of forage break crops compared with pulses harvested for grain. Initial annual ryegrass population was 100 plants/m^2 (Condon 2000).

Weed management tactic	Crop and treatment	Annual ryegrass plants/m^2
Green manuring	Vetch	44
	High density legume	29
Silage	Vetch	44
	High density legume	107
	High density legume, regrowth grazed	16
	Field peas	401
Hay	High density legume	634
	High density legume, regrowth grazed	549
No tactic	Lupins harvested for grain	1,145
	Field peas harvested for grain	721

The extent to which annual ryegrass will be reduced depends on the timing of tactical manuring and control of any regrowth. *Table T3.4–2* presents tactics in chronological order of timing of activity. Green manuring takes place early in the season as yield is not a target, and so the seedset of annual ryegrass is effectively controlled. By contrast, the silage activity commences a little later in the season, with the result that some annual ryegrass can escape the tactic and set seed unless regrowth is controlled (107 weeds/m^2 with no control of regrowth versus 16 weeds/m^2 with grazing of regrowth). In this example haymaking was performed too late in the season to significantly reduce annual ryegrass seedset, and subsequent germinations were high. Also introducing grazing before treatment will improve herbicide coverage by opening the sward and might negate the need for a second control treatment (Condon 2000).

An experiment at Wongan Hills, Western Australia (Hoyle and Schulz 2003) found that annual ryegrass numbers in a wheat crop reduced by 94% following green manuring, 79% following brown manuring and 82% following mulching.

In Western Australia hay freezing pink serradella (cv Cadiz) resulted in the lowest density of annual ryegrass and the highest wheat yields in the year after treatment, compared with green manuring with an offset disc plough or physical pasture topping with a mower. The average reduction of in-crop weed numbers following green manuring, hay freezing and mowing of serradella pasture was 90% (Revell and Hudson 2001).

Key benefit #2

Costs (income loss) from the tactic can be offset by improved yield in subsequent cereal crops and/or by fattening trade stock.

Income loss from manured crops can be mitigated in successive seasons by benefits such as increased canola or wheat yields, improved grain quality and reduced weed control costs. These benefits may in some instances outweigh and exceed the loss of income.

Grazing competitive forage or pulse crops with stock before imposing the treatment can also create significant income from the manured paddock.

Key benefit #3

Weed patches in crops can be treated before hectic harvest time.

Weed infestations (resistant or otherwise) often begin in patches. Killing heavily weed-infested patches prevents production of viable seed and eliminates the risk of weed seed spread by the header.

Both green and brown manuring can be used for treating weedy patches. The more practical option is to use herbicide, which is more effective where weed patches are dense compared with individual weeds scattered through the crop. Hay freezing or baling weed patches can produce a fodder bank to increase the stock-carrying capacity of the property.

Patch treatment should only represent an initial response to the weed problem. It is important to follow up by developing and implementing a weed management plan that uses a range of tactic groups, to reduce seedbank numbers of targeted weeds.

Whole-farm benefits

There are additional benefits from manuring and hay freezing crops:

- Manuring allows continuous cropping to occur with lower production and financial risk.
- Manuring will have a beneficial effect on organic matter and soil nitrogen status. The benefit will be much greater if the crop or pasture being manured has a high legume content. Farm data from the NSW Riverina has shown early-sown pea brown manure crops giving 25 to 30% yield increases in the two subsequent crops.
- Manuring also allows fattening of trade stock before manuring takes place, therefore generating income.
- Green or brown manuring or hay freezing can be used to manage other crop pests and diseases. Using wild radish or other brassica weed species for manuring can also have beneficial soil fumigation effects for diseases.
- A competitive pulse manure crop followed by a canola crop gives an effective break to cereal root diseases and provides extended opportunities for grass weed control.
- Manuring a crop early can give sufficient time for the storage of soil moisture for the following crop.
- Hay freezing provides standing fodder for livestock.

Practicalities

Key practicality #1

Manuring must be carefully timed to prevent seedset and addition to the seedbank.

Tactics aimed at reducing weed seedset must be carried out when the most advanced target weed is at the mid-flowering stage.

Green manuring needs to done a little earlier than brown manuring as seed can continue to develop and mature after the plant has been cut or incorporated with a plough. A general guideline is to green manure at flowering of the most advanced weeds.

Herbicide application for brown manuring and hay freezing can be delayed until the milk stage of the most mature seeds. The herbicide works quickly and prevents further seed development if used at this stage.

Hay freezing for weed control is timed to match weed development and prevent seedset rather than to optimise forage dry matter and quality, and is conducted earlier than conventional haymaking.

Key practicality #2

Choice of crop species will influence crop competitiveness.

Anderson (2005), quoting research by Hoyle and Schultz (2003) investigating the proportion of total biomass that weeds represented within a manuring crop, stated that their results indicated some crop choices were far more effective at suppressing weeds than others (*Table T3.4–3*; also see *Section 5 Agronomy 2 Improving crop competition*).

Table T3.4–3 Summary of weed biomass at flowering in a manure crop averaged across six Western Australian sites (Anderson 2005).

Manure crop	Annual ryegrass mean % of biomass	Range of biomass (%)
Harvested peas	14	7–19
Manured peas	11	1–18
Oats	3	0–7
Pea-oat mixture	3	1–7
Serradella	66	43–92

Table T3.4–4 Annual ryegrass density in wheat crop following green manuring of different crops, Coorow, Western Australia (Anderson 2005).

Treatment in previous season	Annual ryegrass (plants/m²)
Harvested lupin crop	106
Green manured lupins	32
Green manured oats/serradella mixture	29
Green manured oats	19
Green manured mustard	19

Less weed biomass should restrict weed seed production but final weed seed production levels in manure crops and pastures will be dependent on the success of the manuring treatments. *Table T3.4–4* shows in-crop annual ryegrass densities in wheat at Coorow, Western Australia, following various harvest treatments.

In general, manure crop species that had good early vigour and were able to establish quickly (oats or oats and pea mixes) were more effective at suppressing weed growth than those crop or pasture choices with slow early growth. *Table T3.4–5* summarises the ability of the different manuring species to suppress weeds (Anderson 2005).

Table T3.4–5 Summary of suppression ability of different manure crop species (after Anderson 2005).

Excellent	Good	Fair	Poor
Barley	Canola	Faba beans	Clover
Oats	Lupins	Medics	Serradella
Triticale	Vetch		Chickpeas
Wheat			Lathyrus
Field peas			Narbon bean
Mustard			

Although weed growth suppression will be important with glyphosate- or paraquat-resistant weeds, an effective control practice, either herbicide or cultivation, should be performed before weed seedset. Total biomass produced before manuring is one of the important parts of manuring, so selecting crop will create the largest biomass for the expected conditions is very important.

While cereals were good at suppressing annual ryegrass seed production (*Table T3.4–5*), in practical terms they are a poor choice. With these crops growers can be tempted to take the crop through to harvest as a cash return starts to look better and better as the season progresses. Another important reason not to use cereals is that they do not give a cereal disease break.

Key practicality #3

Economics in the year of manuring can be improved by planning for the tactic and by understanding and valuing subsequent benefits.

Manuring or hay freezing a grain crop forgoes the income from grain in that season. However, where other tactics have failed and hay or silage are not suitable options, manuring or hay freezing have significant merit.

Treating weedy patches rather than a whole paddock is often easier to justify, although growers often under-estimate the level of the problem being experienced. At the end of the season growers often wished they had treated the whole paddock. Where herbicide resistance in key weeds is problematic, the economics of completely stopping seedset in one or more years makes manure crop tactics more favourable.

Assess the economics of manuring on a rotational basis to capture ongoing benefits, as opposed to conducting single-year gross margins. The long-term benefits may outweigh the loss of income suffered by sacrificing the crop.

Using high-value stock, such as prime lambs and trade stock, to graze a competitive forage crop before imposing the treatment can make a big difference to the first-year economics. There will, however, be some penalty associated with nutrient removal by grazing animals. If grazing animals are not available, lupins, vetch or field peas may be a useful crop in which to conduct a green manure operation. These crops are reasonably inexpensive to establish ($70 to $100/ha), contribute a nitrogen boost and provide a useful disease break for subsequent cereal crops.

Key practicality #4

Ensure good coverage and herbicide penetration, and observe withholding periods when brown manuring or hay freezing.

Consider grazing well in advance of your planned spray, in order to open up the sward. Use an appropriate water volume, spray pressure and nozzle to ensure the coverage and penetration of the herbicide is adequate to kill thick swards with large quantities of dry matter. Use registered herbicides and adhere to livestock grazing withholding periods when hay freezing.

Key practicality #5

Maximise seed kill by ensuring even and optimum head emergence of target weed.

Prepare the paddock. Use an autumn tickle at a later stage to encourage optimum seed emergence and a reduced weed seedbank when planting a manure crop (see *Tactic 1.4 Autumn tickle*). A dry tickle can be used on heavier textured soils that are less prone to erosion, particularly where stubble is present. On light textured soils prone to wind erosion a 'wet tickle' can be performed after sowing.

Aim for an even head emergence of the target weed for effective hay freezing and brown manuring. Graze heavily in spring and remove the stock in sufficient time for recovery before treatment. Where uneven head emergence is a problem, either because of mixed annual species or because of insufficient grazing pressure, heavier rates of glyphosate at full head emergence of the earliest flowering plants will effectively control seedset of the entire sward.

Key practicality #6

Monitor and manage regrowth.

Monitor and control any regrowth or subsequent germinations. Control surviving weeds either with glyphosate or paraquat, or graze to eliminate subsequent weed seedset.

If glyphosate has been used for brown manuring, follow up with heavy grazing, cultivation or paraquat. This will reduce weed seedset while managing glyphosate and paraquat resistance.

Whole-farm considerations

There are multiple issues to consider when deciding when and how to use a manure crop or pasture:

- Cultivation leads to increased mineralisation of soil organic matter which needs to be considered when using green manuring. Brown manuring benefits soil organic matter.
- Lighter textured soils may have excessive structural damage under green manuring. Brown manuring helps retain soil structure and surface cover.
- The number of tillage passes required by green manuring for a successful kill may be affected by soil moisture, with more cultivations required in a wet spring.
- The feed value and quantity of hay freezing fodder depend on the plant species and dry matter content of the area treated. Generally, feed value drops rapidly and the treated area needs to be grazed within a few months of spraying to gain most benefit.
- The protein content and digestibility of fodder following hay freezing deteriorate rapidly after rain, and the fodder is lost to trampling over time. It does, however, provide and maintain better feed value than hayed-off standing pasture.
- A pasture hay-freezed at ryegrass flowering would be expected to maintain good quality for two months after spraying. After approximately three months the quality of the feed in the treated paddock will be similar to that in untreated paddocks (Arkell 1995).
- Plan to graze soon after treatment to avoid the risk of forage quality loss due to weather damage. Strip grazing with an electric or movable fence can reduce trampling loss.

Contributors

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References

Anderson W 2005. Renovation cropping – can it help my weed problems? *Agricultural memo*, Merredin Agricultural District, June 2005, vol 9, issue 4. Department of Agriculture, Western Australia.

Arkell P 1995. Productive pastures pay – a manual on pasture establishment for the above 700 mm rainfall zone. *Bulletin 4302*, Department of Agriculture, Western Australia.

Condon, K 2000. *Forage Legumes – Profitable Break Crops for Dryland Cropping Rotations*. New South Wales Agriculture, Orange.

Hoyle FC and Schulz L 2003. Restoration of paddock productivity through renovation cropping. *DAW 628 Trial Results, Appendix 3, Final Report DAW 628*. Grains Research and Development Corporation.

Patterson RA 2012. *Agronomics and economics of brown manure in continuous cropping systems. Flexible farming systems - exploring the options*. Narrandera, New South Wales. Grains Research and Development Corporation.

Revell C and Hudson C 2001. Short-term pasture phases for weed control. *Agribusiness Crop Updates*, Perth, Western Australia.

Tactic 3.5 Grazing – actively managing weeds in pastures

Pasture weed management requires maintaining a balance of pasture species (i.e. maximising the mix of desirable plants, legumes and specific grasses while keeping weed levels low).

Most weeds are susceptible to grazing. Weed management using grazing is achieved through reduction in seedset, competitive ability of the weed and the encouraged domination of desirable species. The impact is intensified when grazing coincides with the vulnerable stages of the weed life cycle.

In crop based rotations a two- to three-year pasture phase may significantly reduce weed seedbanks to manageable levels before returning to a cropping phase. During this period, pasture phase grazing in association with other tactics may be used to help reduce weed numbers. Grazing can be coupled with hay and silage making, mowing and pasture spray-topping for increased weed control (see *Tactic 3.3 Silage and hay – crops and pastures* and *Tactic 3.2 Pasture spray-topping*).

Benefits

Key benefit #1

Timed grazing pressure can be used to manipulate pasture composition.

High grazing pressure in autumn will significantly reduce the proportion of annual grasses (Rossiter 1966) because small plants are physically removed by grazing animals. Short periods of intense grazing are recommended to minimise damage to non-weed species.

Different pastures will require different management techniques, and understanding pasture species ecology will aid management decisions. Management of vulpia (*Vulpia* spp.) is enhanced with light grazing pressure in autumn (Taylor and Sindel 2000). Desirable annual species will be encouraged to re-establish under less intense autumn grazing pressure (see *Section 5 Agronomy 4 Improving pasture competition*) and the number of bare areas where weeds may germinate will be reduced.

Key benefit #2

Grazing can be used together with herbicides (spray-grazing) to effectively manage weeds.

Spray-grazing uses sublethal rates of selective herbicides (often phenoxy-based) to increase the palatability of broadleaf weeds for preferential grazing. It is usually undertaken in autumn or early winter and is especially beneficial for the control of erodium (*Erodium* spp.), capeweed (*Arctotheca calendula*), Paterson's curse (*Echium plantageneum*) and wild radish (*Raphanus raphanistrum*) (Bickford 1995). The use of phenoxy-based herbicides causes the flat weeds to curl up and thus become more accessible to livestock.

High stocking rates, up to four times the normal rate for the area, are required for this technique to work effectively. Weeds that are not killed by spraying alone will recover in two to three weeks and grow as normal if they are not grazed heavily after spraying. If carried out correctly, competition from the pasture species will reduce the weed population (Peirce 1993).

Figure T3.5–1 Sheep are effective weed managers if per hectare stocking rates can be kept high enough. *Photo*: Andrew Storrie

Key benefit #3

Grazing can be used to reduce seedset in grass weeds.

Sheep and cattle will preferentially graze the small heads of annual ryegrass (*Lolium rigidum*) (Matthews 1996). Intensive spring grazing can reduce annual ryegrass seed production (Beattie 1993; Doyle et al. 1993) but also limit seed production of the more desirable species.

Grass species with sharp-awned seeds (e.g. *Bromus* spp., *Hordeum* spp., *Vulpia* spp.) are less palatable to stock and intensive grazing for these species should start before full emergence of the seed-head. Research by Taylor and Sindel (2000) found that heavy grazing in spring reduced vulpia seedset significantly (100 DSE/ha for five to seven days to reduce pasture dry matter by 80%).

Key benefit #4

Exploiting differences in species acceptability to sheep can reduce weed numbers.

Some legume species (e.g. biserrula) are less palatable to sheep at certain times of the season. Grazing at these times will increase the pressure on weeds and reduce weed numbers (Revell and Thomas 2004).

Table T3.5–1 shows the impact on annual ryegrass when grazed with three pasture legume species. Note the large reduction in annual ryegrass in cultivar Casbah biserrula compared with the more palatable medic pastures.

Key benefit #5

Tillering of annual grasses can be decreased by timely grazing.

Defer grazing or reduce stocking pressure to decrease tillering of annual grasses. Fewer tillers mean fewer seed-heads and consequently less seedset. This is particularly useful as an aid in controlling barley grass (*Hordeum* spp.) (Burton et al. 2002).

Whole-farm benefits

Well-managed grazing provides other benefits on the farm:

- Grazing increases legume composition of pastures and improves feed quality.
- More productive legumes can improve levels of nitrogen fixation for the benefit of subsequent crops.
- Increased stocking rates under set stocking can increase wool production per hectare and reduce both the mean fleece fibre diameter and the variation in fibre diameter along the staple (Doyle et al. 1993).

Table T3.5–1 Effect of grazing and pasture cultivar on annual ryegrass tiller numbers (as at early October 2001) and estimated annual ryegrass seedset. In-crop annual ryegrass was measured in September 2002 in a wheat crop sown without herbicide application (Revell and Thomas 2004)

Treatment		Pasture cultivar		
		Casbah biserrula	Sava snail medic	Santiago burr medic
Ungrazed	Annual ryegrass tillers (tillers/m^2)	85	93	145
	Length of seed-head (cm)	13	15	13
	Estimated seedset (no./m^2)	4,240	5,352	7,504
Grazed	Annual ryegrass tillers (tillers/m^2)	16	171	139
	Length of seed-head (cm)	5	9	10
	Estimated seedset (no./m^2)	311	6,522	5,396
	In-crop annual ryegrass Sept. 2002 (no./m^2)	37	296	105

Figure T3.5–2 Mowing of pasture can be used to reduce spring growth to enable stock to keep up with weed growth as seen here near Mingenew, WA.
Photo: Andrew Storrie

Practicalities

Key practicality #1

Grazing pressure needs to be high enough to prevent selective grazing.

High grazing pressure (at least two to four times the average district stocking rate) is needed for effective weed control. Stock numbers required to give optimum grazing pressure must be adjusted depending on pasture growth rates, and pasture and stock condition must be continually monitored and adjusted accordingly. If appropriate, consider temporary fencing to increase grazing pressure.

Insufficient grazing pressure in spring favours vulpia, barley grass and brome grass, which have unpalatable seeds (Matthews 1996). Strip grazing is a practical method of overcoming stock shortages.

Key practicality #2

Timing of practices is critical to obtain the desired level of weed control.

Controlling annual grasses in a predominantly winter rainfall area requires rotational grazing in autumn while annual legumes are establishing (*Figure T3.5–3*). Grazing pressure should then be reduced during winter to encourage grasses to grow upright, making them more accessible to grazing.

Introduce high intensity grazing before grasses flower to prevent seedset. If stock numbers are insufficient or pasture growth rates exceed their ability to maintain grazing pressure, silage making and/or spray-topping can be used.

Key practicality #3

Manage grazing to avoid livestock importing weeds or transporting them to other paddocks.

Practising good hygiene between paddocks on a property will help minimise the transfer of weeds from infested paddocks (Taylor and Sindel 2000; also see *Tactic 5.1d Manage livestock feeding and movement*).

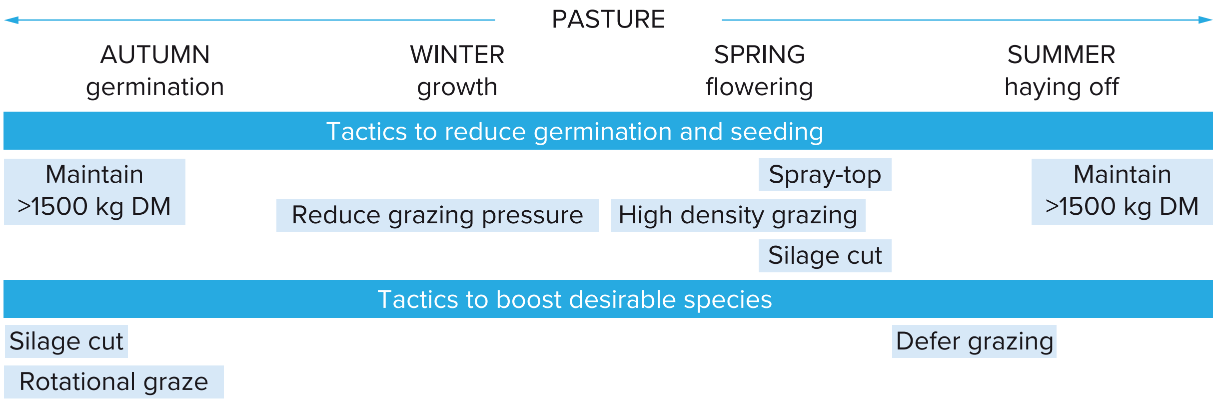
Some suggestions include the following:

- Move stock to frequently used holding areas following grazing on weedy paddocks.
- Hold new stock in yards or a quarantine paddock for at least five days to empty any seeds in the gut before allowing them on to the rest of the property. Research has found 10 days' quarantine will enable most seeds to be cleared from the gut of livestock (St John-Sweeting and Morris 1990; Stanton et al 2002; Stanton et al. 2003).
- Set aside containment areas if hand-feeding stock with imported feed.
- Alter shearing schedules so that fleece length is short when grasses are shedding seed (this also reduces vegetable fault in fleeces).

Key practicality #4

Livestock movement across paddocks can bury weed seeds.

In some species seed burial encourages germination and allows control with herbicides. On the other hand, burial can protect some weed seeds against tactical burning. Knowledge of potential weed species will aid understanding of the likely impact of livestock.



Note: For Western Australian wheatbelt pastures and low rainfall areas across Australia, a dry matter maintenance target is >800 kg of plant material per hectare.

Figure T3.5–3 Timeline for implementing management tactics for annual grass weeds in pastures (Burton et al 2002).

Key practicality #5

High grazing pressure can increase the proportion of broadleaf weeds such as capeweed and erodium.

Rossiter (1996) found that livestock experience difficulty when grazing weeds with a flat rosette growth habit, such as capeweed and erodium. Herbicide application can cause these weeds to curl, making them more accessible to stock. However, grazing pressure must be high so that stock eat these weeds.

Whole-farm considerations

Determine the suitability of grazing as a weed management tactic by considering the following points:

- Livestock traffic can lead to soil compaction and erosion. Fine textured soils are more prone to compaction, especially if grazed after rain.
- Intensive grazing during the flowering and seedset stages of desirable species impedes their ability to set seed. The same paddock should not be intensively grazed in successive years (Doyle et al. 1993).
- Intensive spring grazing on some paddocks may lead to others being under-used. If there is excess feed, mow it for fodder or treat it with herbicides for weed control.

Contributors

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References

Beattie A S 1993. Grazing for pasture management in the high-rainfall, perennial pasture zone of Australia; D Kemp and D Michalk (eds). *Pasture Management Technology for the 21st Century*. CSIRO, Australia, pp. 62–70.

Bickford R 1995. *Pasture Management*. Inkata Press, Australia, pp. 122–123.

Burton J, Dowling P and Junor K 2002. Managing annual grasses to boost pasture production. Tips and tools for making change. Feedbase and Resource Management: *FRM.07.02*. Meat and Livestock Australia.

Doyle PT, Grimm M and Thompson AN 1993. Grazing for pasture and sheep management in the annual pasture zone; D Kemp and D Michalk (eds). *Pasture Management Technology for the 21st Century*. CSIRO, Australia, pp. 71–90.

Matthews JM 1996. Cultural management of annual ryegrass. *Plant Protection Quarterly*, vol. 11 (Supplement 1), pp. 198–200.

Peirce JR 1993. Control of broad-leaved weeds in pastures. *Management of Agricultural weeds in Western Australia*. Department of Agriculture, Western Australia, Bulletin 4243.

Revell CK and Thomas D 2004. Management of crop weeds through the strategic use of annual pasture. *Weed management - balancing people, planet, profit: 14th Australian Weeds Conference*, Wagga Wagga, New South Wales, (eds B. Sindel and SB Johnson), pp. 145–149, Weed Society of NSW.

Rossiter RC 1966. Ecology of the Mediterranean annual-type pasture. *Advances in Agronomy*, vol. 18, pp. 1–56.

St John-Sweeting R S, and Morris KA 1990. Seed transmission through the digestive tract of the horse. *Proceedings of the 9th Australian Weeds Conference*, Adelaide, South Australia, (ed J Heap), pp. 137–139, Crop Science Society of South Australia .

Stanton R, Piltz J, Pratley J, Kaiser A, Hudson D, and Dill G 2002. Annual ryegrass (*Lolium rigidum*) seed survival and digestibility in cattle and sheep. *Australian Journal of Experimental Agriculture*, vol. 42, pp. 111–115.

Stanton R, Pratley J and Hudson D 2003. Sheep are potential vectors for the spread of canola (*Brassica napus*) seed. *Australian Journal of Experimental Agriculture*, vol. 43, pp. 535–538.

Taylor U and Sindel B 2000. *The pasture weed management kit: A guide to managing weeds in southern Australian perennial pastures*. Cooperative Research Centre for Weed Management Systems.

Further reading

Bellotti WD and Moore AD 1993. Management for pasture establishment; D Kemp and D Michalk (eds). *Pasture Management Technology for the 21st Century*. CSIRO, Australia, pp. 26–37.

Burton J and Dowling P 2004. *Pasture Management for Weed Control*. Cooperative Research Centre for Australian Weed Management.

Tactic Group 4 **Prevent viable weed seeds within the target area being added to the soil seedbank**

Tactic 4.1 **Weed seed control at harvest**

The most problematic weed species of annual cropping systems are prolific seed producers capable of establishing large, viable seedbanks in just one season. Despite this, the high proportion of seed retained on upright stems at crop maturity creates the potential to target these seeds at harvest. Thus weed seed control at harvest represents an excellent opportunity to control weed seeds, preventing their input to the seedbank.

Modern grain harvesters are efficient at sorting weed seed from crop grain, with the weed seeds returned to the field, primarily in the chaff fraction (Petzold 1955; Balsari et al. 1994; Walsh and Powles 2007). For example, annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) can retain a large proportion of their seed attached to the plant at the same height as the crop seed-heads at crop maturity. Most of this seed can pass intact through the grain harvester returning to the crop field in the chaff fraction, thus perpetuating an ongoing weed problem (Walsh and Powles 2007). As most small weed seed exits with the chaff fraction, harvest weed seed control options target the harvest residue fraction. For example, up to 95% of annual ryegrass seed that enters the harvester will exit in the chaff fraction.

A recent scoping study in the northern grain region (Widderick and Walker 2012) has shown that there is potential to use harvest weed seed control techniques for some winter crops. In southern Queensland and northern NSW, field surveys at winter crop harvest showed sowthistle (*Sonchus oleraceus*) and possibly wild oat (*Avena* spp.) have the majority of their seeds above harvest height in chickpeas.

The weeds measured included fleabane (*Conyza* spp.) with 96% seed above harvest height, sowthistle with 78% , wild oat with 83% , turnip weed (*Rapistrum rugosum*), cudweed (*Gamochaeta* spp.) and paradoxa grass (*Phalaris paradoxa*) all with 100%, wireweed (*Polygonum* spp.) with 98% and black bindweed (*Fallopia convolvulus*) with 93% . In wheat crops, 66% of sowthistle and 96% of wild oat seeds were above harvest height but fleabane and turnip weed had much less seed above harvest height at 15% and 33% respectively.

Collecting and managing the weed seed-bearing chaff fraction can result in significant reductions in annual weed population densities (Newman 2009). Lower in-crop weed densities are easier to manage and their potential development into herbicide-resistant populations is dramatically reduced. Western Australian farmers have driven the development of several systems that are now available to effectively reduce inputs of annual ryegrass and wild radish into the seedbank (see *Tactic 4.1a Narrow header trail*, *Tactic 4.1b Chaff cart*, *Tactic 4.1c Bale direct system* and *Tactic 4.1d Impact mills – Harrington Seed Destructor® and Seed Terminator*).

Benefits

Key benefit #1

Weed seed control at harvest prevents a large proportion of viable weed seed entering the seedbank.

Weed seed collection at harvest is the last weed control opportunity of the growing season. Preventing weed seed entering the seedbank, although a time-consuming exercise during crop harvest, has substantial long-term benefits.

Harvest weed control strategies can result in the removal of high proportions of total weed seed production: for example, annual ryegrass 80% , wild radish 87% , brome grass (*Bromus* spp.) 68% and wild oat 80% (Walsh et al. 2011). However, the proportion collected will vary according to time between crop maturity and actual harvest as well as a number of agronomic and weather-related factors.

In 14 experiments across southern and Western Australia, Walsh (2012) found that harvest weed seed collection tactics gave between 30% and 90% reduction in annual ryegrass in the following season (*Table T4.1–1*).

Key benefit #2

Small crop grain is collected and removed in harvest residues.

As well as controlling weed seeds, harvest weed control practices also target small and shrivelled crop grain exiting in the chaff fraction. The subsequent reduction in volunteer crop emergences reduces the need for knockdown and in-crop selective herbicide control of these seedlings.

Table T4.1–1 Average range of annual ryegrass control across 14 experiments using different harvest seed destruction techniques (Walsh 2012).

Harvest seed kill method	Range of annual ryegrass control (%) [a]
Windrow burning	30–90
Chaff cart	32–75
Harrington Seed Destructor	35–90

[a] average of 14 experiments

Practicalities

Key practicality #1

Cutting height should be as low as practically possible.

The efficacy of harvest weed control strategies is totally reliant on the amount of weed seeds that enter the front of the harvester. Therefore, a low cutting height (15 to 20 cm) should be used in an effort to collect as many seed-heads as possible into the front of the harvester. Obviously a lower cutting height may slow harvest, particularly for lower capacity harvest machinery.

Key practicality #2

Harvest timing affects the amount of seed collected during harvest.

The longer harvest is delayed past maturity the greater the proportion of weed seeds that will shed, shatter or lodge before harvest, reducing the total proportion of seed able to be collected. Experiments on wild oat in Hawker, South Australia, in 2009 showed that chaff carts were ineffective in controlling wild oat due to rapid shedding of seed post-crop maturation, with seedbank numbers in March going from 92 seeds/m^2 to nearly 6,000 seeds/m^2 in one year (Van Rees et al. 2011). When wild oat seeds above and below harvest height were measured at weekly intervals post-crop maturity it was found that numbers could drop significantly in a one-week interval (*Figure T4.1–2*).

Brassica weeds such as wild radish, wild mustard (*Sinapis arvensis*), turnip weed and Indian hedge mustard (*Sisymbrium orientale*) can establish throughout the year and early cohorts can produce viable seed that can be shed well before crop maturity and harvest (Cheam et al. 2008). This pre-harvest seed shedding behaviour negates the use of harvest seed capture techniques (see *Section 2: Profiles of common cropping weeds*).

Figure T4.1–1 These wild oats will have shed seed well before harvest of the wheat crop reducing the effectiveness of any harvest seed collection techniques
Photo: Peter Hooper

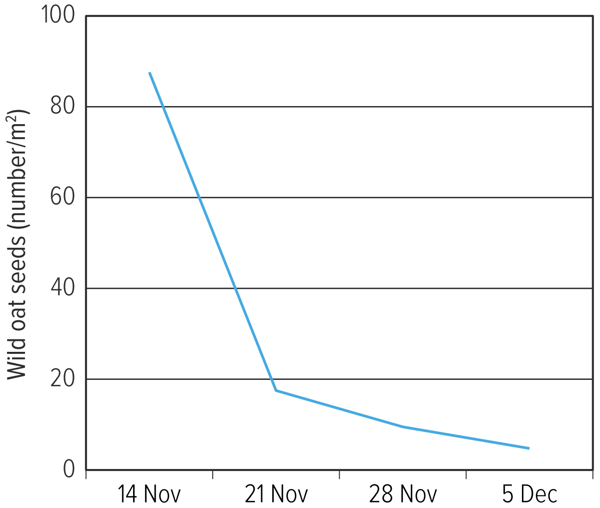

Figure T4.1–2 Rapid decline in wild oat seed numbers more than 15 cm above ground level following crop maturity at Clare, South Australia, 2009, due to shedding (Van Rees et al. 2011).

Key practicality #3

Farmers must have a strategy to dispose of collected harvest residues bearing weed seed.

The collected weed seed-bearing harvest residues must be destroyed or removed from the paddock. Chaff material is usually burned in the paddock but can also be used as a feed source for in situ grazing or in a feedlot. Livestock feeding on chaff dumps can spread weed seeds if not well managed. A Western Australian study found that sheep foraging in chaff dumps reduced the volume of the dump by almost a half (from 11 to 6 m^3) while tripling the chaff-spread area in a three-week period (Devenish and Leaver 2000). Grazed chaff dumps that have been spread out and lowered in height burn more quickly than ungrazed heaps (see *Tactic 1.1 Burning residues*).

Livestock eating fodder contaminated with weed seed should be confined to the paddock in which they are grazing (see *Tactic 4.2 Grazing crop residues*). A percentage of weed seeds ingested by livestock will remain viable and take as long as 10 days to pass through the gut (Stanton et al. 2002). The number of seeds that remain viable will depend on the weed species and the grazing animal so it is important to develop a feed-out strategy to contain the problem. When grazing harvest residues that contain weed seeds remember the following:

- Livestock can spread weed seeds. A significant proportion of the annual ryegrass seeds ingested by sheep and cattle remain viable when excreted: 6% in sheep and 12% in cattle (Stanton et al. 2002).
- In areas where annual ryegrass toxicity is a problem, seek veterinary advice before grazing harvest residues with high annual ryegrass content.

Key practicality #4

Repeated use and dependence on seed collection at harvest for weed control may favour the development of shorter, quicker maturing (early shedding) weed types.

A Western Australian study surveyed paddocks with an eight-year history of seed collection compared to neighbouring paddocks where seed collection had never been used. The study looked at the plant characteristics of annual ryegrass and found no phenotypic evolution had occurred (Ferris 2003). Despite lack of evidence from this study, a risk remains. Diversity is the key to managing weeds and the use of tactics from alternative tactic groups is essential.

Contributors

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References

Balsari P, Finassi A and Airoldi G 1994. Development of a device to separate weed seeds harvested by a combine and reduce their degree of germination. *Proceedings of the 12th World Congress of the International Commission of Agricultural Engineers* Report No. 94–D–062.

Cheam AH, Storrie A M, Koetz E A, Holding D J, Bowcher AJ and Barker JA 2008. *Managing wild radish and other brassicaceous weeds in Australian cropping systems*. Cooperative Research Centre for Australian Weed Management, Adelaide, Australia.

Devenish KL and Leaver LJ 2000. The fate of ryegrass seed when sheep graze chaff cart heaps. *Crop Updates*, Department of Agriculture and Food, Western Australia.

Newman P 2009. *Case Studies of Integrated Weed Management*. Department of Agriculture and Food Western Australia, Geraldton.

Petzold K 1955. Combine harvesting and weeds. *Journal of Agricultural Engineering Research*, vol. 1, pp. 178–181.

Stanton R, Piltz J, Pratley J, Kaiser A, Hudson D and Dill G 2002. Annual ryegrass (*Lolium rigidum*) seed survival and digestibility in cattle and sheep. *Australian Journal of Experimental Agriculture*, vol 42, pp. 111–115.

Van Rees H, Walsh MJ and Hooper P 2011. *Seed Retention in Weeds - Monitoring seed retention in ryegrass, brome grass, wild oats, radish and turnip in south-eastern Australia*. Final Report, Project No. AWRC 08-83. Rural Industries Research and Development Corporation.

Walsh M J 2012. *The Harrington Seed Destructor and harvest weed seed control in Australian grain cropping systems*. Rural Industries Research and Development Corporation, Canberra, Australia.

Walsh MJ, Harrington R and Powles SB 2011. Grain harvest: An opportunity for weed seed control. *Weed Science Society of America*, vol 51, p. 502.

Walsh MJ and Powles SB 2007. Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology*, vol. 21, pp. 332–338.

Widderick M and Walker S 2012. What percentage of northern weed seed might it be possible to capture and remove at harvest time? A scoping study. *Papers of the Grains Research and Development Corporation Adviser Update*, Goondiwindi, 2012 (compiled by ICAN Pty Ltd).

Further reading

Ferris D 2003. No sign of chaff-cart resistant ryegrass! *Crop Updates*, Department of Agriculture and Food Western Australia, Perth, Australia.

Michael P, Vercoe P, Steadman K and Plummer J 2004. Effect of sheep mastication and digestion on the transmission and viability of small-flowered mallow (Malva parviflora) seed. *Weed management - balancing people, planet, profit: 14th Australian Weeds Conference*, Wagga Wagga, New South Wales, (eds BM Sindel and SB Johnson), pp. 516–518, Weed Society of NSW.

Tactic 4.1a Narrow header trail

The burning of crop residues is the oldest form of weed seed destruction used routinely in crop production systems. Stubble burning is typically conducted in autumn on crop fields to reduce stubble levels in preparation for seeding as well as for reducing the carryover of stubble-borne diseases. It is more common in the southern and western grain regions than in the northern region. The destruction of weed seeds has been a somewhat secondary but significant result of this practice.

Figure T4.1a–1 Harvest in action producing narrow chaff rows for burning the following autumn.
Photo: Andrew Storrie

Figure T4.1–2 Doug Smith, Pingrup, WA, demonstrating how easy it is to build a shute to produce narrow windrows.
Photo: Andrew Storrie

During typical whole paddock stubble burning, very high temperatures (300 °C or greater) occur for only a few seconds. However, the effectiveness of weed seed destruction by burning is increased when seeds are exposed to these high temperatures over a period of several minutes. For example, to kill annual ryegrass seed requires temperatures of 400 °C for 10 seconds while 100% kill of wild radish seed retained in pod segments requires 500 °C for this same short 10 second duration (Walsh and Newman 2007). Higher burning temperatures (500 °C+) and longer durations (greater than three minutes) are only possible with high stubble levels. Therefore, when burning is being used as a weed control option, concentrating harvest residues into a narrow windrow improves the weed control potential of this practice.

Benefits

Key benefit #1

Narrow windrow burning effectively reduces viable weed seed numbers in the seedbank.

Narrow windrow burning has been shown to control up to 99% of annual ryegrass and wild radish seed present in the windrow (Walsh and Newman 2007) but is more likely to be in the range of 30 to 90% (Walsh 2012). Additionally, the same levels of weed seed control have been recorded following burning of wheat, lupin and canola windrows.

Key benefit #2

Burning a narrow windrow reduces the percentage of the paddock that is burnt, thereby reducing the area prone to wind or water erosion.

Normally the narrow windrow is 0.6 to 1.5 m wide depending on the width of the header cutter bar.

Practicalities

Key practicality #1

Best success will be achieved by a high temperature burn, accounting for seasonal risks.

Reduction in weed seed numbers due to burning is highly variable and dependent on the exposure of the seeds to high temperatures. This in turn is dependent on the quantity, quality and distribution of residue, the conditions at time of burning, the weed species present and the placement of the weed seeds.

Key practicality #2

Burn windrows when there are light (5 to 10 kph) winds.

Burning windrows in light cross or head winds ensures a slow burn, with windrows burning to the soil surface. By autumn weed seeds are present on the soil surface so, to ensure complete weed seed kill, windrows must burn to the ground (Walsh and Powles 2007).

Key practicality #3

Time burning to suit residue conditions and legislative limitations.

Although burning early in the season is likely to achieve best weed seed control, in many instances this is not practical due to weather conditions, the risk of fire spread and the increased risk of erosion of paddocks bared for longer periods. Early removal of stubble in a fallow period also reduces the efficiency of water conservation.

Although hotter burns will occur when ambient temperatures are higher earlier in the season (Pearce and Holmes 1976), there are practical and legislative limitations to burning during summer.

Walsh and Newman (2007) found that lower temperatures can also be effective in killing weed seeds if exposure periods are increased. Late autumn (or 'cool') burning of residues reduces the viability of seeds susceptible to heat treatment to some extent. In north-eastern Victoria, for example, Davidson (1992) achieved a 57% reduction in annual ryegrass establishment with a late autumn burn.

Data from experiments on the Darling Downs, Queensland (SR Walker, pers. comm. 2005), found that an autumn stubble burn reduced the seedbank of turnip weed by 30% , wild oat by 34% and paradoxa grass by 40% .

The McArthur Grassland Fire Danger Meter (*Figure T4.1a–3*) is a useful tool to determine how your windrows will burn. Information about a hand-held calculator wheel is available from https://www.csiro.au/en/Research/Environment/Extreme-Events/Bushfire/Fire-danger-meters/Grass-fire-danger-meter

The McArthur Grassland Fire Danger Meter estimates fire behaviour from measurements of wind speed, temperature, humidity, level of fuel 'curing' and fuel quantity.

As a rule of thumb, a Grass Fire Weather Index of:

- less than 15 will give a reasonable windrow burn
- eight to 10 is good and probably ideal
- two and lower will not give a good burn as it is too cold and humid
- greater than 15 carries the risk of the fire getting out of control.

Some tips include:

- Don't 'over-thresh' the straw as it will become too fine and won't burn well come March.
- Ignite the windrows when the wind is at 90 degrees across or diagonal to the windrow (rather than parallel) as this prevents the fire developing a face which can carry between the rows.
- Light up across the windrows every 75 m in good conditions and plan to light much closer as conditions cool down. The fires will burn to meet each other.
- Best burning conditions are in the second half of March for southern Australia.
- Plan to commence burning just on dark when it is cooler but also plan to have the burning finished when the dew falls, as this limits stubble smouldering and flare-ups during the next day.
- Time constraint means that only 200 to 300 ha (per team) can be burnt each night.
- Use 'Meteogram' weather forecasts for your area. Meteograms predict weather variables such as wind, temperature and humidity up to seven days ahead.
- Don't guess the conditions; measure them and take a note of the result, because every year is different so a lower or higher fire index might be needed to achieve the right burn.
- Adjust the fire lighting pattern to best match harvest pattern (*Figure T4.1a–4*).

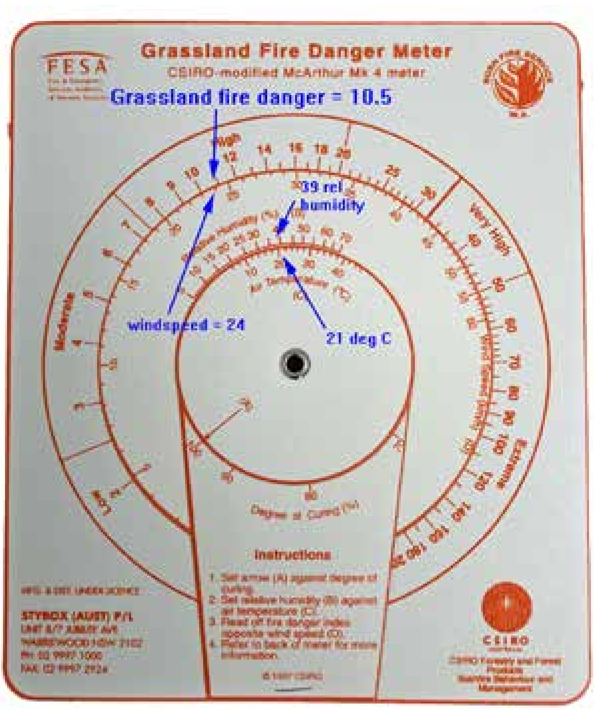

Figure T4.1a–3 The McArthur Grassland Fire Danger Meter that can be carried in the glove-box.

Key practicality #4

Windrow burning is not suitable for barley stubble or high yielding wheat crop stubble.

It is very difficult to contain the burn to barley windrows due to the high proportion of leaf material at harvest, or wheat windrows from crops yielding more than 3t/ha. Burning barley windrows often results in the whole paddock burning and complete loss of stubble cover.

Key practicality #5

Windrows need to be moved each year to prevent concentration of potassium.

The use of auto-steer on harvesters has led to potassium accumulation and increases in soil pH in windrow strips where burning of narrow windrows is commonly practised (Newman 2012).

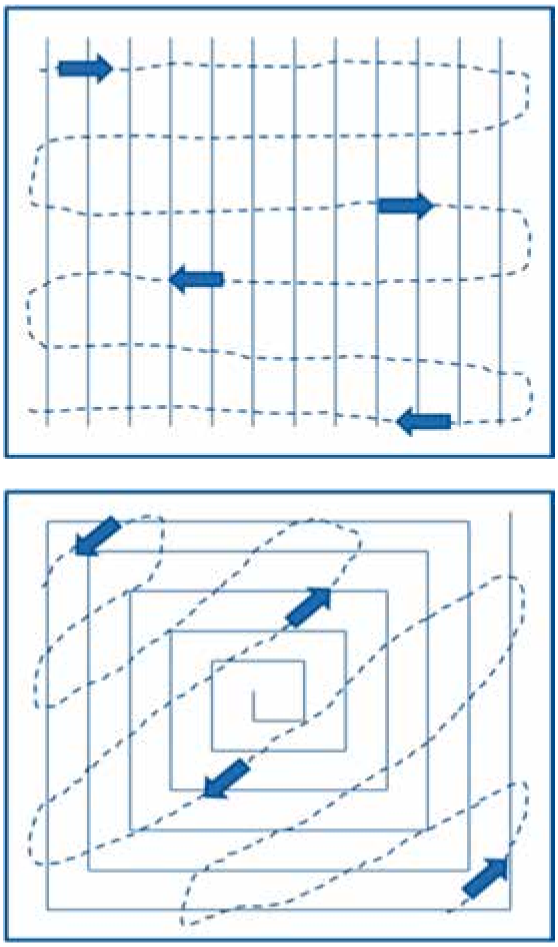

Figure T4.1a–4 Recommended lighting patterns are determined by the harvest pattern.

Contributors

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References

Davidson RM 1992. Population dynamics of herbicide resistant annual ryegrass, *Lolium rigidum*, in pasture. *Proceedings of the 1st International Weed Control Congress*. Melbourne, Australia, (eds JH Comebellack), pp.141–143, Weed Science Society of Victoria

Pearce GA and Holmes JE 1976. The control of annual ryegrass. *Journal of Agriculture, Western Australia*, vol. 17, pp. 77–81.

Newman P 2012. Nutrient removal – the hidden cost of chaff carts and windrow burning. *2012 Agribusiness Crop Updates*, pp. 194–197. Department of Agriculture and Food, Western Australia, Perth, Australia.

Walsh MJ and Newman P 2007. Burning narrow windrows for weed seed destruction. *Field Crops Research*, vol. 104, pp. 24–40.

Walsh MJ 2012. The Harrington Seed Destructor and harvest weed seed control in Australian grain cropping systems. *Final Report, Project No. 6834*. Rural Industries Research and Development Corporation.

Tactic 4.1b Chaff cart

Chaff carts are towed behind headers during harvest to collect the chaff fraction. Collected piles of chaff are then either burnt the following autumn or used as stock feed. Because of the considerable volume of chaff material produced during harvest, chaff heaps are typically burned the following autumn. *Table T4.1–2* shows the value of using chaff carts versus no cart for the removal of weed seed from the paddocks.

Figure T4.1b–1 Chaff cart in action at Tarin Rock, WA.
Photo: Andrew Storrie

Table T4.1–2 Annual ryegrass seed collection during harvest for header and chaff cart systems in five locations in Western Australia, 1999 (Walsh and Powles 2007).

Location	Annual ryegrass seeds (number per m^2)				Proportion of seed removed (%)	
	Entering header	On ground pre-harvest	Total production	On ground post-harvest	Standing annual ryegrass	Total annual ryegrass
Mingenew (a) (no cart)	12,000	8,000	18,200	17,800	4	2
Mingenew (b)	7,800	9,200	16,900	11,000	76	38
Mingenew (c)	13,000	10,000	23,100	11,900	86	50
Moora	4,500	3,800	8,300	4,900	73	39
Lake Varley	14,500	5,900	20,500	9,700	74	52

Figure T4.1b–2 Chaff dumps prior to burning.
Photo: Andrew Storrie

Figure T4.1b–3 Large capacity chaff carts are needed for high yielding crops.
Photo: Andrew Storrie

Figure T4.1b–4 Dumping system for large capacity chaff cart.
Photo: Andrew Storrie

Benefits

Key benefit #1

Collecting crop residue with a chaff cart can significantly reduce the numbers of weed seeds returning to the seedbank.

Chaff cart systems have been found to collect 30 to 85% of annual ryegrass seed and 85 to 95% of wild radish seed entering the header (Walsh and Powles 2007; Walsh 2012). In South Australia Matthews et al. (1996) reported an annual ryegrass seedbank reduction of 52% , while Gill (1996) reported a 60 to 80% reduction. A survey in Western Australia by Llewellyn et al. (2004) found that growers expect to achieve an average 60% (40 to 80% range) reduction in the number of annual ryegrass seeds returning to the seedbank.

Key benefit #2

Growers are using stock to graze chaff dumps reducing the need for supplementary feeding over summer and autumn. In on-farm experiments conducted in Western Australia in 2015–16 by Ed Riggall from AgPro management showed that sheep increased liveweight gain when grazing chaff heaps. An added bonus was an increase in lambing percentage from ewes grazing chaff heaps.

Practicalities

Key practicality #1

Burning chaff heaps

Chaff heaps are typically dumped in lines across a paddock during harvest. The following autumn when fire restrictions have been lifted a firebreak is cultivated around these dump lines which are then burnt during late afternoon to early evening. The introduction of the conveyor belt chaff delivery system allows some straw to be collected along with the chaff material. Including straw maintains air pockets inside the heaps, increasing the speed of burning. To further decrease burning time, chaff heaps can be spread out just before burning to allow more air into the compacted chaff.

Key practicality #2

Grazing chaff heaps might spread weed seeds.

Although Stanton et al. (2002) found that 6 to 10% of ryegrass seed remained viable when fed to sheep and cattle respectively, there is little field evidence that sheep grazing chaff dumps cause the spread of ryegrass from the dumps. Cattle, on the other hand, spread dumps more than sheep do and have a higher likelihood of spreading seed. If there is concern about the spread of seed, such as glyphosate and paraquat resistance, do not graze dumps with cattle.

Key practicality #3

Chaff dumps can smoulder for days, upsetting neighbours and town residents.

If dumps are damp or not sufficiently aerated they can smoulder for several days. This creates smoke hazards, particularly during inversion conditions. Avoid burning during inversions (stable high pressure systems) by monitoring seven-day forecasts from the Bureau of Meteorology.

Contributors

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References

Stanton R, Piltz J, Pratley J, Kaiser A, Hudson D and Dill G 2002. Annual ryegrass (*Lolium rigidum*) seed survival and digestibility in cattle and sheep. *Australian Journal of Experimental Agriculture*, vol. 42, pp. 111–115.

Walsh MJ and Newman P 2007. Burning narrow windrows for weed seed destruction. *Field Crops Research,* vol. 104, pp. 24–40.

Walsh MJ and Powles SB 2007. Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology,* vol. 21, pp. 332–338.

Further reading

Gill GS 1996. Management of herbicide resistant ryegrass in Western Australia – research and its adoption. *Where in the world is weed science going?: 11th Australian Weeds Conference*, Melbourne, Victoria, (ed RCH Shepherd), pp. 542–551, Weed Science Society of Victoria.

Llewellyn RS, Lindner RK, Pannell DJ and Powles SB 2004. Grain grower perceptions and use of integrated weed management. *Australian Journal of Experimental Agriculture*, vol. 44, pp. 993–1001.

Matthews JM, Llewellyn R, Powles S and Reeves T 1996. Integrated weed management for the control of herbicide resistant annual ryegrass. *Proceedings of the 8th Australian Agronomy Conference*, Toowoomba.

Tactic 4.1c Bale direct system

The bale direct system uses a baler attached to the harvester to collect all chaff and straw material. Approximately 95% of annual ryegrass seed entering the harvester is collected and removed in the baled material (Walsh and Powles 2007). As well as controlling weeds the baled material has an economic value as a livestock feed source.

Figure T4.1c–1 Baling crop residue directly from the header minimises weed seed return to the seedbank.
Photo: Michael Walsh

Benefits

Key benefit #1

Direct baling of chaff and straw residues exiting the harvester is a highly effective harvest weed control tool.

Collecting all harvest residues directly from the rear of the harvester allows the harvest management and removal of weed seeds. The bales produced are usually sold off-farm as a feed source. This effectively allows the removal of weed seeds from the paddock without the need for burning or further residue management.

Practicalities

Key practicality #1

Set-up of bale direct system

This system requires a large hydraulic motor driven baler to be attached to the back of the harvester. Therefore this system has to be set up on a header with sufficient excess horsepower to drive the baler. See www.glenvarbaledirect.com.au/ for the story and development of header-towed baling systems.

Key practicality #2

Sale of baled material

The availability of suitable markets for the baled material has limited the adoption of this system in Western Australia. Typically where used the bales are sold into an export market as a livestock feed source. However, these markets tend to fill easily, hence effectively limiting the adoption of this technology.

In the eastern states of Australia cattle feedlots can be useful markets for these bales.

Contributors

Di Holding, Eric Koetz, Vanessa Stewart and Steve Sutherland

References

Walsh MJ and Powles SB 2007. Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology*, vol. 21, pp. 332–338.

Further reading

Bowcher A and Holding D 2004a. On farm solution: managing resistant ryegrass by collecting chaff at harvest. *Fact Sheet Ref:16/2004/fs*, Cooperative Research Centre for Australian Weed Management

Bowcher A and Holding D 2004b. On farm solution: managing resistant ryegrass by baling crop residue at harvest. *Fact Sheet Ref:23/2004/fs*, Cooperative Research Centre for Australian Weed Management.

Ferris D 2003. No sign of chaff-cart resistant ryegrass! *Crop Updates*, Department of Agriculture and Food Western Australia, Perth, Australia.

Tactic 4.1d Impact mills – Harrington Seed Destructor® and Seed Terminator

There are currently two types of impact mills on the market in Australia. The Harrington Seed Destructor® (HSD) is the invention of Ray Harrington, a progressive farmer from Darkan, Western Australia. Initially developed as a trail-behind unit, the HSD system comprises a chaff processing cage mill and chaff and straw delivery systems. The current configuration is now integrated into new harvesters. Originally powered by a hydraulic drive system independent of the harvester, the newest iteration uses a mechanically driven vertical mill. The Seed Terminator developed in South Australia is another type of impact mill also using the mechanical drive from the harvester to power the mill. Research by Walsh et al. (2017) found that HSD, chaff carts and narrow-windrow burning have similar effects on annual ryegrass seed collected during harvest.

Benefits

Key benefit #1

Impact mills control high proportions of weed seeds present in the chaff fraction at harvest.

Research by Michael Walsh (University of Sydney) and John Broster, (Charles Sturt University) showed the HSD system consistently destroyed 96 to99% of 11 weed seed species present in the chaff fraction during harvest.

Similar numbers were measured by researchers at University of Adelaide and Trengove Consulting on experiments with the Seed Terminator in 2017.

Key benefit #2

All harvest residues remain in the paddock.

Retaining all harvest residues in the field reduces the loss and/or banding of nutrients compared with windrow burning and chaff carts (Newman 2012).

Figure T4.1d–1 Harrington Seed Destructor Mark III during the 2012 harvest.
Photo: Michael Walsh

Practicalities

Key practicality #1

Cost

At the time of writing the HSD had a capital cost of approximately $160,000 while the Seed Terminator costs $115,000. The running costs, including depreciation, are approximately $17/ha (Kondinin Group 2018).

Key practicality #2

Selection for more prostrate or early shedding biotypes or species

Like all harvest seed management technologies, if used as a primary weed management tactic the impact mill has the potential in the medium to long term to select for weed biotypes and species that are more prostrate, or lodge or shed earlier than current main biotypes and species.

Contributors

Michael Walsh and Andrew Storrie

References

AHRI Insight #94. February 2018. *iHSD-encouraging research despite challenges during 2017 harvest*. Michael Walsh and John Broster.

Kondinin Group: *Research report. Residue Management at harvest, Weed seed options*. February 2018. Vol 097. www.farmingahead.com.au

Newman P 2012. Nutrient removal – the hidden cost of chaff carts and windrow burning. *2012 Agribusiness Crop Updates*, pp. 194–197. Department of Agriculture and Food Western Australia, Perth, Australia.

Walsh MJ and Powles SB 2007. Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology*, vol. 21, pp. 332–338.

Walsh MJ, Harrington R and Powles SB 2011. Grain harvest: An opportunity for weed seed control. *Weed Science Society of America*, vol. 51, p. 502.

Walsh MJ, Harrington R and Powles SB 2012. Harrington Seed Destructor: a new non-chemical weed control tool for global grain crops. *Crop Science*, vol. 52, p. 1343–1347.

Walsh MJ 2012. The Harrington Seed Destructor and harvest weed seed control in Australian grain cropping systems. *Final Report, Project No. 6834*. Rural Industries Research and Development Corporation.

Walsh MJ, Aves C and Powles SB 2017. Harvest weed seed control systems are similarly effective on rigid ryegrass. *Weed Technology*, vol. 31, no. 2, pp. 178–183.

Tactic 4.1e Chaff lining and chaff decks

Chaff lining offers a low cost alternative for harvest weed seed management. The chute directs all material from off the sieves including weed seeds and concentrates it into a narrow row.

Figure T4.1e–1 Chaff chutes direct all material form off the sieves including weed seeds into a concentrated row.
Photo: Warwick Holding

Chaff decks move the chaff and weed seeds onto the wheel tracks in a controlled traffic system. Traffic on the wheel tracks creates a less favourable environment for weeds to germinate (Kondinin Group 2018).

Benefits

Key benefit #1
Weed control can be targeted at a very small area; anecdotal evidence from growers suggest that they are applying herbicide to only 8% of the paddock. The hostile environment for weed germination means a lot of the weed seeds rot away and those that germinate experience very high competition.

Key benefit #2
Chaff tramlining reduces dust which has a large benefit on summer spraying as it improves leaf-herbicide contact.

Figure T4.1e–2 Weeds such as annual ryegrass are concentrated in a small area of the paddock enabling targeted control.
Photo: Warwick Holding

Figure T4.1e–3 Chaff on the tramlines reduces dust and after a few years makes a hostile environment for weed seed to survive and weeds to germinate.
Photo: Warwick Holding

Figure T4.1e–4 Chaff decks used in a controlled traffic farming system.
Photo: Warwick Holding

Practicalities

Key practicality #1

Cost

Chaff deck prices range from $16,000 to $21,000 and can be fitted by the grower. The cost savings in herbicide application can be as much as $45/ha when only targeting the 'weedy' tramlines (WeedSmart, 2018).

The chaff chutes can be purchased off the shelf or home-made and adapted to individual harvesters. Kits range from $3,500 to $5,000, while grower-fabricated designs can be built for as little as $200.

Figure T4.1e–5 Chaff decks use a conveyor to move the chaff and weed seeds onto the wheel tracks in a controlled traffic farming system.
Photo: Warwick Holding

Figure T4.1e–6 Grower fabricated chaff chutes.
Photo: Warwick Holding

Key practicality #2

Herbicide residues

Concentrating stubble for windrow burning or chaff lining may see accumulation of aminopyralid, clopyralid or picloram residues which may adversely affect following sensitive crops such as pulses.

Contributors

Michael Walsh, Eric Koetz and Andrew Storrie

References

Kondinin Group, 2018. Research report. Residue Management at harvest, Weed seed options. February 2018 No. 097. www.farmingahead.com.au, viewed 11 November 2018

WeedSmart, 2018. Case Study: Warwick and Di Holding – From narrow windrow burning to chaff decks and weed lining. www.weedsmart.org.au/case-studies/warwick-di-holding-yerong-creek-nsw/, viewed 13 November 2018

Further reading

Walsh MJ, Newman P and Powles SB 2013. Targeting Weed Seeds In-Crop: A New Weed Control Paradigm for Global Agriculture. *Weed Technology*, vol. 27, pp. 431–436.

Tactic 4.2 Grazing crop residues

Grazing weed contaminated crop residue can be a cost-effective way of controlling weed growth. Animal digestion of weed seeds prevents a large proportion from entering the seedbank.

Note that the feed value of the crop residue will be variable, and grazing has the potential to spread undigested weed seeds.

Benefits

Key benefit #1

Grazing reduces the number of weed seeds added to the soil seedbank.

Depending on the weed species, grazing can greatly reduce the number of viable seeds in the soil seedbank. Animals eat the seed-heads and vegetative growth of the weed, thus decreasing the number of seeds entering the seedbank.

Key benefit #2

Grazing can be used to dispose of, and gain value from, weed seed contaminated fodder.

Weed seed contaminated fodder includes not only hay, silage and feed grain but also harvest residues that may be weed infested. Harvest residues can be collected using chaff carts to remove residue and weed seeds from the header, leaving chaff dumps in the paddock which can be used as a low value livestock feed source.

Some farmers who use chaff dumps find they do not need to hand feed sheep over summer, compared with farmers who do not use chaff carts at harvest (Peltzer pers.comm.).

Whole-farm benefits

There are additional benefits when using grazing of crop residue as a weed management tactic:

- Weed seeds can provide a significant proportion of the nutritional value when stock graze crop residue.
- Post-harvest grazing may reduce crop establishment problems by reducing stubble burdens.
- Seed burial through trampling may enhance weed germination pre-sowing. Using a knockdown herbicide and delaying sowing can then capitalise on this process.
- Seed of desirable plants (pasture species) may be distributed in faeces.

Figure T4.2–1 Sheep can be an effective tool for grazing weeds in crop residues.
Photo: Andrew Storrie

Practicalities

Key practicality #1

Grazing livestock can distribute weed seeds across a paddock.

Feeding experiments have shown the viability of annual ryegrass (*Lolium rigidum*) seed excreted by sheep to be 4% and when excreted by cattle 12% (Stanton et al. 2002). Annual ryegrass seed was detected in both sheep and cattle faeces within 24 hours of the stock being introduced to the weed seed contaminated diet, and they continued to excrete viable seeds for five days after being removed from the diet.

Experiments in Western Australia (Devenish and Lever 2000) found that sheep are unlikely to spread major quantities of ryegrass seed from chaff dumps, while observations of sheep camps found small numbers of ryegrass plants. It is not recommended that cattle graze contaminated stubble and chaff dumps.

Contaminated fodder needs to be checked for its feed value and the presence of toxins such as annual ryegrass toxicity. It should be fed in an area that can be readily monitored (e.g. a feed-lot) to minimise the spread of seeds.

Key practicality #2

The impact of grazing on weed numbers entering the seedbank is dependent on the biological features of the weed.

Grazing is successful in reducing weed seed numbers in weeds that are palatable and where the seeds can be easily eaten and digested. However, seed palatability varies from weed to weed. The presence of awns, thorns or biochemical traits makes weeds less attractive to grazing animals.

Seed location: Stock must be able to access seed to ingest it. Seed still in the head, or in chaff dumps or feed troughs, is easier to access than seed lying on the soil surface.

Seed size: Once shed from the seed-head, small seeds are more difficult for animals to graze. Small seeds are also more likely to survive ingestion and digestion.

Hard seeds: A high proportion of hard seeds will remain viable after digestion. The digestive process can also break seed dormancy, encouraging the germination of seeds shed in faecal matter.

Michael et al. (2004) examined the viability of small-flowered mallow (*Malva parviflora*) seed following ingestion. The seed was placed into the rumen of fistulated sheep (sheep with direct access to the rumen through an external artificial plug). Up to 93% of those seeds with an intact seed coat remained viable regardless of digestion time.

Key practicality #3

Livestock trampling tends to bury weed seed, which can decrease the efficiency of burning as a means of killing seeds. Depending on the weed species, burial may also increase germination rates.

When grazing, stock will knock seed to the ground and bury weed seeds with their hooves. Shallow burial during grazing may result in increased germination, not unlike that achieved with an autumn tickle (see *Tactic 1.4 Autumn tickle*), due to the placement of the seed in a better environment for germination.

Whole-farm considerations

Grazing may also cause:

- an increased risk of soil, water and wind erosion
- increased soil compaction
- potential toxicity issues for sheep, e.g. lupinosis.

Contributors

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References

Michael P, Vercoe P, Steadman K and Plummer J 2004. Effect of sheep mastication and digestion on the transmission and viability of small-flowered mallow (*Malva parviflora*) seed. *Weed management - balancing people, planet, profit: 14th Australian Weeds Conference*, Wagga Wagga, New South Wales, (eds BM Sindel and SB Johnson), pp. 516–518, Weed Society of NSW.

Stanton R, Piltz J, Pratley J, Kaiser A, Hudson D and Dill G 2002. Annual ryegrass (*Lolium rigidum*) seed survival and digestibility in cattle and sheep. *Australian Journal of Experimental Agriculture*, vol. 42, pp. 111–115.

Further reading

Devenish KL and Leaver L 2000. The fate of ryegrass seed when sheep graze chaff cart heaps. *Crop Updates: Weeds, Perth*. Department of Agriculture and Food Western Australia.

Tactic Group 5 **Prevent introduction of viable weed seed from external sources**

Tactic 5.1 **On-farm hygiene**

'Risk aware' growers can implement strategies to reduce and avoid unnecessary introduction and spread of weeds. These strategies will reduce not only the likelihood of introducing new weed species but also the risk of importing herbicide-resistant weeds.

Modelling the impact of importing herbicide resistant seed (Diggle 2004)

Good on-farm hygiene can help manage herbicide resistant gene flow.

Modelling was used to predict the rate of glyphosate resistance development in annual ryegrass in a 100 ha paddock in Western Australia. Two scenarios were tested:

1. crop seed contaminated with 10 annual ryegrass seeds/kg, of which one was glyphosate resistant
2. no contamination of crop seed.

The modelling demonstrated that if glyphosate was applied as a knockdown every year in the 100 ha paddock, the initial five glyphosate resistant plants in 500 million would increase to agronomically important levels in 17 years (*Figure T5.1–1*).

The introduction of similarly contaminated seed in the second year would cause resistance to develop five years earlier.

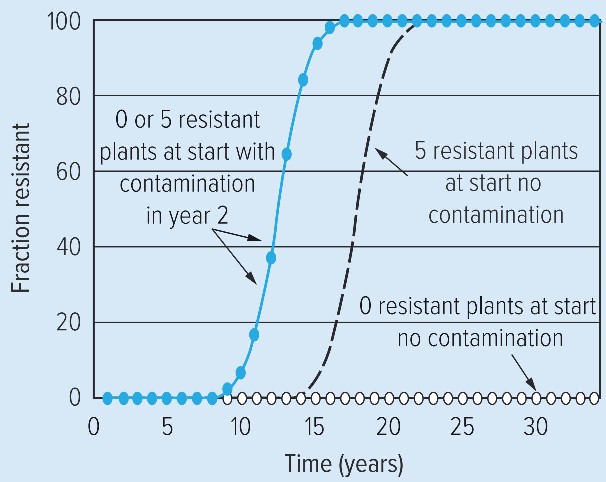

Figure T5.1–1 A pictorial description of modelling the impact of contamination with herbicide resistant seed (Diggle 2004)

The greater the level of contamination with resistant seeds, the faster resistance will develop.

Where no resistant individuals are present and none are introduced, no resistance develops.

Weed importation and spread can be minimised at several critical points, namely:

- sowing of the seed
- fencelines and non-cropped areas in cropping paddocks (e.g. water courses)
- machinery and vehicle usage
- stock feed and livestock movement
- in fields following floods and inundation.

A well-managed on-farm hygiene strategy will address all of these elements.

Benefits

Key benefit #1

Planning and enforcing a farm hygiene strategy minimises the risk of adding weeds to the seedbank from external sources.

The benefits of planning and enforcing good on-farm hygiene include the following:

- Weed seeds will not be added to the seedbank from other areas of the same paddock, other paddocks on the same farm, other farms or other regions.
- Management costs will be reduced in the long term.
- Weed problems will be quarantined or confined to known areas where they can be more effectively managed.
- The risk of introducing herbicide-resistant weed populations from alternative sources into paddocks and on to the farm will be reduced.

Tactic 5.1a Sow weed-free seed

Benefits

Key benefit #1

Weed seeds are not added to the seedbank unnecessarily.

Weed seed is regularly spread around and between farms as a contaminant of sowing seed. Seed for sowing is commonly grower-saved and more often than not contaminated with weed seeds, frequently at very high levels (Powles and Cawthray 1999; Moerkerk 2002; Roya Niknam et al 2002; Michael et al. 2010).

Moerkerk (2002) reports that of 243 samples of cereal sowing seed from Victoria and southern NSW, only 39% met Victorian certified seed standards and only 21% was free of foreign seed. Similarly, of 98 pulse samples, 41% met Victorian certified seed standards and 24% was free of foreign seeds. A broad range of weed types was found, with annual ryegrass being the most common in both cereal and pulse seed.

In a survey of grower seed in Western Australia, Michael et al. (2010) found an average of 62 weed and volunteer crop species per 10 kg of cleaned seed. Uncleaned seed for sowing was found to have 25 times more foreign seeds than cleaned seed. This seed was found to have varying levels of herbicide resistance, so farmers were unwittingly sowing herbicide-resistant weeds around their farms.

Practicalities

Key practicality #1

Check seed analysis before purchasing seed-lots to avoid importing weed seed.

Growers should understand the certification standards and allowable weed seed contamination levels of commercial seed in their state. The Seed Analysis Certificate, which should be supplied with all seed purchases, provides details of the type and level of weed seed contamination.

Purchasing certified or commercial seed is not a guarantee of weed-free status. Always check the fine print and the Seed Analysis Certificate. When purchasing seed of a public variety from another grower, be alert to weed seed contamination and where possible:

- Know the weed status of any farm from which you buy seed.
- Plan seed purchases ahead of time and inspect the paddock where the seed is being grown.
- Obtain a sample of the seed and have it analysed for both weed seed contamination and germination.
- Determine the herbicide resistance status of weeds present on the source farm and paddock, and avoid purchasing seed from paddocks with known resistance.

To estimate the number of weed seeds being introduced at sowing:

1. Obtain a random 1 kg sample of the seed to be sown.
2. Separate the foreign seed from the crop seed.
3. Count each type of foreign seed, including weeds and volunteer crop seeds.
4. Multiply the number of weed seeds of each species by the proposed crop sowing rate (kg/ha). This will give you the number of weeds you will be sowing per hectare of crop.
5. To calculate the density of weeds/m^2, divide the weeds/ha by 10,000.

While the number may work out to be only small (perhaps one to two weeds/m^2 or less), it is important to remember that many weed species are prolific seed producers and a single plant growing in ideal conditions can contribute a large number of seeds to the seedbank.

Key practicality #2

Plan ahead when retaining seed on-farm for sowing.

Demarcate seed paddocks and ensure weed numbers in those paddocks are very low. Hand-pull problem weeds in the seed paddocks. In the long term it will pay off to apply stringent management tactics to a seed block to avoid spreading weeds in seed.

With multiple farms it is often advisable to have seed paddocks on each farm and not transfer grower-saved seed from farm to farm. This way weeds will not be spread from one property to another.

Seed cleaners cannot guarantee a weed-free sample and should not be relied on to remove all foreign seed. Ensure the seed cleaning contractor is prepared to take the time to do a thorough job and that the seed cleaning plant is thoroughly cleaned before coming on to the property.

Some weed seeds are very similar in size and weight to the seed being cleaned and are unlikely to be removed during seed cleaning. This is particularly true of a mobile seed cleaning plant without a gravity table. Transporting seed to a larger seed cleaning plant with a gravity table may obtain better results, but the economics of doing so should be considered first.

Key practicality #3

Keep good records of seed purchases.

Keeping records of seed purchases enables a degree of traceability if there are problems such as weed contamination or low germination. Do not expect the seed merchant to have a copy of the seed lines you have bought. Keep good records so the source of any problems can be traced.

Tactic 5.1b Manage weeds in non-crop areas

Benefits

Key benefit #1

Weed management in non-crop areas can prevent ‘creep effect’ into crops.

Weed infestations often start in non-crop areas (e.g. around buildings, along roadsides or along fencelines). Controlling these initial populations will prevent weeds from spreading to other parts of the property. This is particularly important for weeds with wind-blown seed such as fleabane and sowthistle.

North American research found that seed of Canadian fleabane (*Conyza canadensis*) regularly disperses at least 500 m from the parent plant although 99% of the seed falls within 100 m (Dauer et al. 2007). Less than 1% of the seed will travel further than this and it often has lower viability (20 to 40%) due to its smaller seed size (Borger 2012).

Figure T5.1b–1 Small flowered mallow infesting fenceline between two crop paddocks – an ideal situation for spread.
Photo: Andrew Storrie

Figure T5.1b–2 Fencelines should be kept weed-free, but don’t rely on glyphosate alone for weed control.
Photo: Andrew Storrie

Figure T5.1b–3 Flaxleaf fleabane along this fence will easily spread into neighbouring fields.
Photo: Andrew Storrie

Practicalities

Key practicality #1

Weeds in non-crop areas can impact greatly on farm weed status, but are often easily controlled.

Weeds in non-crop areas have no crop competition and so are able to produce large quantities of seed. Observant growers will have noticed that new weeds often tend to creep into the crop area from non-crop areas unless they are kept in check.

Weeds along fencelines, paddock edges and non-crop areas of crop paddocks can be controlled by knockdown herbicides, hay or silage cutting, and/or cultivation, or preferably a combination of all these options. Unlike other activities, timing for fenceline weed control is reasonably flexible with a wide window of opportunity, although control should be carried out before seed maturity.

Tactic 5.1c Clean farm machinery and vehicles

Benefits

Key benefit #1

Good vehicle hygiene (i.e. regular cleaning) can reduce the risk of new infestations and weed spread.

Moerkerk (2006) inspected 110 vehicles and plant machinery and found 250 contaminant species or taxonomic groups, including 24 Victorian noxious weeds. The majority of seeds were found in the cabin of passenger and four-wheel drive vehicles, with the engine bay being the next most frequent location.

Figure T5.1c–1 Vehicles are major sources of new weed infestations.
Photo: Andrew Storrie

Practicalities

Key practicality #1

Develop and adhere to a clean machinery and vehicle protocol aimed at reducing new additions to the weed seedbank.

Clean all farm machinery and vehicles before relocation. Pay special attention when moving from areas and/or paddocks with high weed burdens, new incursions or herbicide-resistant weed populations.

If possible, harvest paddocks in order from least weedy to most weedy, and finish clean areas in a paddock before harvesting more weedy areas. Avoid harvesting individual patches of a problem weed. This will slow the spread of weeds but will still add seeds to the seedbank. Alternatively, it may be possible to minimise the spread by using seed collection carts, modifying header trails or collecting seed in the grain sample for later removal.

Take the time to clean bins, trucks and grain handling equipment (e.g. augers) between paddocks or seed-lots. This is a crucial step before harvesting and handling grain which will be retained for sowing subsequent crops.

Enforce machinery cleaning standards with all harvest, baling, windrowing and grain transporting contractors.

Figure T5.1c–2 Vehicles, in this case a ute grill, are major sources of new weed infestations.
Photo: Andrew Storrie

Figure T5.1c–3 Tyres and mud in wheel arches can transport weed seeds long distances.
Photo: Andrew Storrie

Figure T5.1c–4 Slashers and mowers must be cleaned before being moved to a new area.
Photo: Andrew Storrie

Tactic 5.1d Manage livestock feeding and movement

Benefits

Key benefit #1

Careful management of livestock will reduce the likelihood of new infestations and weed spread.

New livestock, or those returning to the property from agistment, can carry weed seeds from other areas. Weeds can be easily imported from different regions or states because livestock can travel significant distances by road within a 24 hour period.

Figure T5.1d–1 Livestock being brought onto a property need to be quarantined in a small paddock before moving onto the farm.
Photo: Andrew Storrie

Practicalities

Key practicality #1

Quarantine contaminated fodder in a sacrifice paddock or feedlot so that weeds are contained in a small area.

Be aware of any contaminants that grain or hay may contain, and feed livestock in a way that limits the spread of contaminants. Hay that has been contaminated with weed seeds (and, increasingly, herbicide-resistant weed seeds) is unfortunately a major source of imported weed seeds. Drought feeding further exacerbates the issue as producers often drop their guard during stressful periods, and weeds are more difficult to control in dry conditions. Knowledge of where feed has come from may allow for pre-emptive strategies for identifying and controlling imported problem weeds.

The same feeding precautions should be observed where chaff heaps collected from the header at harvest are grazed and/or baled for fodder or for feeding grain. See *Tactic 4.1 Weed seed control at harvest* and *Tactic 4.2 Grazing crop residues* for information on the survival of weed seeds following digestion by sheep and cattle.

Silage is less risky because cutting is carried out when the weed seeds are less mature. More importantly the silage process kills most weed seeds, although some do survive the ensiling process (see *Tactic 3.3 Silage and hay – crops and pastures*).

Stock should be 'emptied out' after feeding on fodder contaminated by weed seed before returning to pasture. New stock should also be emptied out before moving to pasture. If there is a designated feeding or sacrifice area 'emptying' will be easily achieved, and any weeds that grow in this area can be monitored, managed and contained.

Plan livestock movement to avoid introducing or spreading new weeds. Remember that fleeces, hides and/or mud or dirt in hooves can harbour and distribute weed seeds in addition to those relocated through faeces.

Tactic 5.1e Monitor paddocks following flood for new weed incursions

Floods and inundation of fields are a common source of new weed infestations through the transport of seeds and vegetative propagules such as stolons, rhizomes and tubers. This source of weed invasion is likely to increase with the predicted increase in climate variability (MacDonald et al. 2006; Truscott et al. 2006).

Figure T5.1e–1 This creek is infested with glyphosate resistant annual ryegrass, noogoora burr and a range of other weeds. During the next flood and on native animals and livestock seeds of these weeds will spread across previously uninfested paddocks. *Photo*: Andrew Storrie

Benefits

Key benefit #1

Low level infestations of new weeds can be controlled at low cost and most likely eradicated.

By monitoring post-flood the chance of eradicating new weed species is greatly improved.

Practicalities

Key practicality #1

Good observation for new or different weeds is needed to identify potential new threats.

Effective monitoring needs the observer to be on the lookout for what is different or new. This requires a familiarity with the plant species normally present. Anything thought to be new should be collected for correct identification. Contact the local department of agriculture or primary industries or local adviser to help identify the specimens in question.

Contributors

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References

Borger C 2012. Dispersal of *Conyza bonariensis* (flaxleaf fleabane) seeds. Fleabane - an emerging weed in southern farming systems. Regional and National Workshops, Charles Sturt University, Wagga Wagga, Australia.

Dauer JT, Mortensen DA and Van Gessell MJ 2007. Temporal and spatial dynamics of long-distance *Conyza canadensis* seed dispersal. *Journal of Applied Ecology*, vol. 44, pp. 105–114.

Diggle A 2004. The reality of rotating herbicides. *Proceedings of Crop Updates 2004, Weeds*. Department of Agriculture, Western Australia, pp. 53–54.

MacDonald M, Whalley W, Sindel B, Julien M and Duggin J 2006. Flood induced recruitment of Lippia. *Waging war on weeds : battle plans and winning strategies: 21st Annual Conference of the Grassland Society of NSW*, Wagga Wagga, Australia, (eds B Hackney), pp. 135–136, Grassland Society of NSW.

Michael PJ, Owen MJ and Powles SB 2010. Herbicide-Resistant Weed Seeds Contaminate Grain Sown in the Western Australian Grainbelt. *Weed Science*, vol. 58, pp. 466–472.

Moerkerk M 2002. Seed box survey of field crops in Victoria during 1996 and 1997. *Proceedings of the 13th Australian Weeds Conference*, Perth, pp. 55–58.

Moerkerk M 2006. Risk of weed movement through vehicles, plant and equipment: Results from a Victorian study. Managing weeds in a changing climate: *15th Australian Weeds Conference*, Adelaide, South Australia, (eds C Preston, JH Watts and ND Crossman), pp. 458–461, Weed Management Society of SA.

Powles SB and Cawthray G 1999. Weed seed infestation of crop seed. *Proceedings of Crop Updates*, Perth.

Roya Niknam SR, Moerkerk M and Cousins R 2002. Weed seed contamination in cereal and pulse crops. Weeds 'threats now and forever': *13th Australian Weeds Conference*, Perth, Western Australia, (eds H Spafford Jacob, J Dodd and JH Moore), pp. 59–62, Plant Protection Society of WA.

Truscott AM, Soulsby C, Palmer SCF, Newell L and Hulme PE 2006. The dispersal characteristics of the invasive plant *Mimulus guttatus* and the ecological significance of increased occurrence of high-flow events. *Journal of Ecology*, vol. 94, pp. 1080–1091.

Further reading

Australian Custom Harvesters Incorporated https://customharvesters.org.au

Blackshaw RE and Rode LM 1991. Effect of ensiling and rumen digestion by cattle on weed seed viability. *Weed Science*, vol. 39, pp. 104–108.

Bowcher AJ and Holding DJ 2005. On-farm solutions: reducing weed seed contamination at sowing. Cooperative Research Centre for Australian Weed Management fact sheet, www.weeds.crc.org.au.

Holding D and Bowcher A 2004. Weeds in winter pulses - integrated solutions. *Technical Series No. 9*. CRC for Australian Weed Management, pp. 47–48.

St John-Sweeting R S, and Morris KA 1990. Seed transmission through the digestive tract of the horse. *Proceedings of the 9th Australian Weeds Conference*, Adelaide, South Australia, (ed J Heap), pp. 137–139, Crop Science Society of South Australia.

Stanton R, Piltz J, Pratley J, Kaiser A, Hudson D and Dill G 2002. Annual ryegrass (*Lolium rigidum*) seed survival and digestibility in cattle and sheep. *Australian Journal of Experimental Agriculture*, vol. 42, pp. 111–115.

Stanton R, Pratley J and Hudson D 2003. Sheep are potential vectors for the spread of canola (*Brassica napus*) seed. *Australian Journal of Experimental Agriculture*, vol. 43, pp. 535–538.

Storrie A 2009. *Collecting and preparing plant specimens for identification*. New South Wales Department of Primary Industries, Orange, Australia.

SECTION 5: AGRONOMY TO ENHANCE THE IMPLEMENTATION AND BENEFITS OF WEED MANAGEMENT TACTICS

Agronomy 1 **Crop choice and sequence**

Many agronomic management implications arise from the sequence in which crops are sown. These implications include benefits that can enhance weed management. Planning crop rotation in advance minimises disease and insect problems and maximises crop fertility. With disease, insects and fertility managed optimally, crops become more competitive against weeds.

The implementation and/or effectiveness of some weed management tactics rely on specific crop type and variety, or the sequence of cropping. For example, Tactic Group 2 tactics that aim to kill weeds (often with a herbicide) can be greatly enhanced by growing a more competitive crop type or variety.

At the same time the ability to control a target weed in a specific crop may be so limited that it is best to avoid growing that particular crop in paddocks where the target weed is a problem. For example, winter pulses should not be grown in paddocks where black bindweed (*Fallopia convolvulus*) or wireweed (*Polygonum* spp.) are a problem, and sunflowers should not be grown in paddocks with heavy broadleaf weed burdens.

Crop and variety choice is also important when implementing weed management tactics that relate to controlling in-crop seedset (Tactic Group 3). These tactics are much less detrimental to crop yield and quality where the crop variety matures before the weed species.

Table A1.1 provides key information about winter crop types to assist in making crop choices. Knowledge of relative competitiveness, sowing time, maturity, available herbicide options and difficult to control ('No Go') weeds is important. Similar information about specific varieties should be sought on a local basis.

Weed competitiveness varies between crop types and between varieties within a crop type. Growing a competitive crop in paddocks with high weed pressure will enhance the reduction in weed seedset obtained through employing weed management tactics. It will also reduce the impact that surviving weeds have on crop yield.

Sowing bread wheat or barley is recommended to maximise crop competition (Storrie et al 1998). For example, in areas where summer crops can be grown successfully, a winter fallow–summer sorghum rotation before wheat is a very effective way of managing wild oats (*Avena* spp.) and paradoxa grass (*Phalaris paradoxa*).

Table A1.1 Crop choice options to aid weed management

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
Barley	High	Mid–late	Early	Several for grass; many for broadleaf	• Barley grass • *Vulpia* spp. • Brome grass	Most broadleaf	• Autumn tickle • Double knockdown • Delayed sowing • Crop desiccation • Winter clean pasture in previous year	• Variety choice • Improved fertiliser placement • Increased sowing rate • Good seed (clean and high germination rate) • Direct drill
Canola – imidazolinone tolerant (IT) varieties	Medium	Early	Early	Many for grass; several for broadleaf	• Group B resistant brassicas (e.g. wild radish, wild mustards, wild turnip)	• Grass weeds – particularly brome grass • Groups A and M resistant grass weeds • 'Imi' susceptible broadleaf weeds	• Autumn tickle • Burn residues (not sandy soils) • Crop desiccation • Windrowing • Seed catching • Windrow/burn residues • Winter clean pasture in previous year	• Variety choice • Improved fertiliser placement • Direct drill
Canola – standard varieties	Medium	Early	Early	Several for grass; limited for broadleaf	• Group A resistant grasses, brassicas (e.g. wild radish, wild mustards, wild turnip) • Fumitory • Black bindweed • Vetch	• Grass weeds	• Autumn tickle • Burn residues (not sandy soils) • Crop desiccation • Windrowing • Seed catching • Windrow/burn residues • Winter clean grasses in previous year	• Variety choice • Improved fertiliser placement • Direct drill

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
Canola – glyphosate tolerant (RR) varieties	Medium	Early	Early	Many for grass; several for broadleaf	• Glyphosate-resistant weeds • Brassica weeds	• Grass weeds • Some broadleaf weeds	• Autumn tickle • Burn residues (not sandy soils) • Crop desiccation • Windrowing • Seed catching • Windrow/burn residues	• Variety choice • Improved fertiliser placement • Direct drill
Canola – triazine tolerant (TT) varieties	Medium	Early	Early	Many for grass; several for broadleaf	• Triazine-resistant brassicas	• Grass weeds • Triazine susceptible broadleaf weeds • Fumitory	• Autumn tickle • Burn residues (not sandy soils) • Crop desiccation • Windrowing • Seed catching • Windrow/burn residues • Winter clean grasses in previous year	• Variety choice • Improved fertiliser placement • Direct drill
Chickpeas	Poor	Mid–late	Late	Many for grass; limited for broadleaf	• Fumitory • Black bindweed • Wireweed (no-till and stubble retention) • Vetch	• Grass weeds such as feathertop Rhodes grass	• Double knockdown • Wide row – shielded spraying or inter-row cultivation and band spraying • Crop-topping • Desiccation • Wick/blanket-wiping	• Improved fertiliser placement • High sowing rate
Faba beans	Medium	Mid	Mid–early	Many for grass; limited for broadleaf	• Wild radish • Muskweed • Vetch	• Grasses	• Crop-topping • Windrowing • Windrow/burn residues	• Improved fertiliser placement • High sowing rate

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
Field peas	Medium	Late	Early	Many for grass; several for broadleaf	• Fumitory • Bifora • Vetch	• Grasses	• Delayed sowing • Double knockdown • Crop-topping • Desiccation • Green/brown manuring	• Variety choice • Improved fertiliser placement
Lentils	Poor	Late	Early	Many for grass; limited for broadleaf	• Brassicas • Vetch	• None	• Wick/blanket-wiping • Crop-topping	• Improved fertiliser placement
Lupins – Narrow-leafed and *L. albus*	Poor	Early	Late	Many for grass; many for broadleaf	• Sand plain (blue) lupin	• *Vulpia* spp.	• Residual herbicides • Windrowing • Crop-topping • Desiccation	• Improved fertiliser placement • High sowing rate
Oats – graze and grain	High	Early–mid	Early–mid	Limited for grass; many for broadleaf	• Wild oat • Brome grass • Barley grass • *Vulpia* spp.	• Broadleaf weeds	• Hay or silage • Silage • Short, high intensity grazing • Hay freezing	• High nitrogen rate • Improved fertiliser placement • High sowing rate
Oats – hay	High	Late	Late	Limited for grass; many for broadleaf	• Brome grass • Barley grass • *Vulpia* spp. • Annual ryegrass • *Emex* spp.	• Strict guidelines for export	• Delayed sowing • Double knock • Post-cut knockdown • Hay • Hay freezing	• High sowing rate • High nitrogen rate • Improved fertiliser placement
Oats – grain only	Medium–high	Mid–late	Early–mid	Limited for grass; many for broadleaf	• Wild oat • Brome grass • Barley grass • *Vulpia* spp.	• Broadleaf weeds	• Delayed sowing • Double knock • Winter clean	• Long fallow • High sowing rate • Improved fertiliser placement

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.
[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
Triticale – grain only	Medium–high	Late	Late	Several for grass; many for broadleaf	• Cereal rye • Brome grass • *Vulpia* spp.	• Broadleaf weeds	• Delayed sowing • Double knock	• Long fallow • Improved fertiliser placement • Narrow row spacing
Triticale – graze and grain	High	Early–mid	Late	Several for grass; many for broadleaf	• Cereal rye • Brome grass • *Vulpia* spp.	• Broadleaf weeds	• Double knock • Short time, high intensity grazing	• Improved fertiliser placement • High sowing rate • High nitrogen rate
Wheat – early sown	High	Early	Mid	Many	• Multiple resistant annual ryegrass • Barley grass	• Broadleaf weeds • Wild oat • Annual ryegrass	• Seed carts, impact mills. • Burn residues	• Improved fertiliser placement • Narrow row spacing • High sowing rate
Wheat – main season	Medium–high	Mid	Mid	Many	• Multiple resistant annual ryegrass • Barley grass	• Broadleaf weeds • Wild oat • Annual ryegrass	• Selective spray-topping • Seed carts, impact mills. • Burn residues	• Variety choice • Improved fertiliser placement • High sowing rate
Wheat – quick maturing – short season varieties	Medium	Mid–late	Early	Many	• Multiple resistant annual ryegrass • Barley grass	• Broadleaf weeds • Wild oat • Annual ryegrass	• Delayed sowing • Autumn tickle • Double knock • Windrowing, seed carts, impact mills. • Burn residues	• Improved fertiliser placement • High sowing rate • Narrow row spacing
Wheat – graze and grain	High	Early	Late	Many	• Multiple resistant annual ryegrass	• Broadleaf weeds • Wild oat • Annual ryegrass	• Short, high intensity grazing • Burn residues	• Improved fertiliser placement • High sowing rate • High nitrogen rate

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
Wheat – Durum	Medium	Mid–late	Early	Many (tolerance limit with some herbicides)	• Multiple resistant annual ryegrass • Group A resistant wild oat	• Broadleaf weeds	• Delayed sowing • Burn residues	• Improved fertiliser placement • Narrow row spacing • High sowing rate
Lucerne	High (density dependent)	N/A	N/A	Limited for seedlings; several for mature stands	• Must use trifluralin for establishment – wireweed	• Grasses	• Spray-topping • Winter cleaning • Green/brown manuring • Silage or hay • Grazing management	• High phosphorus rate • Good nodulation • Variety choice
Subclover	Low–medium	Early–mid	N/A	Several	• Bedstraw	• Grasses	• Spray-topping • Green/brown manuring • Silage or hay • Grazing management • Spray-grazing • Wick/blanket-wiping	• Rotation • High phosphorus rate • Good nodulation • Variety choice
French (pink) serradella (e.g. Cadiz)	Low–medium	Early–mid	N/A	Several for grass; limited for broadleaf	• Bedstraw • Broadleaf weeds	• Grasses	• Hay-freezing • Green/brown manuring • Spray-topping • Silage or hay • Grazing management • Wick/blanket wiping	• Rotation • High sowing rate • Good nodulation • Variety choice

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [a]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [b]
High density annual legumes (arrowleaf, berseem, Persian, sulla)	High if sown early; low if sowing delayed	Early	N/A	Limited	–	• Grasses	• Spray-topping • Green/brown manuring • Silage or hay • Grazing management • Spray-grazing • Wick/blanket wiping	• Rotation • High phosphorus rate • Good nodulation • Species and variety choice
Sorghum	Density dependent	Spring – summer	Variable	Limited for grass; several for broadleaf	• Johnson grass (*Sorghum halepense*) • *Sorghum almum* • Feathertop Rhodes grass	• Winter grasses • Summer broadleaf weeds	• Inter-row shielded spray or cultivation	• Variety choice • Narrow row spacing • High sowing rate • Summer fallow • No-till • Summer/winter fallow
Sunflowers	Low	Spring – summer	Variable	Several for grass; limited for broadleaf	• Burrs (*Xanthium* spp.) • *Datura* spp. • *Physalis* spp. • Bladder ketmia • *Ipomoea* spp. • Parthenium weed and many summer broadleaf weeds	• Winter grasses • Summer grasses	• Inter-row shielded spray or cultivation	• Rotation • Summer/winter fallow
Mung beans	Low	Spring – summer	Early	Several for grass; limited for broadleaf	• Burrs (*Xanthium* spp.) • *Ipomoea* spp.	• Winter and summer grasses	• Inter-row shielded spray or cultivation	• Rotation • Narrow row spacing • High phosphorus rate • Good nodulation • Summer/winter fallow

[a] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

[b] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop sequencing to minimise soil- and stubble-borne disease and nematodes

A healthy crop that is not constrained by disease is far more competitive with weeds and less affected by them as a result.

An integrated approach to disease management is the best way to limit yield losses. Sound rotation of crops and varietal selection can minimise the negative impact of soil- and stubble-borne diseases and parasitic nematodes on crop yield and seedling vigour.

Any constraint (such as weeds) which limits the growth of the rotation crop is likely to have a negative impact on the effectiveness of that crop as a disease break.

Benefits

Key benefit #1

Crops with dense canopies act as more effective break crops.

Research (Simpfendorfer et al. 2006) has shown that break crops with dense canopies, such as canola and mustard, are more effective for crown rot management than chickpeas, which grow slowly (*Figure A1.1*). Mustard canopy development is the fastest (*Figure A1.3*), while chickpeas do not reach full canopy closure until much later in the season. The denser canopy enhances microbial decomposition of cereal residues which harbours the crown rot fungus.

Practicalities

Key practicality #1

Selecting crop sequences and varieties to deal with the significant pathogens and nematodes of the paddock in question is good management.

In northern New South Wales (NSW) and southern Queensland crown rot and root lesion nematodes are key issues to consider when growing wheat. In southern cropping systems key issues include cereal cyst nematode and the fungal diseases 'take-all' and *Rhizoctonia*.

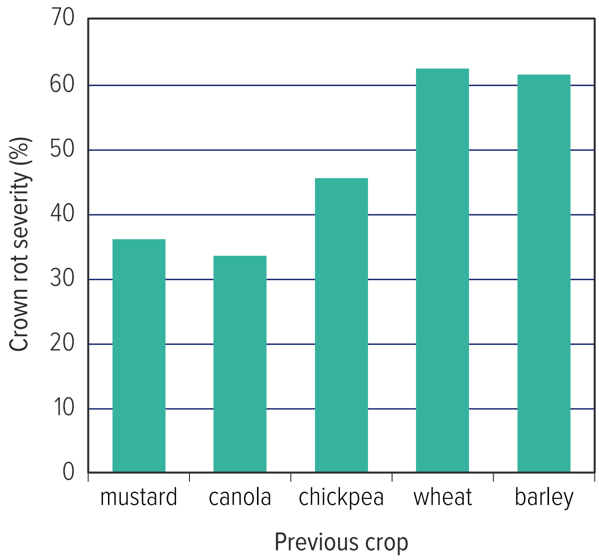

Figure A1.1 The effect of previous break crops on the level of crown rot in spring wheat at Tamworth, New South Wales (Kirkegaard et al 2004).

Figure A1.2 Common sowthistle growing in fallow (no competition) vs growing in crop (wheat and barley). There was no in-crop herbicide applied to control the weed. The lack of sowthistle in-crop is entirely due to crop competition. The 2001 Condamine (Queensland) season had a relatively dry start so the crop established before the weeds.
Photo: Michael Widderick

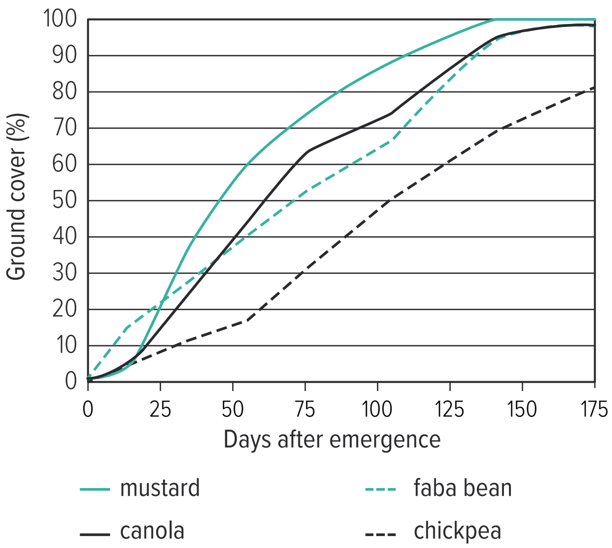

Figure A1.3 Development of ground cover through the 2004 season for various break crops (Simpfendorfer et al. 2006).

As varietal selection usually involves a trade-off between tolerance to specific diseases and desirable crop traits it is important to conduct a risk–benefit analysis for all diseases and significant yield, quality and agronomic traits for the individual paddock and crop varieties in question.

Key practicality #2

Weeds are alternate hosts to some pathogens. Effective integrated weed management during the fallow and in-crop can reduce disease pressure.

Grass weeds are alternate hosts for fungal pathogens which cause crown rot and take-all in winter cereal crops. Broadleaf weeds can also act as alternate hosts for sclerotinia, which can affect a wide range of pulse and oilseed crops. The root lesion nematode *Practylenchus neglectus* will multiply readily in wild radish (*Raphanus raphanistrum*) and exceptionally well in wild oat. Similarly, barley grass (*Hordeum* spp.) acts as a suitable host for *P. thornei*.

Using crop sequencing as a disease break is only effective if alternate weed hosts are controlled during the fallow and in-crop.

Key practicality #3

Rhizoctonia can affect seedling crop growth, leaving the crop at greater threat from weed competition.

Using either knockdown herbicides or tillage to remove plant growth for a period before sowing can significantly reduce the level of *Rhizoctonia* inoculum in the soil. Tillage to 10 cm depth immediately before sowing also physically disrupts fungal hyphae and suppresses the disease in the short term.

In a no-till system, using modified sowing points that provide soil disturbance below the seed can also limit *Rhizoctonia* occurring. Be aware of *Rhizoctonia* and understand when and where it is likely to occur in your region so that appropriate management strategies can be implemented.

Figure A1.4 A pasture phase gives the opportunity to control difficult weeds such as Vulpia with low herbicide resistance risk herbicides, such as simazine.
Photo: Andrew Storrie

Key practicality #4

Weeds can increase moisture stress within a wheat crop, exacerbating yield loss from crown rot.

The most obvious crown rot infection symptom in wheat and barley crops is the premature ripening of heads on infected tillers to produce what is termed a ‘whitehead’. Whiteheads contain either no grain or severely shrivelled, lightweight grain which greatly reduces grain yield and quality. Whitehead formation is related to moisture stress after flowering, when the crown rot fungus is believed to block the ‘plumbing’ system of the plant, preventing the movement of water from the soil into the heads.

Poor weed control over the summer fallow and in-crop means that valuable stored soil moisture is used growing weeds rather than the crop. This can increase moisture stress late in the season and exacerbate whitehead production in winter cereal crops infected with crown rot.

Contributors

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Agronomy 2 **Improving crop competition**

Improving crop competition can improve weed control tactic effectiveness and reduce weed impact on crop yield. Key factors influencing a crop's competitive ability with weeds are the rate and extent of crop canopy development. A crop that rapidly establishes a vigorous canopy, intercepting maximum sunlight and shading the ground and inter-row area, will provide optimum levels of competition.

Canopy development can be influenced by:

- crop and variety
- row spacing, crop orientation, sowing rate and sowing depth
- crop nutrition
- foliar and root diseases and nematodes
- levels of beneficial soil microbes such as vesicular arbuscular mycorrhiza (VAM)
- environmental conditions including soil properties and rainfall.

Each will in turn affect plant density, radiation adsorption, dry matter production and yield. Early canopy closure can be encouraged through good management that addresses the factors above.

Crop type

The most competitive crop type will depend on the regional and individual paddock conditions, including soil type and characteristics (e.g. plant-available water, drainage, pH), rainfall and cropping history. Crop species or varieties that are susceptible to early insect or disease damage also become more susceptible to subsequent weed invasion and competition.

Choose a crop that suits the situation and, if possible, choose the most competitive variety. Generally, the best suited variety for the situation will also be the most competitive.

Benefits

Key benefit #1

A competitive crop improves weed control by reducing weed biomass and seedset.

Crops can be roughly ranked according to competitive ability (*Table A2.1*). Oats are the most competitive crop against annual ryegrass (*Lolium rigidum*). Chickpeas have been shown to have limited ability to compete against weeds and would be equal to narrow-leafed lupins (Whish et al. 2002).

In a 1998 trial at Newdegate, Western Australia, the annual ryegrass dry matter in barley and oats was half that in wheat and triticale at 450 plants/m^2 (competitive ability ranked oats as greater than barley which in turn was greater than wheat, with triticale last). This reduced annual ryegrass seed production by over 2,000 seeds/m^2 (Peltzer 1999).

Table A2.1 The relative competitive ability of a number of annual winter crops and the crop yield reduction (percentage) from 300 plants/m^2 of annual ryegrass at Wagga Wagga, New South Wales (Lemerle et al. 1995).

Crop	Rank (1 to 7)#	Yield reduction from annual ryegrass (%)
Oats	1	2–14
Cereal rye	2	14–20
Triticale	3	5–24
Oilseed rape	4	9–30
Spring wheat	5	22–40
Spring barley	6	10–55
Field pea	7	100
Narrow-leafed lupin	7	100

1 most competitive, 7 least competitive

Within each crop there is a wide range of competitive abilities. Lemerle et al. (1996) tested a large range of wheat varieties from Australia and overseas. Selected data from their results is shown in *Table A2.2*.

Table A2.2 The impact of the competitive ability of a range of wheat varieties on dry matter production of annual ryegrass at Wagga Wagga, New South Wales (Lemerle et al. 1996).

Source of wheat genotype	Annual ryegrass dry matter production (g/m^2)
Varieties released before 1950	103
Victorian Department of Agriculture	138
Cargill	148
NSW Department of Primary Industries	151
Durum	259

The wide range in the ability of field pea varieties to either tolerate competition from weeds or to suppress weed growth and seedset is illustrated in *Table A2.3*. When planning weed management in paddocks with large weed numbers it is important to consider competitive ability as well as yield when choosing a crop and variety.

Table A2.3 The relative ability of field pea varieties to suppress weed growth and seedset and to tolerate competition from weeds (annual ryegrass and wheat) (MacDonald 2002).

Tolerance to competition	Ability to suppress weeds		
	Low	Medium	High
Low	Bonzer Bluey Muktar	Glenroy Soups Progreta	
Medium	Bohatyr	Alma Dundale Parafield	
High		Jupiter	Morgan

Hybrid varieties of canola provide better competition than triazine tolerant varieties against weeds (Lemerle et al. 2010; Lemerle et al. 2014). Vigorous biomass production by hybrid varieties suppressed weed biomass and reduced the impact of weeds on grain yield when annual ryegrass was present at 200 plants/m² (*Figure A2.1*).

There is significant variation in the ability of different cereal species and cultivars to compete with weeds. In 1935 Pavlychenko and Harrington found that barley was more competitive with weeds than other cereals due to early root development. On the Darling Downs, Queensland, Marley and Robinson (1990) found that barley was more competitive than wheat with turnip weed (*Rapistrum rugosum*) and black bindweed (*Fallopia convolvulus*).

Modern semi-dwarf wheats are less competitive than older types (Lemerle et al. 1996; *Table A2.2*). New research has identified high vigour (HV) lines of wheat with increased early vigour resulting in reduced weed seed production (Zerner et al. 2016). Current commercial wheats also exhibit considerable differences in their abilities to compete with weeds. For example, at a wheat plant density of 150 plants/m² Lemerle et al. (1995) recorded yield losses ranging from 20% to 40% in strongly and weakly competitive cultivars. New HV lines of wheat with high early vigour and increased plant height were found to reduce weed biomass and maintain crop yield (Zerner et al. 2016).

Data also shows considerable variability between cultivars for weed competition between years and sites (Cousens and Mokhtari 1998; Lemerle et al. 2001; Coleman et al. 2001), making reliable recommendations about the competitive status of individual varieties difficult.

Cultivars of wheat were assessed for competitiveness with annual ryegrass across south-eastern Australia (Lemerle et al. 2001). Nearly all the variation in crop yield could be attributed to cultivar by environment effects. Only 4% of variability could be attributed to the combined effects of cultivar, weed and environment. Some cultivars exhibited a competitive advantage in some environments, highlighting the need to grow locally suitable cultivars.

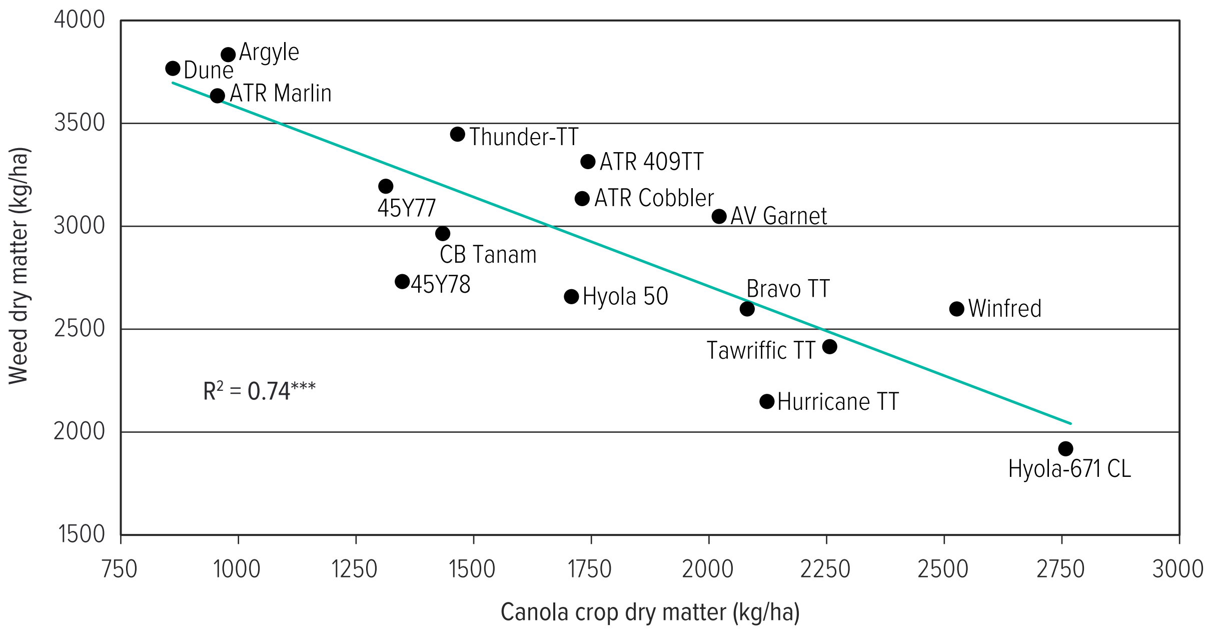


Figure A2.1 The impact of the competitive ability of a range of canola varieties on dry matter production of annual ryegrass at Wagga Wagga, New South Wales (Lemerle et al. 2010).

Manipulation of species choice and crop agronomy will be more reliable than crop variety choice (within a species) for improving competition for weed control.

Sowing rate

The optimum plant density for each crop will differ with growing conditions, time of sowing and economic viability, so seek local advice. In unfavourable conditions (e.g. delayed sowing or poor soil conditions) growth of individual plants becomes limited, so higher plant densities may improve competitive ability and yield.

At any sowing time, increasing sowing rate can result in earlier crop canopy closure and greater dry matter production, improving weed suppression and the effectiveness of other weed management tactics.

Benefits

Key benefit #1

High crop sowing rates reduce weed biomass and weed seed production.

Weed biomass is highly correlated to weed seed production (Radford et al. 1980; Watkinson and White 1985). Increasing crop density can reduce weed biomass, translating into reduced weed seedset and seedbank replenishment (see *Table A2.4*). In addition, crop yields in the presence of weeds usually increase with crop density (Godel 1935; Martin et al. 1987; Marley and Robinson 1990; Lemerle et al. 2004;). The combined weed suppressive effects of competitive sorghum cultivars sown at high crop densities has been shown in Queensland research by Wu et al. (2010). They showed that sowing the cultivars at 8 plants/m^2 reduced the weed density, weed biomass and weed seed production of a model weed by 22, 27 and 38% respectively, compared to the same cultivars sown at 5 plants/m^2.

High sowing rates increase crop competitive ability by:

- promoting early canopy closure and increased dry matter production
- making better use of resources (water, nutrients and light) in competition with the weeds.

In turn, improved crop competition increases the effectiveness of herbicides and other weed management tactics used and suppresses weed seedset by survivors.

Table A2.4 Summary of some of the research conducted in Australia to assess the effect of increasing crop sowing rate in the presence of weeds.

Key message	Study	Weed impact	Crop impact	Comments
At least 200 plants/m^2 are required to suppress annual ryegrass	Wheat sowing rate × with or without annual ryegrass (50–450 plants/m^2) Nine sites across southern Australia (rainfall 200–400 mm) (Lemerle et al. 2004)	Increased crop density (100 to 200 plants/m^2) halved weed dry matter from 100 g/m^2 to approximately 50 g/m^2	Under weed-free conditions yield peaked when wheat was sown at 200 plants/m^2, and declined only slightly (4–5%) at wheat plant densities up to 425 plants/m^2 In the presence of weeds yield increased with wheat density up to 425 plants/m^2 over all sites Presence of weeds reduced yield (compared to weed-free) by 23% at 100 plants/m^2 and only 17% at 200 plants/m^2	Crop densities of at least 200 plants/m^2 were required to suppress annual ryegrass Probability of reduced crop grain size and increased screenings was negligible up to 200 plants/m^2
More competitive wheat crops have the potential for improving weed control and reducing herbicide rates	Wheat sowing rate × herbicide dose rate Wild oat or paradoxa grass Southern Queensland (Walker et al. 2002)	Lowest paradoxa grass seed production was at 80 crop plants/m^2 and 100% recommended herbicide rate Lowest wild oat seed production was at 130 crop plants/m^2 and 75% recommended herbicide rate (or 150 plants/m^2 and 50% herbicide rate)	Highest crop yield with paradoxa grass was at 80 crop plants/m^2 Highest crop yield with wild oat was at 130 crop plants/m^2	At high crop density 100% recommended herbicide rate reduced yield (especially in wild oat). This then impacted adversely on suppression of weed seed production.
Annual ryegrass decreases with increases in wheat sowing rate without affecting wheat grain yield or quality	Wheat sowing rate × variety ×row spacing Victorian mallee (Birchip Cropping Group 1998)	Annual ryegrass heads/m^2 declined with increasing wheat sowing rate from 60 to 120 kg/ha	Wheat yields increased with sowing rate and narrower row spacings	Grain screenings declined with increasing sowing rate and narrow row spacings
Increasing crop density led to a decrease in weed seed production	Wheat and barley × sowing rate Wild oat, paradoxa grass or turnip weed Southern Queensland (Walker et al. 1998)	Increasing crop density from 50 to 100 plants/m^2 reduced the average wild oat seed production from 550 to 230 seeds/m^2 in wheat and from 21 to 7 seeds/m^2 in barley	In dry season no impact In wetter season wheat tiller density and grain yield increased with the higher crop densities Barley yield was reduced by 4% with the increase from 100 to 150 plants/m^2 as a result of decreased grain size	In wheat, sowing rates of 100–150 plants/m^2 with low herbicide rate improved the weed seedset control
Doubling the wheat sowing rate decreased the dry matter of annual ryegrass by 25%	Competitive differences between wheat cultivars Southern New South Wales (Lemerle et al. 1996)	Doubling wheat sowing rate to 110 kg/ha reduced ryegrass dry matter by 25%	Uniform density of ryegrass reduced wheat yields by 80% with above average growing season rainfall, and by 50% with below average rainfall	Ranking of the competitiveness of varieties was the same at both crop plant densities

Key message	Study	Weed impact	Crop impact	Comments
Increasing plant population decreased yield losses caused by weeds	Wheat/barley density effects on wild radish and black bindweed Southern Queensland (Marley and Robinson 1990)	Weed biomass in barley was 38% less than that in wheat. Going from 60 to 120 crop plants/m^2 reduced weed biomass by 50%.	Over 10 experiments broadleaf weeds reduced barley yields by 8% and wheat yields by 17%. Losses due to weeds decreased with increasing crop population	Barley produced greater early biomass
Increased wheat density led to decreased wild oat tiller numbers	Wheat density relationships with wild oat density Northern New South Wales (Martin et al. 1987)	Increasing wheat density decreased wild oat seed yield via reduced tiller numbers	Increasing wheat population above the weed-free optimum is not a viable alternative to herbicide or rotation 50 wheat plants with 50 wild oat plants/m^2 reduced wheat yield by 21%	Optimum wheat population in northern NSW is 100 plants/m^2 Weed-free wheat yield declined with increasing crop density
Increasing crop density led to a decrease in weed biomass	Wheat spatial arrangement × sowing rate Annual ryegrass (50 or 200 plants/m^2) Central-eastern New South Wales (Medd et al. 1985)	Crop spatial arrangement did not affect competition against weeds at any density Increased density (75 to 200 plants/m^2) reduced weed biomass	Yield was highest at high crop plant densities (200 plants/m^2) Grain size was reduced by 10–15% at high crop density	Wheat yields and ryegrass density were not affected by spatial arrangement of the crop
Increasing crop sowing rate led to a decrease in weed biomass and weed seed production	Wheat sowing rate × wild oat density Southern Queensland (Radford et al. 1980)	Weed biomass and seed production reduced with increased crop sowing rate, especially at low weed population densities	Optimum wheat yield was at higher density in wild oat infested plots (compared to weed-free plots)	Increased wheat density up to 150 plants/m^2 resulted in optimum yield when wild oats were present

Key benefit #2

Crop yield and grain quality may improve with increased sowing rates while benefiting weed control.

Most small grain comes from secondary tillers. At higher plant populations there is a greater reliance on primary tillers.

Most data indicates that wheat plant densities ranging from 120 to 200 plants/m^2 result in similar or higher yield and actually lead to lower screenings in most seasons, when compared to low sowing rates (Anderson and Barclay 1991; Birchip Cropping Group 1998; Lemerle et al. 2004; Sharma and Anderson 2004; Minkey et al. 2005). However, in some situations high sowing rates can lead to yield decline and/or increased grain screenings.

Anderson and Barclay (1991) found that in weed-free conditions in the central wheatbelt of Western Australia, increasing the wheat plant density from 50 to 200 plants/m^2 substantially increased crop yield, with no evidence of yield decline at higher densities. In central western New South Wales in a low rainfall environment there was mixed response of grain yield to plant density variation from 50 to 250 plants/m^2, depending largely upon seasonal rainfall. Data from the 2001 to 2004 seasons showed that the probabilities for changes in yield with increasing plant numbers were 9% for a decrease, 36% for no change and 55% for an increase (Motley et al. 2005).

In Western Australia a study of sowing rate experiments by Anderson et al. (2004) estimated the minimum wheat population required to optimise yield potential based on both pre-sowing rainfall and growing season rainfall (*Table A2.5*). Sowing rates presented are seen as the minimum rates needed to avoid yield loss resulting from insufficient plant numbers. Increases of up to 50% on the plant densities and sowing rates cited can be used beneficially to increase crop competition against weeds.

Six experiments conducted in Western Australia evaluated the impact of increasing wheat plant populations on the level of screenings. Only two sites showed an increase in screenings, while the other four sites showed significantly reduced screenings with an increased sowing rate (Sharma and Anderson 2004).

Practicalities

Key practicality #1

If using higher sowing rates to improve the competitive ability of a crop, remember to optimise the sowing rate for grain yield and quality potential.

Using high sowing rates (within the optimum range for the region and target grain yield) will not only ensure maximum grain yield, but also tend to minimise small grain screenings in years with average rainfall during grain filling. Sowing rates in excess of the optimum can increase screenings in some cases (and in a few cultivars) but the economic importance of this is likely to be relatively small.

In situations where terminal stress is likely, choose a cultivar that has good average grain size and stability of grain size.

Table A2.5 Estimates of minimum wheat plant population (plants/m^2) based on pre-sowing rainfall (PSR, mm) and growing season rainfall (GSR, mm) in Western Australia (Anderson et al. 2004).

PSR (mm)	GSR (mm)	Yield expectation (t/ha)	Minimum population needed (plants/m^2)	Approximate sowing rate (kg/ha)
0	150	1.50	60	22
	200	2.25	90	39
	250	3.00	120	56
100	200	2.55	102	47
	250	3.30	132	65
	300	4.05	162	86
200	250	3.60	144	76
	300	4.35	174	92
	250	5.10	204	116

Row spacing

Row spacing affects stubble handling ease at sowing and of controlling disease events in some crops. It also influences crop fertiliser use options. When all other factors are equal, narrow crop rows usually deliver much better crop competition than wider rows. However, wider row spacings may, in some instances, lead to more uniform crop establishment through more accurate seed and fertiliser measurement and placement. This can result in improved early vigour and, ultimately, increased crop competition. Summer crop (e.g. sorghum and sunflower) row spacing studies in Queensland have shown that as row spacing widened (greater than 1 m) crop yield penalty from uncontrolled weeds actually declined even though weed biomass and weed seed production increased (Osten et al. 2006).

When making decisions regarding row spacing, consider:

- paddock conditions (e.g. the weed burden and stubble load)
- the capacity of the equipment or machinery available
- crop type and variety
- opportunities or limitations for pest control (e.g. inter-row weed control)
- opportunities for improved fertiliser placement (e.g. deep banding).

Whichever row spacing is used, always ensure an optimum sowing rate is maintained. Depth of seed placement, covering depth, seed–soil contact, crop density, fertiliser placement and under-furrow soil strength are further considerations. These will affect crop seedlings competitiveness with weeds and the germination and growth of weeds.

Another important parameter in the sowing operation is the ratio of disturbed to undisturbed soil surface. Sowing equipment components should minimise soil surface disturbance. Each point on a tyne-based sowing machine will disturb a strip of soil equal to twice the operating depth of the point plus the width of the point. As operating speed increases, soil throw makes this ratio even higher. Weed seeds left on the soil surface are less likely to germinate and more likely to suffer predation.

For cultural weed control, seeders need to be able to place seed at high rates on narrow rows and close to precision placed fertiliser, with tillage localised under each crop seed or group of seeds (Gregor et al. 2004).

Figure A2.2 Chickpeas growing in wide rows (750 mm) at Nyngan, NSW.
Photo: Greg Condon

Benefits

Key benefit #1

Increasing crop density increases weed suppression. In cereals higher crop densities can achieve further suppression if narrower row spacings are used.

When the weed burden is high the impact of weed competition on crop yield is high, and the benefit obtained from narrow rows on weed management tactics is significant.

A number of experiments in Western Australia reported improved suppression of annual ryegrass in wheat sown in narrow (18 cm) rows compared with wide (36 cm) rows, particularly at high sowing rates (Minkey et al. 2000; Newman and Weeks 2000; Reithmuller 2005). *Figure A2.3* shows a clear trend between ryegrass suppression, sowing rate and row spacing in a 1998 Western Australian experiment. Ryegrass numbers reduce with increased sowing rates and narrower row spacing.

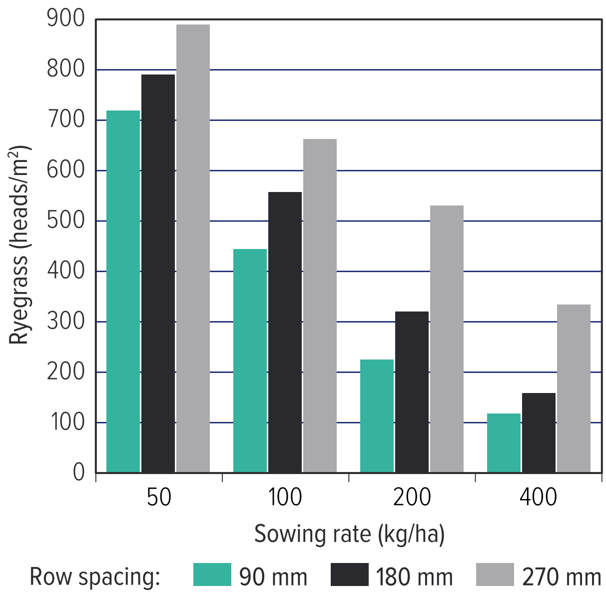


Figure A2.3 The impact of sowing rate (kg/ha) and row spacing (mm) on annual ryegrass head counts (Minkey et al. 1999).

In pulses row spacing has less impact on weed suppression. In northern NSW, Whish et al. (2002) found that there was no difference in weed competition in desi chickpeas at 32 cm and 64 cm row spacings. Similar results were found in lupins (18 cm and 36 cm) in Western Australia (Jarvis 1992) and field peas (23 cm and 46 cm) at Wagga Wagga, NSW (Lemerle et al. 2002). However, recent research has shown that faba bean and chickpea at a narrow row spacing of 25 cm and a high plant density of 70 and 80 plants/m^2 respectively significantly reduced sowthistle biomass and seed production while increasing crop yield. Similarly narrow row spacing (25 cm) in mung bean and soybean could also lead to reduced weed growth and increased crop yield (Widderick et al. 2018).

A compound sowing technique (conventional + broadcast sowing) has recently been found to dramatically increase crop competition in the inter-row compared with conventional sowing. In a heavy annual ryegrass infestation, the compound sowing technique without the use of IBS trifluralin reduced annual ryegrass biomass by 71–77% at both the narrow (23 cm) and wider row (46 cm) spacings when compared to conventional sowing (Benjamin 2018). The technique was also called “zero row spacing”, which has been adopted by farmers in recent years (Benjamin 2017).

Practicalities

Key practicality #1

It is important to match row spacing and sowing rate to obtain crop plant densities that are optimal for both yield and competition against weeds.

Row spacing has less effect on wheat yields where grain yields are less than 3.5 t/ha (Martin et al. 2010) although yield can be limited in seasons of above average rainfall. Although in the lower wheat yielding (2 t/ha) zones of the northern region, the Central Queensland Sustainable Farming Systems project (2002– 2007) did find 50 cm row spacing to have negative impact on yield, particularly in average to good seasons (Osten pers. comm. 2013). Broadleaf crop yields are less sensitive to row spacing. However, in central Queensland research (Osten et al. 2006) has shown sunflower yields reduce as row spacing widens. In presence of weeds, yield reduced by 35% and 44% when moving from 0.75 m rows out to 1 m and 1.5 m rows respectively.

Minkey et al. (2005) found that narrow row spacings, particularly at higher sowing rates, reduced annual ryegrass seed production.

Marley and Robinson (1990) found variable yield results in wheat and barley where row spacings varied between 17.5 cm and 35 cm. Turnip weed biomass increased 38% with the wider spacing, leading to more weed seeds at harvest and grain quality problems.

A study in southern Queensland compared wheat and barley sown in 25 cm and 50 cm rows with crop ability to compete with sowthistle (*Sonchus oleraceus*). The barley out-competed the sowthistle regardless of row spacing, while the wheat sown in wide rows (50 cm) resulted in higher sowthistle biomass (Widderick 2002).

Whole-farm considerations

In order to operate practically in retained stubble at narrow row spacings, an advanced technology seeder may be a necessary capital expense.

Sowing depth

Benefits

Key benefit #1

Sowing depth can be used to enhance crop competitive ability.

Maximum competitive ability will come from a crop sown at optimum and uniform depth to get rapid and uniform establishment.

Much of the yield loss from weed competition occurs in the first few weeks of crop growth. A crop with a few days' or one week's head start on weeds will be significantly advantaged. Sowing healthy seed (with a high germination rate) into ideal soil moisture at the optimal depth for establishment gives the crop a competitive advantage against weeds.

Optimum sowing depth for each particular soil type and crop type will vary. Achieving an optimum and uniform sowing depth will result in synchronous emergence, benefiting crop yield and improving crop competition.

Practicalities

Key practicality #1

Use furrow sowing or moisture seeking techniques at sowing to establish the crop before the weeds.

Moisture seeking or sowing at depth (below 5 cm) into subsurface soil moisture is a common practice in many regions where sowing rainfall is unreliable. This can be done with all pulse species and cereals, and it results in improved establishment due to more favourable soil moisture for both the seed and subsequent seedlings under dry conditions. Moisture seeking ensures timely establishment of the crop ahead of the germinating weeds, giving it a competitive advantage.

An extension of moisture seeking is furrow sowing, which is the practice of sowing at depth but only returning a light cover of soil over the seed, effectively leaving it at the bottom of a seed furrow. With crops that have poor coleoptile strength, this extends the option to moisture seek long after a rainfall event while maintaining crop seedling vigour. This only applies when there are no significant rainfall events near sowing time.

Key practicality #2

Take care to sow seed at optimum depth.

Crops sown too shallow can sometimes be more prone to herbicide damage. Herbicides can become more mobile and active on sandy or coarse-textured soils. On these soils, applying herbicides such as simazine before sowing, and sowing deeper and incorporating the herbicide by sowing to minimise damage is recommended.

Sowing too shallow can also result in uneven germination, with some seed being placed in dry soil and not germinating until a follow-up rain is received.

Sowing too deeply can lead a crop to expend much of its stores of energy by having to push up through the soil. When such crops do emerge they are often slow-growing, weak competitors and are more susceptible to disease, insect attack and/or herbicide damage until they recover.

Equipment costs for independent depth control on each row will need to be considered when making row spacing decisions, and the optimal trade-off between row spacing and depth control may vary with the type of crops grown and the paddock topography.

Sowing time

Benefits

Key benefit #1

Sowing at the recommended time for the crop type and variety will maximise the competitive ability of the crop which, in turn, will reduce weed biomass and seed set.

Time of sowing has a major effect on early crop vigour, canopy development, dry matter production and final yield, and all these factors have a direct impact on the competitive ability of a crop.

Delayed sowing reduces these factors, giving the weeds an advantage. Delaying sowing beyond the optimum window recommended in a given district will reduce early vigour, extend the time taken to reach canopy closure and reduce overall dry matter production. It is therefore important to sow within the recommended time period, not only to maximise yield but also to make the crop competitive.

Practicalities

Key practicality #1

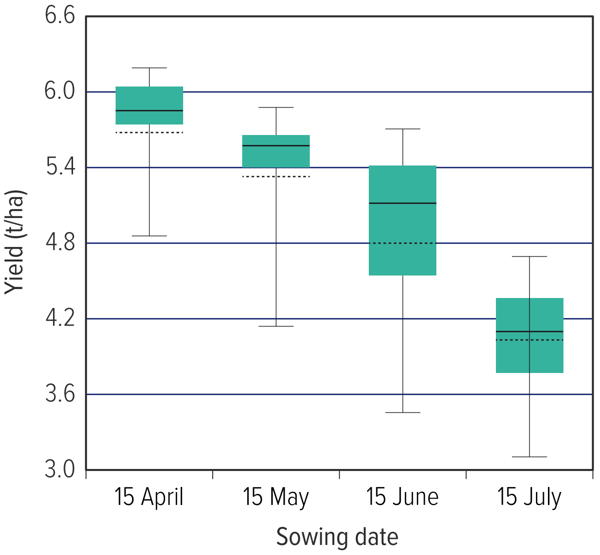
When using delayed sowing to allow for control of the first germination of weeds, choose the crop type and variety most suited to later sowing to minimise yield loss.

If using delayed sowing with a non-selective knockdown herbicide as a weed management tactic, be aware of associated risk of yield reduction. Preferably use crop types and varieties that can be successfully sown later, such as field peas, chickpeas, barley or 'short season' wheat.

The yield reduction in a 'medium maturity' wheat from delayed sowing is shown in *Figure A2.4*, while

Figure A2.5 shows that delaying the sowing time of chickpeas causes a smaller reduction in yield. This effect will be more pronounced in regions with shorter growing seasons.

It is important to note that significant shifts in seed dormancy can occur in some species (e.g. brome grass) causing them to germinate later. In such situations delaying sowing will have minimal impact on weeds, resulting in greater emergence in-crop.



Notes: dashed line = average yield
solid line = median yield
top bar = 90th percentile
bottom bar = 10th percentile

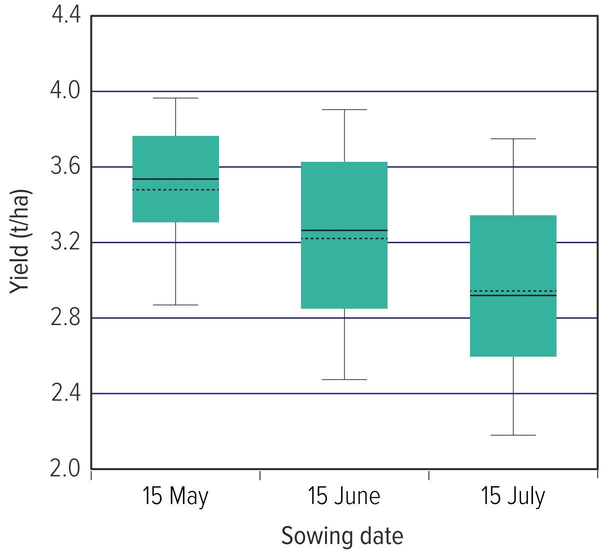
Soil: lithosol
PAWC: 190 mm
Starting water: full
Crop denity: 100 plants/m^2
Applied N: 100 kg/ha
Soil fertility: moderate

Figure A2.4 Predicted effect of sowing date on yield of a 'medium maturity' wheat cultivar at Tamworth, New South Wales (Cox et al. 2012).

Key practicality #2

Sow problem weedy paddocks last to allow a good weed germination and subsequent kill prior to sowing.

As delays in sowing lead to a rapid decline in yield in several key crop types, significant delays are rarely used as a planned strategy. However, a widely adopted tactic is to plan to sow weedy paddocks last. The sowing operation as a whole is not delayed and the benefit of delayed sowing (allowing a knockdown herbicide application time to work) is applied to paddocks where it is needed most.



Notes: dashed line = average yield
solid line = median yield
top bar = 90th percentile
bottom bar = 10th percentile

Soil: lithosol
PAWC: 190 mm
Starting water: full
Crop denity: 20 plants/m^2

Figure A2.5 Predicted effect of sowing date on yield of chickpeas at Tamworth, New South Wales (Cox et al. 2012).

Crop row orientation

The competitive ability of cereal crops can be increased by orientating crop rows at a right angle to the direction of sun light, that is, sow crops in an east-west direction. East-west crops more effectively shade weeds in the inter-row space than north-south sown crops. The shaded weeds have reduced access to photosynthetically active radiation (PAR) resulting in a reduction in biomass production and reduced seedset (Borger et.al.2014).

Altering the orientation of a broadleaf crop has less impact on weed growth. This is because broadleaf plants will alter the angle of their leaves over the course of the day to 'track' the sun as it moves across the sky. Therefore, as the leaves of the broadleaf crop move to catch the most sunlight, they cast less shade over the inter-row space. Broadleaf crops are also slow to reach maximum canopy and therefore maximum light interception until late in the season allowing weeds to germinate and grow.

Changing crop row orientation should be used as a part of an integrated weed management program and not seen as a 'stand-alone' tactic.

Benefits

Key benefit #1

Choosing an east-west orientation for cereal crops suppresses weed growth and may increase crop yield.

In paddocks with a high weed burden, crop orientation can have a significant impact on crop and weed growth. Trials at Merredin and Beverley, Western Australia (2002 to 2005) indicated that weed biomass was reduced by 51 per cent in wheat crops and 37 per cent in barley crops, when crops were sown in an east-west rather than north-south orientation. Grain yield increased by 25 per cent in wheat and 17 per cent in barley crops (Borger et al 2010).

When the weed burden is low, the impact of crop orientation on grain yield and weed biomass may not be apparent. In 2010 and 2011, trials at Merredin, Katanning and Wongan Hills, Western Australia (*Table A2.6*), annual ryegrass in east-west sown wheat and barley crops produced an average of 3000 seeds/m^2, compared to 5700 seeds/m^2 produced by annual ryegrass plants in north-south crops (Borger et. al. 2014).

Practicalities

Key practicality #1

It is important to consider the weed species in the field.

Broadleaf weeds can alter the angle of their leaves to 'track' the sun throughout the day. Therefore, while a cereal crop can shade broadleaf weeds, the weeds will still move their leaves to get the maximum benefit from any sunlight reaching them through the crop canopy. As a result, crops sown in an east-west orientation are less successful in suppressing the growth of broadleaf weeds compared with grass weeds. Further, any weed species that grow taller than the crop will also not be shaded.

Key practicality #2

It is important to consider the layout and latitude (location) of the paddock to be sown.

It may not be possible to sow crops in an east-west direction in all paddocks, depending on the layout of individual fields.

The latitude of the farm will also influence the efficiency of weed suppression due to crop orientation. Sun angle in winter (i.e. how high the sun is above the horizon) is greatest at the equator (where the sun is close to being directly overhead at midday). Sun angle decreases as you move towards the poles. A low sun angle will cause an east-west crop to cast shade on the inter-row space for a greater proportion of the day. Therefore, crop orientation will have a greater impact on farms in southern Australia, compared to northern Australia.

Key practicality #3

Using an east-west crop orientation may be more practical with auto-steer.

If crops are sown in an east-west orientation, it is necessary to drive almost directly into the sun at sunrise and sunset during seeding, harvest and crop spraying. This will be unpleasant for the tractor driver and increases the risk of accidents; however, this is less of a problem when using auto-steer.

Figure A2.6 An east-west orientated wheat crop (left) will shade weeds in the inter-row space to a greater degree than a north-south orientated crop (right).
Photo: Catherine Borger

Table A2.6 Annual ryegrass (ARG) seed production in east-west and north-south orientated crops, at six trials in Western Australia. Seed production was reduced in east-west crops in five out of six trial sites (Borger 2014)

Year	Location	East-west orientation (ARG seeds/m²)	North-south orientation (ARG seeds/m²)	LSD	P value
2010	Merredin	557	826	331	0.008
	Wongan Hills	24	300	36	0.038
	Katanning	529	465	131	0.967
2011	Merredin	27	125	35	0.048
	Wongan Hills	2610	6155	3469	0.047
	Katanning	14113	26276	1342	0.033

Whole-farm considerations

Increased shading by an east-west crop reduces the soil surface temperature in the inter-row space and reduces evaporation, leading to increased surface soil moisture. This cool, moist environment in the inter-row space may increase disease development in the crop in some locations, although this was not observed in these trials (Borger et al. 2010).

Soil properties

Benefits

Key benefit #1

Matching the crop (and variety) to the soil type can improve crop vigour and biomass production, which in turn will optimise crop competitive ability.

Crops growing in unsuitable soils are far more susceptible to disease and insect attack and can become more prone to damage from pre-emergent herbicides. Poor early vigour can also result from growing crops in unsuitable soils. When not actively growing, crop seedlings are unable to detoxify herbicide, which further reduces crop vigour and biomass. Slow crop growth is also advantageous to the weed. Nodulation of pulses can be reduced, thus decreasing plant biomass and competitiveness.

On very acidic soils (pH less than 4.5) grow narrow-leafed lupins, triticale or acid tolerant wheat as these are more suited to such soils than other crops. On heavy textured soils that suffer periodic waterlogging during early winter, the best-suited break crop is faba bean.

Sowing equipment should be tailored to suit soil properties to obtain the highest plant count in the shortest time. In heavy clay soils, presswheel pressure may need to be increased as the soil dries.

Improving soil constraints to plant growth (e.g. acidity, salinity, sodicity, boron toxicity) can dramatically improve crop growth. On an acidic soil in southern New South Wales the use of lime to ameliorate soil acidity resulted in suppressed weed growth and improved crop yields (Li and Conyers 2004). The period over which benefits will be returned depends on the amount of lime applied. Gazey and Andrew (2010) reported increased cereal yields at Kellerberrin in the Avon River Basin in Western Australia up to 17 years after lime was applied at 2.5 t/ha or more. The optimum rate of 5 t/ha of lime for the tenesol soil could be applied in a single operation, or through several applications over a number of years.

Fertiliser use and placement

Benefits

Key benefit #1

Matching fertiliser inputs of both macro- and micro-nutrients to crop target yield and quality will maximise the crop's competitive ability against weeds.

Macronutrients including nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg) are most important for plant growth. Ensure that these nutrients are in good supply before considering micronutrients such as copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), molybdenum (Mo), boron (B) and chlorine (Cl). In some locations there may be known deficiencies of some micronutrients that need to be addressed for either good plant growth or subsequent animal growth. For example, cobalt (Co) and selenium (Se) are deficient in southern Western Australia and Mo is deficient in the ironstone soils of Tasmania (Peverill et al. 1999).

Practicalities

Key practicality #1

Fertiliser placement can improve crop growth, yield and competitive ability.

Aim to place fertiliser nutrients, in both space and time, where they are most available to the crop plants to optimise competitive ability. Without exposing germinating seed to toxicity risks, a three-hopper sowing machine allows placement of an N–P–K starter fertiliser with the seed, while extra N is banded below, to avoid toxicity. The banding depth will also affect both soil disturbance (see *Row spacing* in this section) and depth control (see in this section).

For example, research in New South Wales (Koetz et al. 2002) found that N banded close to the crop reduced the impact of weeds on crop yield to about one third compared with broadcasting N at sowing (*Table A2.7*).

Table A2.7 Impact of N fertiliser (urea) placement on wheat yield in the presence and absence of annual ryegrass (expressed in quantitative yield - t/ha - and percentage loss due to weeds) (Koetz et al. 2002).

Fertiliser placement	Ryegrass	Yield (t/ha)	Yield loss (%)
Broadcast before sowing	weed free	6.8	
	+ ryegrass	4.9	28
Top-dressed at end of tillering (Zadoks decimal code 31)	weed free	6.8	
	+ ryegrass	5.4	19
Banded midway between wheat rows at sowing	weed free	6.5	
	+ ryegrass	5.6	14
Banded under wheat rows at sowing	weed free	6.8	
	+ ryegrass	6.1	10

The tactical application of N (in method and timing) reduced the production of excessive weed biomass and limited weed seed production and subsequent replenishment of the weed seedbank. In situations of high soil N content and high wheat shoot number, delayed application of N will be beneficial to wheat yield if weeds are a problem (Koetz et al. 2002).

Unlike N, P is immobile in the soil. The grain yield advantage of banding P with the seed compared to broadcasting, in terms of yield in weed-free situations, has been demonstrated many times (Jarvis and Bolland 1990; Egan and Bunder 1993; Scott et al 2003). Banding P under the seed rows means that crop roots can readily access it, even under dry conditions. In addition, the available P is not mixed with a large volume of soil which will immobilise it after broadcasting.

Disease and insect pest management

One of the key strategies for managing diseases and insect pests is enterprise sequencing (see *Crop sequencing to minimise soil- and stubble-borne disease and nematodes* in this section). It is well known that annual and some perennial grasses are hosts for some root diseases and a significant grass-free period is required to reduce these pathogens before cereals should be grown. A range of other pathogens is also carried between seasons on crop residues.

Benefits

Key benefit #1

Preventing and/or controlling crop disease and insect damage maximises crop health and competitive ability, avoiding blow-outs in weed seed production.

A healthy crop will compete best with weeds. Preventing and controlling crop diseases (e.g. take-all, crown rot, *Rhizoctonia*, stripe rust) and insect damage (e.g. *Helicoverpa*, aphids, red-legged earth mites) will give crops a fighting chance against weeds.

Practicalities

Key practicality #1

Monitor crop health and control pests and diseases.

Sowing equipment capable of disturbing the soil below the seed zone will reduce attack by fungal diseases such as *Rhizoctonia*.

Because disease, mite and insect damage can reduce the general health and competitiveness of crops, it is important to take adequate precautions against these threats. Thorough monitoring and strategic control programs can manage them all economically.

Key practicality #2

Areas of crop death (or weakness) become a haven for weeds to proliferate.

The loss of a large number of crop plants within a defined area makes an ideal haven for weeds. These areas need to be managed to prevent weed seed 'blow-outs'. Sacrificing the low crop yield of a high weed density area will greatly reduce the numbers of weed seeds entering the soil (see *Tactic 2.4 Spot spraying, chipping, hand roguing and wiper technologies, Tactic 3.3 Silage and hay – crops and pastures* and *Tactic 3.4 Manuring, mulching and hay freezing*).

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Agronomy 3 **Herbicide tolerant crops**

Herbicide tolerance and other genetic traits such as disease resistance are introduced into crops in two ways: either by conventional breeding methods or by genetic modification, which is the introduction of genes from another organism.

Crops with herbicide tolerance traits bred using conventional methods have been used in Australia for some years. For example, triazine tolerant (TT) canola was first used in commercial production in 1994 and imidazolinone tolerant (IT) wheat was introduced in 2001. Genetically modified (GM) herbicide tolerant (HT) cotton has been commercially grown in Australia since 2000, while Roundup Ready® canola was first commercialised in some states in 2008.

HT crops are tolerant to a herbicide that would normally cause severe damage. One example is the Group B imidazolinone herbicide used in Clearfield® canola cultivars where these crops have been conventionally selected and bred for tolerance to this herbicide. Roundup Ready (RR) is the name given to cultivars that have been bred using GM technology which include a gene that provides the cultivar with tolerance to the herbicide glyphosate. Cultivars without these traits would be killed or severely damaged.

HT crops can offer weed control tactics from different herbicide mode of action (MOA) groups than would normally be used in these crops. Growing HT crops can simplify weed control practices and in some instances lead to lower herbicide use.

With the ease and high levels of weed kill often experienced with glyphosate use in RR crops, the frequency of use of other control tactics has declined. Diversity in weed management tactics has decreased and selection pressure for glyphosate resistance development has increased. In an attempt to offset this, many of the stewardship packages associated with HT technologies require the use of alternative technologies in situations where weed density or resistance risk to a particular herbicide is high.

Glossary

Pollination: the transfer of pollen from an anther to a stigma, effecting fertilisation

Self-pollination: the transfer of pollen from the anther to the stigma of flowers on the same plant

Cross-pollination: the transfer of pollen from the anther of one individual plant to the stigma of another plant of the same species. Some species must have this pollen transfer between plants in order to produce fertile seeds.

Out-crossing (also known as hybridisation): the transfer of pollen from the anther of one individual to the stigma of another individual of a different species.

Benefits

Key benefit #1

Herbicide tolerant crops provide additional crop choice, enabling the use of alternative weed management tactics to target specific weeds while maintaining crop sequences.

Inclusion of a HT crop in a cropping program, along with a range of other weed management tactics, can ensure good control of otherwise hard-to-control weeds and avoid blow-outs in the seedbank. For example, TT and Roundup Ready® canola has been used as an effective break crop in paddocks infested with wild radish (*Raphanus raphanistrum*), whereas conventional canola has fewer viable control options for this weed.

Key benefit #2

Herbicide tolerant crops can be grown where herbicide residues may be present in the soil from a previous crop.

A crop that is tolerant to a herbicide can potentially be grown if the herbicide in question is a residual that was used in the previous crop, while a crop that is not tolerant to that herbicide would be severely damaged. For example Clearfield® canola can often be grown following a cereal crop treated with a Group B herbicide even if herbicide residues are suspected. This can happen when there is insufficient rain between spraying and subsequent planting time.

Key benefit #3

Herbicide tolerant crops can reduce the total amount of herbicide used and weed control costs.

Before RR cotton there was far greater use of one or more pre-emergent herbicides, inter-row tillage and in-crop selective herbicides, and large teams of cotton chippers were a relatively common site, chipping out weed escapes in the crop.

A similar situation exists with RR canola where the easy weed control afforded by the ability to use glyphosate in the crop has replaced a number of other weed management tactics. In RR crops there is a tendency for less use of pre-emergent herbicide, fewer other in-crop herbicides and, as there are often fewer weeds, less emphasis on 'at harvest' weed seed capture and subsequent management.

Practicalities

When using HT crops in an integrated weed management program the following key practicalities must be addressed.

Note: specific HT crop technology stewardship programs are an excellent source of more detailed information. Examples include:

- PRAMOG® (Paddock Risk Assessment Management Option Guide) used with Roundup Ready® Canola
- Clearfield® Stewardship Program
- Triazine Tolerant (TT) Canola Program
- Liberty Link® Stewardship.

Key practicality #1

Always use HT crops as part of an integrated weed management program.

A HT crop should represent just one part of an integrated weed management program. A range of weed management tactics from a mix of tactic groups, including non-herbicide measures and herbicides from alternative groups, should be used in conjunction with the HT crop and its associated herbicide.

Follow best management practices as defined by the relevant stewardship program and product label.

Basic guidelines include:

- Farm history and forward planning for herbicide and crop rotations should be compiled and developed to account for the level of existing paddock risk and allow or plan for use of alternative or multiple MOA herbicides.
- If weeds are suspected of being herbicide resistant, reconsider what options are planned and test before growing a HT crop to ensure effectiveness of the herbicides applied.
- Integrated weed management should be planned and practiced on a paddock-by-paddock basis. Always consider paddock history as well as options for future use.
- When planning future crop sequences and management of herbicide resistant weeds that may include HT crop volunteers, consider rotating herbicide MOA groups for all herbicides used and use tactics from a range of tactic groups.
- Reduce selection pressure by using herbicide combinations and non-herbicide tactics. For example, in the integrated weed management plan for a Group B HT crop, use the Group B herbicide in conjunction with a herbicide from another MOA group that has significant activity against the target weed/s. A residual herbicide such as trifluralin (Group D), Sakura® (Group K) or Boxer Gold® (Groups J and K) used at sowing to target annual ryegrass (*Lolium rigidum*) will reduce the selection pressure placed on the ryegrass population to the Group B herbicide. This is essential in situations where there is likely to be a high density of annual ryegrass.

Key practicality #2

Ensure the user is aware of, and adheres to, stewardship agreement restrictions placed on the 'frequency of use' of herbicides within MOA groups.

There are limitations on the number of herbicides from a particular MOA group that can be applied within specified time intervals.

Herbicide resistance management guidelines for Australia for MOA groups can be downloaded from the CropLife Australia Limited website (www.croplifeaustralia.org.au).

Key practicality #3

Use technologies and weed management strategies that are appropriate to the weed spectrum and pressure.

- RR technology as at 2018 requires application at or before the sixth true leaf of the crop. TruFlex technology however allows for later application, up to first flowering. Weeds emerging after this time will either escape treatment or need to be controlled with other herbicides or control measures. In situations of high weed pressure, as has occurred in several situations with wild radish and annual ryegrass, this has resulted in significant weed seed blow-outs in RR crops. In situations where there is a high weed burden, reliance on glyphosate alone also places a high selection pressure for glyphosate resistance. Using a pre-emergent herbicide at planting that

provides season-long suppression or control of weeds is recommended.
- In 2021 the Australian cotton industry will potentially have access to varieties with dicamba, glufosinate and glyphosate tolerance. Research and evaluation of the traits performance in Australian conditions is currently underway.
- In a situation of heavier infestation of broadleaf weeds, all the above would be used but with the weed control base broadened by the addition of a pre-emergent herbicide at sowing.

Key practicality #4

Adhere to all herbicide label directions.

Not all HT crops are tolerant at all growth stages. In addition, there are also application rate limitations to tolerance levels and some herbicides have specific requirements for application.

Key practicality #5

Good paddock management records must be kept, referred to and be accessible whenever required.

Mistakes are costly if a herbicide is applied to the wrong crop, and easily accessible records will provide valuable information in relation to which weeds and paddocks are more at risk of developing herbicide resistance. Such knowledge can be valuable when determining the intensity of post-spray scouting practices.

To avoid mistakes:

- Use paddock signage for easy identification of paddocks sown to HT crops in both the crop year grown and in the following season.
- Integrate the control of HT crop volunteers into normal weed management planning processes.
- Prevent any HT crop plants that germinate from setting seed in the fallow period.
- Control all crop volunteers in following crops with effective weed management tactics.

Key practicality #6

Use agronomic practices to minimise out-crossing (hybridisation) to other crops.

Canola

Out-crossing (hybridisation) can occur with several related species and with other cultivars of canola. In western Canada genes from HT canola have been found to be widespread in conventional canola spread across the landscape from canola volunteers (van Acker et al. 2003). This has occurred despite the frequency of cross-pollination being low as pollen viability is short-lived and decreases with distance from the pollen source. There is also significant competition between selfed and foreign pollen in fertile plants.

Hybridisation risk will increase according to the population size of both canola crop and weed. In situations where canola is widely grown and closely related weeds are in high density nearby, the hybridisation risk between crop and weed is higher. Two important weeds, wild radish (*Raphanus raphanistrum*) and Buchan weed (*Hirschfeldia incana*), are known to cross-pollinate at a low frequency with canola (Ellstrand et al. 1999).

Where Group B and/or Group I herbicide resistant wild radish is a significant weed, RR canola cultivars may provide a useful alternate method of control. However, due to the proximity with a close weedy relative, the chance of hybrids arising is increased. In July 2005 a hybrid between GM canola and wild mustard (*Sinapis arvensis*) was discovered in the United Kingdom (Brown 2005). Although the two plants were found to be sterile, the incident highlights the potential for hybridisation despite the low risk.

The result of out-crossing in canola differs between types of herbicide tolerance. For example, triazine tolerance is not transferred with the pollen in TT canola cultivars, while the tolerance genes for imidazolinone and glyphosate are transferred in the pollen. In all cases out-crossing with wild relatives such as wild radish is possible. However, in the case of triazine tolerance the pollen would have to come from the wild radish and fertilise the ovary on the TT canola plant for the progeny to express herbicide tolerance.

To reduce HT canola out-crossing risk:

- Do not precede or follow HT canola with another canola crop.
- Control volunteer canola plants at all times.
- Control all brassica weeds both in-crop and in adjacent sites (e.g. along fence lines) particularly before flowering.
- Ensure equipment and machinery is cleaned between each canola crop sown, harvested or transported.
- Avoid growing HT canola in paddocks adjacent to conventional canola cultivars.
- Seal bins and cover loads during harvest and transport.

Wheat

Wheat as a weed is usually restricted to the fallow period and the crop following the wheat. While it does occur as a weed on road verges and in some other non-crop situations, its presence is mainly due to poor hygiene and it usually does not persist.

While wheat can out-cross with wild *Triticum* species at a rate of up to 10% (Van Acker et al. 2003) there are no known wild or established weedy populations of *Triticum* or closely related species such as goat grass (*Aegilops* spp.) in Australia.

To minimise the spread of HT wheat and the contamination of conventional wheat:

- Control all crop volunteers in the fallow and following crop.
- Do not follow the HT wheat with another wheat crop.
- Ensure good weed control around fence lines while the HT crop is being grown and in the following fallow and season.
- Do not grow HT wheat next to crops of conventional wheat.
- Cover loads during transport.

The creation of 'super weeds'?

Definition from the Weed Science Society of America; 'a weed that has evolved characteristics that make it more difficult to manage due to repeated use of the same management tactic'. Over-dependence on a single tactic as opposed to using diverse approaches can lead to such adaptations.

- Hybridisation identification between canola and wild mustard in the United Kingdom (Brown 2005) caused some alarm among environmentalists.
- Many factors influence the ability of a plant to out-cross. These include the relative timing of flowering of the two species, pollen dispersal (by wind and/or animal), viability, pollen compatibility, environmental factors and the proximity of plants with similar reproductive genetics.
- Work by Timmons et al. (1995) showed that canola pollen travelled 1.5 km in sufficient quantities to pollinate other canola plants. A review by Rieger et al. (1999) showed that while low levels of hybridisation between canola as the pollen donor and wild mustard and wild radish was possible, the offspring were often sterile. Rieger et al. (2001) showed in field experiments in South Australia that the frequency of hybridisation into canola from wild radish was one in 400 million, with resulting hybrids found to be fertile.
- While such gene transfer can be expected, the ramifications are unlikely to be substantial. In situations where it is the canola that acts as the pollen recipient, resulting seeds will be harvested and processed. When canola receives the pollen from other related species, the seeds produced are usually matromorphic (i.e. not receiving the genetic material from the pollen).

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Further information

WeedSmart https://weedsmart.org.au/stewardship/

Office of the Gene Technology Regulator (OGTR) www.ogtr.gov.au/

CropLife Australia www.croplifeaustralia.org.au/

Canola Council of Canada *www.canola-council.org/*

Seed and technology companies

Bayer Cropscience Australia www.bayercropscience.com.au

Cargill Australia www.cargill.com.au/

Nuseed Australia www.nuseed.com.au/

Pacific Seeds www.pacificseeds.com/

Pioneer www.australia.pioneer.com/

Agronomy 4 **Improving pasture competition**

Pastures represent an important component of many rotations and can range from one to five years' duration to break up extended periods of cropping. Incorporating pastures can help restore soil fertility (i.e. organic matter and soil nitrogen) that may have declined due to frequent cropping and, in turn, improve the competitive ability of crops.

Pastures provide a valuable opportunity to manage weed problems using tactics that can not be used in cropping situations, such as grazing (see *Tactic 3.5 Grazing – actively managing weeds in pastures*), mechanical manipulation and non-selective herbicides.

Benefits

Key benefit #1

Dense stands of well-adapted pasture species compete against weeds, reducing weed numbers and weed seed set.

Where desirable species dominate pasture by greater than 80%, weeds have less opportunity to establish. It follows then that weeds may be best controlled by pasture plants themselves which compete for light, moisture, space and nutrients.

Strong competition against weeds is encouraged by:

- high plant densities of desirable plants
- use of fertilisers to provide the best possible soil conditions for vigorous growth of legumes and desirable grasses
- tactical grazing that incorporates 'grazing-free' periods which enable desirable species to increase in size, favour root development and competitive ability, and allow for seedset and subsequent seedling recruitment.

Key benefit #2

Competitive pastures greatly improve the effectiveness of other tactics used to manage weeds in the pasture phase.

The best scenario for weed competition is high densities of desirable annual pasture plants germinating before or at the same time as weeds. *Table A4.1* illustrates the value of high densities of biserrula germinating at the break of season to suppress weed growth.

For perennial pastures maintain herbage above 1500 kg DM/ha with greater than 80% ground cover to reduce the germination of annual grass weeds. Apply fertiliser (and lime where soil pH is less than 5.5) to increase desirable species vigour.

Whole-farm benefits

Whole-farm benefits include:

- improved feed quality and quantity
- higher stocking rates with better pastures
- forage preservation (hay or silage) due to higher production
- less supplementary feeding.

Practicalities

Key practicality #1

Select species and varieties to suit your conditions.

Select the most appropriate species and varieties according to soil type, climatic conditions and farming system (e.g. permanent pasture or rotation with grain crops). Desirable species need to be managed to ensure an adequate seedbank develops (Bellotti and Moore 1993) because large seedbanks are required to drive high density pasture regeneration.

Table A4.1 Influence of pasture production on weed growth (Miling, Western Australia 2005). These annual legumes regenerated after a wheat crop and were ungrazed (Revell unpublished).

Species / variety	Seedling regeneration (plants/m^2) 15/4/05	Seedling regeneration (plants/m^2) 16/5/05	Spring herbage production (t/ha)	% weeds in spring
Subclover cv Dalkeith	177	188	3.6	11
Burr medic cv Santiago	253	689	3.8	17
Biserrula cv Casbah	602	756	6.7	3

Key practicality #2

Once a pasture gets below a threshold density for a desirable pasture species it should be manipulated to build up seed reserves, or reseeded with improved cultivars.

Pasture re-establishment by re-sowing desirable species will improve pastures that are severely degraded. Optimise this operation by implementing weed control before sowing (e.g. spray-topping, use of knockdown herbicides, cultivation).

In a pasture–crop rotation, if the pasture density declines to a level where weeds invade (e.g. due to drought, poor establishment or overgrazing) it may be necessary to shorten the pasture phase, spray-top or use a knockdown herbicide, and move into the cropping phase early.

Key practicality #3

Mixtures of pasture species will add diversity to the pasture base and improve the capacity for desirable plants to fill gaps created by disturbance (e.g. drought, cropping).

Species mixtures can improve pasture resilience by providing a range of seed characteristics and/or pest and disease tolerance. Typical mixtures include annual grasses and legumes. Including perennial grasses and legumes should be considered in high rainfall (long growing season) environments.

Whole-farm considerations

- Ensure that appropriate grazing management (deferred and rotational grazing) is used.
- Devise strategies and paddock plans for pasture re-establishment (preferably one to two years in advance).
- Ensure that pasture legumes are inoculated with their correct rhizobium.

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Agronomy 5 **Fallow phase**

Fallows are defined as the period between two crops, or between a crop and a defined pasture phase, where the objective is to store and conserve soil water and nitrogen for the next crop and reduce the weed seedbank. The term 'fallow' has different meanings in different parts of Australia.

There are five broad categories:

1. In a winter rainfall (southern) continual cropping sequence of two or more crops, the period between the harvest of one crop and sowing of the next crop represents the shortest fallow period. This is typically about four months. Since the short fallow commences after harvest, it has no impact at all on the previous winter-growing weed seed production. In wet summers, summer-growing weeds can be controlled but this has no direct in-crop weed management benefits in a winter cropping sequence, other than reduced nutrient tie-up, improved moisture accumulation and better sowing conditions through the killing of vine-forming weeds such as melons (*Citrullus* spp. and *Cucumis* spp.) and wireweed (*Polygonum* spp.).
2. In a winter rainfall (southern) pasture–crop sequence the period between killing the pasture (this is usually August to September but it can be earlier) and sowing the first crop would be thought of as a long fallow and would last about eight months. Because such fallows should start well before weed seed maturity, they are an ideal opportunity for weed seedbank management.
3. In northern areas of New South Wales and southern Queensland where rain-fed summer crops can be grown, fallow periods exist between winter cereal harvest and the sowing of a summer crop (e.g. sorghum), or roughly December through to the following October, a period of around 10 months. Similarly, a fallow can exist between sorghum harvest (about March) through to cereal sowing in the following year (about May to June), a period of around 14 months.

   In low rainfall environments some farmers opt to 'skip a year' and call this a long fallow. Harvest would take place in November of Year 1 and sowing would not occur again until April to May of Year 3, a period of about 18 months. These long fallows include both a winter and summer growing season. The winter growing season presents a valuable management opportunity for winter-growing weeds. Similarly, the summer season offers weed management options for summer-growing annual weeds. However, this type of fallow opens the system to high erosion risk, particularly if stubble covers are low.
4. In northern cropping systems it is also common to have consecutive winter-growing crops, depending on available subsoil moisture. As in category 1 above, the fallow period between these crops is about six months and has no impact on winter-growing weed species. Since it includes a summer period, a short northern fallow will have an impact on summer-growing annual weeds.
5. In central Queensland, where cropping tends to be opportunistic, winter crops are harvested in September to October and summer crops may be sown from December to February provided sufficient rain has filled the soil profiles during that three to five month fallow period between crops. As in southern Queensland, spring crops of sorghum, sunflower or mung bean may be sown (usually in September) with harvest from January to March. Again, depending on rain, double cropping to a winter crop may occur. Double cropping opportunities are not frequent and the fallow period between crops is very short (one to two months).

All of these fallows present opportunities to manage late spring and summer emerging weeds. Summer crops sown in January to February are harvested in June or July. If no spring cropping opportunities arise, this country is either fallowed for six to seven months through to the following December to February for back-to-back summer crops, or fallowed for nine to 10 months to April or May for a winter crop. In these fallow situations, the first scenario targets late winter, spring and summer weeds for management, while the latter scenario targets the same but also includes autumn emerging weeds.

Benefits

Key benefit #1

A fallow period on its own, or in sequence with a number of crops, can be highly effective in reducing weed seed numbers in the soil seedbank.

Fallows can be initiated and maintained using herbicides, cultivation or a combination of both. It is important that stubble cover be maintained for as long as possible to protect the soil surface during the fallow period. On mixed farms properly managed grazing can be used to suppress weeds, particularly weed root development.

Table A5.1 contrasts winter rainfall and summer rainfall cropping systems. Note the fallow lengths in the summer rainfall system and the fact that winter fallows are a regular occurrence.

Note: Glyphosate is the main management tool for no-till or minimum-till fallows in both systems. Resistance in annual ryegrass (*Lolium rigidum*) has become an increasingly common problem in all cropping systems. In northern cropping systems the species that have evolved glyphosate resistance in fallows include awnless barnyard grass (*Echinochloa colona*), liverseed grass (*Urochloa panicioides*), windmill grass (*Chloris truncata*) and flaxleaf fleabane (*Conyza bonariensis*). Feathertop Rhodes grass (*Chloris virgata*) has become a major problem in no-till or minimum till farming systems since 2006 as it is difficult to control with glyphosate. See *Section 2: Profiles of common cropping weeds* for more information on individual species.

Key benefit #2

A fallow period can incorporate a number of tactics to reduce weed seedling and seedbank numbers.

A range of non-selective control techniques can be used to prevent weed seed production. Options include grazing, cultivation and herbicides, or combinations of these. No in-crop or in-pasture weed treatment offers this level of weed control and reduced risk of evolving resistant weeds.

Key benefit #3

A double-knock of glyphosate followed three to 10 days later with paraquat (depending on the situation) gives high levels of weed control and controls any hard-to-kill or glyphosate resistant survivors.

Use of a double-knock in fallow greatly reduces glyphosate resistance development risk and can be used to drive down seedbanks of glyphosate resistant weeds. See *Tactic 2.2b Double knockdown or*
'double knock' for more information.

Key benefit #4

Under carefully planned conditions it is possible to use other herbicide MOA groups (Groups C, B, I or K) in fallow.

Great care is needed to reduce the possibility of herbicide carryover and the evolution of weeds resistant to these other MOA groups. Research since 2007 in northern grain region fallows has shown that adding a residual herbicide to a single fallow herbicide application, or to the second knock herbicide application, is a reliable method to get close to 100% control of annual weeds. A major problem that occurs, particularly with summer fallow, is that rain following knockdown herbicide application stimulates another cohort of weeds to germinate and emerge. Also weeds might have already germinated but not emerged before the knockdown herbicide was applied. Adding a herbicide with soil residual activity helps control weeds not yet emerged. Optical camera sprayers are available in fallows allowing growers to target small patches or escapes from broadacre applications. There are a range of restricted use permits for the control of difficult weeds in fallow situations, including with optical sprayers. The list is available on the APVMA website.

https://portal.apvma.gov.au/permits

Table A5.1 Contrast between simple winter and summer rainfall cropping systems.

Season	Winter rainfall area		Summer rainfall area	
Autumn	fallow	plant wheat	fallow	plant wheat
Winter	wheat crop		wheat crop	
Spring	wheat crop		wheat crop	
Summer	wheat crop	fallow	wheat crop	fallow
Autumn	fallow	plant canola	fallow	
Winter	canola crop		fallow	
Spring	canola crop		fallow	plant sorghum
Summer	canola crop	fallow	sorghum crop	
Autumn	fallow	plant wheat	sorghum crop	fallow
Winter	wheat crop		fallow	
Spring	wheat crop		fallow	
Summer	wheat crop	fallow	fallow	
Autumn	fallow	plant canola	fallow	plant wheat

Key benefit #5

In a fallow phase it is easier to judge weed control tactic efficacy as there should be no surviving weeds.

In-crop or in-pasture it is possible that surviving weeds can remain undetected by being hidden among desirable plants, allowing herbicide resistant weeds to develop unnoticed. By contrast, weeds that survive control tactics are more obvious in fallows although they may be hidden among standing and prostrate stubbles.

Whole-farm benefits

- *Soil moisture will be conserved*. This is often cited as the number one advantage of fallowing. In lower and/or less reliable rainfall areas water conservation in-fallow is regarded as essential for reliable crop production. In northern cropping systems sowing summer or winter crops on low subsoil moisture levels is regarded as high risk. By contrast in the eastern Riverina district of NSW, for example, stored fallow water may only provide significant benefit in one year out of four, simply because the growing season rainfall is sufficient and reliable.
  With changing rainfall patterns in southern and south-western Australia, more summer rainfall means clean fallows will become more important in storing soil moisture to enable timely sowing following the season break.
- *Available nutrient levels will be optimised*. Weeds tie up available nutrients in their tissues. In past seasons a number of observations of 'timely' control versus 'late' control of fallow weeds in southern NSW revealed a benefit of 40 to 50 kg of available N/ha (Medway 1995), representing a significant saving in nitrogen fertiliser.
- *Fallow paddocks can provide fire protection for farms and livestock*. Stubble-free fallows provide a safe refuge for stock during bushfires.

A review of summer fallow practices and weed control in 2014 by John Cameron and Mark Congreave identified a number of benefits of fallow weed control.

- Stopping weed growth in the fallow can lead to yield increases in the following crop via several pathways. These include:
- Increased plant available water
- A wider and more reliable sowing window
- Higher levels of plant available N
- Reduced levels of weed vectored diseases and nematodes
- Reduced levels of rust inoculum via interruption of the green bridge
- Reduced levels of diseases vectored by aphids that build in numbers on summer weeds
- Reduced weed physical impacts on crop establishment".

Practicalities

Key practicality #1

Control fallow weeds when they are small.

Small weeds are less likely to be stressed and are easier to control with both herbicide and cultivation in fallows. Small weeds also use less moisture and available nutrients.

Key practicality #2

Avoid over-reliance on cultivation.

Cultivation increases the erosion risk through loss of soil structure. If cultivation is used it should be for a range of reasons such as incorporating lime plus a double-knock for a fallow spray. Over-reliance on cultivation will also lead to a different range of weed problems, such as the spreading of perennial weeds including field bindweed (*Convolvulus arvensis*) and silver-leaf nightshade (*Solanum elaeagnifolium*).

In some systems fertiliser can be added or soil-applied herbicides incorporated while cultivating a fallow just before sowing.

Key practicality #3

Rotate herbicide MOA groups.

Avoid over-reliance on one herbicide MOA group. This rule applies to non-selective knockdowns as well as selective herbicides. Using paraquat will require more forward planning to achieve equivalent results than choosing glyphosate, as application to small weeds gives the most reliable control.

Key practicality #4

Residual herbicides may be used for managing fallow weeds.

Using residual herbicides creates an advantage by reducing knockdown herbicide application frequency, which has huge logistical advantages for the grower. Under dry conditions residual herbicides may last long enough to affect the following crop or pasture phase, so be aware of plant-back periods.

Key practicality #5

Avoid cultivating wet soil.

Cultivation of wet soil causes compaction and smearing. Transplanting of weeds under these conditions is common.

Whole-farm considerations

During the fallow, moisture accumulation can lead to deep drainage into groundwater and increased salinisation of the landscape. Using opportunity cropping when the soil profile is full reduces deep drainage risk; however, weed and disease management issues must be taken into account.

Contributors

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Agronomy 6 **Controlled Traffic Farming or tramlining for optimal herbicide application**

Controlled Traffic Farming (CTF) refers to a cropping system designed to limit soil compaction damage by confining all wheel traffic to permanent lanes for all field operations, including seeding, harvesting and spraying activities.

Soil compaction between the tramlines is greatly reduced, resulting in increased crop health. This form of precision agriculture results in several potential benefits for weed management, namely:

- more efficient pesticide application use due to reduced overlaps
- greater ability to access the field if soil is wet for timely spray application
- the ability to treat weeds in the inter-row more easily
- additional options for managing weed seeds at harvest.

Benefits

Key benefit #1

Accurately spaced tramlines provide guidance and a firmer pathway for more timely and accurate herbicide application, which in turn improves weed control and reduces input costs.

Accurate tramlines or controlled traffic lanes clearly reduce the problems of overlap or underlap, and are generally credited with reducing overall input costs by about 10% (Rainbow 2005).

Use of tramlines or traffic lanes also enables improvements in application timings because trafficability in high soil moisture conditions is increased.

Key benefit #2

Precision guidance in wide-row cropping systems adds potential for new physical and chemical weed management options.

In wide-row CTF systems, options to use inter-row shielded and band spraying are increased; however, registrations for products that can be applied in this manner are limited. High precision guidance systems also improve the potential for effective inter-row cultivation, with precision placement relative to the crop row minimising the level of damage to the crop.

Physical control in the cropping phase has traditionally been dependent on the skills of the operator, with inter-row cultivation (see *Tactic 2.3 Weed control in wide-row cropping*) sometimes followed by manual chipping (see *Tactic 2.4 Spot spraying, chipping, hand roguing and wiper technologies*). By using precision guidance a more effective control is possible to within 2 to 3 cm of the plant row; however, some root pruning and crop damage is unavoidable.

Weed seeds caught at harvest can be placed on the permanent wheel track and controlled by applying higher rates of herbicides (but not exceeding label rates) on the wheel track only. While continuous compaction by machinery will not control all weeds in wheel track areas, it will kill some and does create a poor environment for weed establishment (see *Tactic 4.1 Weed seed control at harvest*).

Improved herbicide efficacy has been reported when applying summer fallow sprays as the dust level from the wheel tracks is reduced.

Figure A6.1 CTF improves the efficiency and accuracy of all operations.
Source: Di Holding

Key benefit #3

Complete controlled traffic farming avoids wheel compaction of the crop zone, resulting in a more competitive crop.

Reduced compaction results in better rainfall infiltration and better soil structure. This increases plant available water levels in the soil profile.

Compacted traffic zones are often more trafficable in wet conditions. This eliminates a proportion of planting delays caused by wet soil, with a timely sowing date contributing to improved crop growth and competition with weeds.

Precision is easier in most controlled traffic crop operations because firm permanent traffic lanes develop. This is particularly noticeable during planting and inter-row operations when working softer, more uniform soil. Tractor power and fuel requirements reduce significantly and zero tillage is facilitated.

Figure A6.2 Controlled traffic allows accurate inter-row sowing.
Photo: Warwick Holding

Practicalities

Key practicality #1

Tramlines can be installed relatively cheaply, with immediate economic benefits gained from more accurate field operations with less overlap.

Tramlines can be installed using marker arms or manual lay-out, but they are increasingly being carried out using 2 cm real time kinematic (RTK) global positioning system (GPS) guidance.

Key practicality #2

Tramlines may be moved to minimise erosion and prevent concentration of nutrients, but future machinery may be capable of spreading residue evenly for even nutrient distribution.

The even spreading of stubble when harvesting with wider header fronts is an issue with CTF. One suggestion is to have 'temporary' tramlines between normal tramlines that are only used in high residue years when there is a dry harvest, to even up nutrient distribution. Conducting this practice only during dry harvests reduces the effects of compaction by the header wheels.

Researchers are also investigating new harvesting machinery that will move the swath rather than moving the header, to avoid the concentration of nutrients between the wheel tacks.

Contributors

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References

Anderson WK and Barclay J 1991. Evidence for differences between three wheat cultivars in yield response to plant population. *Australian Journal of Agricultural Research*, vol. 42, pp. 701–713.

Anderson WK, Sharma DL, Shackley BJ and D'Antuono MF 2004. Rainfall, sowing time, soil type, and cultivar influence optimum plant population for wheat in Western Australia. *Australian Journal of Agricultural Research*, vol. 55, pp. 921–930.

Bellotti WD and Moore AD 1993. Management for pasture establishment; D Kemp and D Michalk (eds). *Pasture Management Technology for the 21st Century*. CSIRO, Melbourne, Australia, pp. 26–37.

Benjamin C 2018. Is it possible to apply additional competition to inter-row weeds? https://weedsmart.org.au/is-it-possible-to-apply-additional-competition-to-inter-row-weeds/. Viewed 13 November 2018

Benjamin C 2017. Zero row spacing could take crop competition to a new level. https://weedsmart.org.au/zero-row-spacing-could-take-crop-competition-to-a-new-level/ Viewed 22 October 2018

Birchip Cropping Group 1998. Competitive crops. www.bcg.org.au/members/va/media/BCG/Competitive_crops.pdf. Downloaded 13 November 2018

Borger CPD, Hashem A and Pathan S 2010. Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science*, vol. 58, pp. 174–178.

Borger C, Hashem A and Powles S 2014. Manipulating crop row orientation and crop density to suppress *Lolium rigidum*. *Weed Research*, vol. 56, pp. 22–30.

Brown P 2005. GM crops created superweed, say scientists. *Guardian Unlimited*. https://www.theguardian.com/science/2005/jul/25/gm.food. Viewed 12 December 2018

Burton J and Dowling P 2004. *Pasture management for weed control – a grazier's guide to controlling annual weeds in southern improved pastures*. NSW Agriculture and the Cooperative Research Centre for Australian Weed Management, Adelaide.

Coleman PK, Gill, GS and Rebetzke GJ 2001. Identification of quantitative trait loci for traits conferring weed competiveness in wheat (*Triticum aestivum* L.). *Australian Journal of Agricultural Research*, vol. 52, pp. 1235–1246.

Cousens RD and Mokhtari S 1998. Seasonal and site variability in the tolerance of wheat cultivars to interference from Lolium rigidum. *Weed Research*, vol. 38, pp. 301–307.

Cox HL, Hammer GL, Mclean GB, Cowbrick TH and King CA 2012. 'WhopperCropper' (software). Queensland Department of Agriculture, Fisheries and Forestry.

Egan J and Bunder R 1993. Fertilizer strategies for lupins. *South Australian Field Crop Evaluation Program – Annual report – 1993*, pp. 104–105. Primary Industries and Resources South Australia, Adelaide.

Ellstrand NC, Prentice HC and Hancock JF 1999. Gene flow and introgression from domesticated plants into their wild relatives. *Annual Review of Ecology and Systematics*, vol. 30, pp. 539–563.

Gazey C and Andrew J 2010. Long-term effect of lime application on soil pH, crop yields and annual ryegrass competition. *Agribusiness Crop Updates 2010*, pp. 229–233. Department of Agriculture and Food WA and Grains Research and Development Corporation, Perth, Australia.

Godel GL 1935. Relation between rate of seeding and yield of cereal crops in competition with weeds. *Science Agriculture*, vol. 16, pp. 165–168.

Gregor D, Lemerle D, Chan KY and Tullberg J 2004. Preliminary development and testing of a novel opener for weed inhibition in conservation cropping. *GRDC Research Update Southern Region (Irrigation)*. Grains Research and Development Corporation.

ICAN 2014. Summer Fallow Weed Management: A Reference Manual For Grain Growers And Advisers In The Southern And Western Grains Regions Of Australia. https://grdc.com.au/GRDC-Manual-SummerFallowWeedManagement. Downloaded 25 October 2018

Jarvis RJ 1992. Lupin row spacing. *Technote no. 2/92*. Western Australian Department of Agriculture.

Jarvis RJ and Bolland MDA 1990. Placing superphosphate at different depths in the soil changes its effectiveness for wheat and lupin production. *Fertiliser Research*, vol. 22, pp. 97–107.

Kirkegaard JA, Simpfendorfer S, Holland J, Bambach R, Moore KJ and Rebetzke GJ 2004. Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Australian Journal of Agricultural Research*, vol. 55, pp. 321–334.

Koetz E, Lemerle D, Good T and Sutherland S 2002. Strategic nitrogen application for weed suppression in wheat. *Weeds 'threats now and forever': Proceedings of the 13th Australian Weeds Conference*, Perth, (eds H Spafford, J Dodd and JH Moore), pp. 67–70. Plant Protection Society of WA.

Lemerle D, Cousens RD, Gill GS, Peltzer SJ, Moerkerk M, Murphy CE, Collins D and Cullis BR 2004. Reliability of higher seeding rates of wheat for increased competitiveness with weeds in low rainfall environments. *Journal of Agricultural Science*, vol. 142, pp. 395–409.

Lemerle D, Sutherland S, Koetz E and Smith A 2002. Suppressing weeds in conservation farming. *Weeds 'threats now and forever': Proceedings of the 13th Australian Weeds Conference*, Perth, (eds H Spafford, J Dodd and JH Moore), pp. 705–708. Plant Protection Society of WA.

Lemerle D, Verbeek B and Coombes NE 1995. Losses in grain yield of winter crops from *Lolium rigidum* competition depends on species, cultivar and season. *Weed Research*, vol. 35, pp. 503–509.

Lemerle D, Verbeek B, Cousins RD and Coombes NE 1996. The potential for selecting wheat varieties strongly competitive against weeds. *Weed Research*, vol. 36, pp. 503–513.

Lemerle D, Verbeek B and Orchard B 2001. Ranking the ability of wheat varieties to compete with *Lolium rigidum*. *Weed Research*, vol. 41, pp. 197–209.

Lemerle D, Lockley P, Luckett D and Wu H 2010. Canola competition for weed suppression. *New Frontiers in New Zealand: Together we can beat the weeds: 17th Australasian Weeds Conference*, Christchurch, New Zealand (eds ZM Zydenbos), pp. 60–62. New Zealand Plant Protection Society.

Lemerle D, Luckett DJ, Lockley P, Koetz E and Wu H 2014. Competitive ability of Australian canola (*Brassica napus*) genotypes for weed management. *Crop and Pasture Science*, vol. 65, pp. 1300–1310.

Li G and Conyers MK 2004. The effect of weeds on wheat grain yield in limed and unlimed soils. *New directions for a diverse planet: 4th International Crop Science Congress*, Brisbane, Australia, (eds T Fischer, N Turner, J Angus, L McIntyre, M Robertson, A Borrell, D Lloyd).

MacDonald G 2002. *Genotypic differences in competitive ability within peas*. Cooperative Research Centre (CRC) for Australian Weed Management Research Project 2.2.2.3: Optimising the competitiveness of winter pulse crops through genetic improvement and agronomy. CRC for Australian Weed Management.

Marley JM and Robinson GR 1990. *Strategies for Broadleaf Control in Barley*. Final report to Barley Research Committee for Queensland.

Martin RJ, Cullis BR and McNamara DW 1987. Prediction of wheat yield loss due to competition by wild oats (*Avena* spp.). *Australian Journal of Agricultural Research*, vol. 38, pp. 487–499.

Martin P, Scott B, Edwards J, Haskins B and Smith J 2010. Row spacing in cereal and broadleaf crops. *Mallee Sustainable Farming 2009 Research Compendium*, pp. 147–152.

Medd RW, Auld BA, Kemp DR and Murison RD 1985. The influence of wheat density and spatial arrangement on annual ryegrass *Lolium rigidum* Gaudin competition. *Australian Journal of Agricultural Research*, vol. 36, pp. 361–371.

Medway J 1995. Objective monitoring – measuring your progress. *Riverina Outlook Conference 1995*.

Minkey DM, Bowran D, Hashem A and Reithmuller G 1999. Effect of row spacing and seeding rate of wheat on the competitive ability of annual ryegrass in a zero tillage seeding practice. *Proceedings of the Crop Protection Updates 1999*, Western Australian Department of Agriculture, Perth.

Minkey D, Hashem A, Reithmuller G and Harries M 2000. Effect of seeding density, row spacing and trifluralin on the competitive ability of annual ryegrass in a minimum tillage system. *Proceedings of the Crop Updates 2000*. Western Australian Department of Agriculture, Perth.

Minkey D, Reithmuller G and Hashem A 2005. Effect of row spacing and seeding rate of wheat on the emergence and competitive ability of annual ryegrass in a no-tillage seeding system. *Proceedings of the GRDC Agribusiness Crop Updates*, Perth.

Motley K, Roberts K and Rice A 2005. The effect of sowing rate on the performance of wheat in the Forbes and Parkes districts. *CWFS Research Compendium 2004–2005*, pp. 72–76.

Newman P and Weeks C 2000. High wheat seeding rates coupled with narrow row spacing increases yield and suppresses grass. *Proceedings of the Crop Updates 2000*, Western Australian Department of Agriculture, Perth.

Osten V, Wu H, Walker S, Wright G and Shields A 2006. Weeds and summer crop row spacing studies in Queensland. *Managing weeds in a changing climate: 15th Australian Weeds Conference*, Adelaide, South Australia, (eds C Preston, JH Watts and ND Crossman), pp. 347–350. Weed Management Society of SA.

Pavlychenko TK and Harrington JB 1935. Root development of weeds and crops in competition under dryland farming. *Crop Science*, vol. 16, pp. 151–160.

Peltzer S 1999. Controlling weed seed production with crop seeding rate. *Proceedings of the Crop Updates*. Department of Agriculture, WA, Perth.

Peverill KI, Sparrow LA and Reuter DJ 1999. *Soil Analysis: An Interpretation Manual*. CSIRO Publishing, Australia.

Radford BJ, Wilson BJ, Cartledge O and Watkins FB 1980. Effect of wheat seeding rate on wild oat competition. *Australian Journal of Experimental Agriculture and Animal Husbandry*, vol. 20, pp. 77–81.

Rainbow R 2005. Managing soil compaction in a no-till system. *GRDC Research Update Southern Region.* Grains Research and Development Corporation.

Reithmuller G 2005. Ryegrass seed set increases with increasing wheat row spacing and stubble retention. *Proceedings of the GRDC Agribusiness Crop Updates*, Perth.

Rieger MA, Potter TD, Preston C and Powles SB 2001. Hybridisation between *Brassica napus* (L) and *Rhaphanus raphanistrum* L. under agronomic field conditions. *Theoretical and Applied Genetics*, vol. 103, pp. 555–560.

Rieger MA, Preston C and Powles SB 1999. Risks of gene flow from transgenic herbicide-resistant canola (*Brassica napus*) to weedy relatives in southern Australian cropping systems. *Australian Journal of Agricultural Research*, vol. 50, pp. 115–128.

Scott BJ, Carpenter DJ, Braysher BD, Cullis BR and Evans CM 2003. Phosphorus fertiliser placement for lupins in southern New South Wales. *Australian Journal of Experimental Agriculture*, vol. 43, pp. 79–86.

Sharma DL and Anderson WK 2004. Small grain screenings in wheat: interactions of cultivars with season, site, and management practices. *Australian Journal of Agricultural Research*, vol. 55, pp. 797–809.

Storrie A, Cook T, Medd R and Edwards J 1998. Selective spray-topping for long term control of wild oats. New South Wales Department of Agriculture Agnote.

Timmons JD, O'Brien ET, Charters YM, Dubbels SJ and Wilkinson MJ 1995. Assessing the risk of wind pollination from fields of genetically modified *Brassica napus* ssp. oleifera. *Euphytica*, vol. 85, pp. 417–423.

Walker SJ, Medd RW, Robinson GR and Cullis BR 2002. Improved management of *Avena ludoviciana* and *Phalaris paradoxa* with more densely sown wheat and less herbicide. *Weed Research*, vol. 42, pp. 257–270.

Walker SR, Robinson GR and Medd RW 1998. Management of wild oats and paradoxa grass with reduced dependence on herbicides. *Agronomy – Growing a Greener Future: Proceedings of the 9th Australian Agronomy Conference*, Wagga Wagga, NSW, Australia, (eds DL Michalk and JE Pratley), pp. 572–574. Australian Society of Agronomy Inc.

Watkinson AR and White J 1985. Some life-history consequences of modular construction in plants. *Philosophical Transactions of the Royal Society*, London B, vol. 313, pp. 31–51.

CropARM (formerly WhopperCropper®) http://www.armonline.com.au/#/wc

Whish JPM, Sindel BM, Jessop RS and Felton WL 2002. The effect of row spacing and weed density on yield loss of chickpea. *Australian Journal of Agricultural Research*, vol. 53, pp. 1335–1340.

Widderick MJ 2002. Ecology and management of the weed common sowthistle (*Sonchus oleraceus* L.). PhD thesis, University of New England, Armidale.

Widderick M, McKiernan A, Harvey G, Heuke L, Walsh M and Chauhan B 2018. Deprive Weeds Of Sunlight And Space – Crop Competition Research In The Northern Grains Region. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/03/deprive-weeds-of-sunlight-and-space-crop-competition-research. Viewed 13 December 2018

Zerner MC, Rebetzke GJ and Gill GS 2016. Genotypic variation of weed competitive ability for bread wheat (*Triticum aestivum* L) genotypes in multiple environments. *Crop and Pasture Science*, vol. 67, pp. 695–702.

Further reading (for Controlled Traffic)

GRDC Precision Agriculture links page - http://www.grdc.com.au/

Blackwell P, Davies S, Riethmuller G, Bakker D, Hall D, Lemon J, Hagan J, Isbister B and Yokwe S 2013. 22 Questions you may ask about controlled traffic in WA. *Technical note*. Department of Agriculture and Food, Western Australia, North Stirlings–Pallinup Natural Resources and Northern Agricultural Catchments Council.

Webb B, Blackwell P, Riethmuller G and Lemon J 2004. Tramline farming systems. Technical Manual, Department of Agriculture Western Australia, Grains Research and Development Corporation Project DAW 718.

SECTION 6: IMPLEMENTING AN IWM PROGRAM USING TACTIC GROUPS

Successful integrated weed management (IWM) depends on having:

- clear weed management objectives
- a well-defined plan.

In general, the key weed management objective is to reduce both weed numbers and the size of the weed seedbank in the soil. There may also be specific objectives for each farm business, or each paddock within a farm business. For example, managing a herbicide resistant weed population may be a specific objective within one paddock, while avoiding the introduction (or spread) of a specific weed may be an objective in another paddock.

A plan should be developed for each paddock or management zone based on the following five steps:

1. Review past actions
2. Assess the current weed status
3. Identify weed management opportunities within the cropping system
4. Match opportunities and weeds with suitable and effective tactics
5. Combine ideas using a rotational planner.

Use *Section 2: Profiles of common cropping weeds* (and other resources) to develop a full understanding of the target weed. Then use Section 4 Tactics for managing weed populations (and other resources) to research the weed management tactics available and the likely benefits, impacts and limitations of each tactic, including those not directly related to weed management. Match the tactics to the weed and the farm business. Consider fine-tuning agronomic practices (see *Section 5: Agronomy to enhance the implementation and benefits of weed management tactics*) to enhance the impact of the weed management tactics being used.

Step 1 **Review past actions**

History of herbicide use

Managing herbicide resistance evolution in weed populations requires a good knowledge of past herbicide use. Collate herbicide use information on a paddock-by-paddock basis for as many years as records are available. A record of all herbicides previously applied will flag any herbicide groups and weeds that may be at high risk of developing resistance.

The IWM plan should be:

- flexible (i.e. able to respond to seasonal conditions)
- based on a good understanding of the life cycle and characteristics of the target weed or weeds
- based on thorough knowledge of the farm (i.e. climate, soil and history)
- linked to long-term goals of the farm business
- cost-effective in the medium to long term.

When there are greater than acceptable numbers of survivors from an application of herbicide (taking into consideration the meteorological conditions when it was applied), good records can help identify whether resistance is a likely cause.

The history of herbicide use information can then be used to:

- prioritise weed management tactics so as to avoid the use of high-risk herbicide mode-of-action (MOA) groups in paddocks with numerous applications or use of high rates in the past
- identify those paddocks at risk, where weed populations can be prioritised for resistance testing and for more detailed monitoring of weed numbers and distribution.

Information on the effectiveness of herbicides applied can be used to save time and money by highlighting potential herbicide resistant populations. Where control has been unsatisfactory, make a record of the target weed and the situation in which it is growing, the growth stage and health of the weed and any possible explanation as to why the tactic failed (e.g. incorrect use of the tactic, poor application technique or timing, adverse weather conditions).

History of non-herbicide tactic use

Gather as much information as possible on any non-herbicide tactics that have been used in the past, whether or not they were targeting weed management, and an indication of how effective they were at reducing weed numbers. Record, for each paddock, events such as:

- cultivation, including 'light' cultivations
- residue burning
- slashing or mowing
- silage and hay cuts
- stubble grazing
- rotational changes such as pasture production.

The available information does not necessarily translate into an increased adoption of IWM, as there is usually a gap between evidence-based IWM and current practice. However, there is an increased need for information in those situations where herbicide resistant weeds are most likely to evolve. Growers need sufficient information about past herbicide and non-herbicide tactics used so that they understand the importance and rationale for the adoption of these technologies into their IWM programs.

Step 2 **Assess the current weed status**

Record the key weed species (see *Section 2: Profiles of common cropping weeds*), including in-crop and fallow weeds, and the distribution and density of each. Always note the date when making paddock assessments.

When recording the distribution of each weed across the paddock, observe if it is:

- widespread and scattered at low plant density
- widespread and at high plant density
- in a small localised area and, if so, where
- in high density patches and, if so, where.

When recording the plant density of each weed, observe the distribution of the weed across the paddock. If the weed is distributed uniformly, estimate the average density. If it occurs in patches, assess the average density within those discrete areas (see *Assess weed population density* in this section).

Together, distribution and density give a clear picture of the weed status at a given time. Thorough and repeated (perhaps annual) weed assessment records effectively identify changes in weed species and distribution within a paddock and across the farm. While conducting these observations any new weed incursions will also be identified. A global positioning system (GPS) or physical markers can be used to map the location of isolated weed incursions or weed patches so they can be tracked and managed from year to year.

Current herbicide resistance status of weed populations

To ensure effective and economical decision-making about future management, it is essential to determine why weeds survive an application of herbicide. If the reason for herbicide failure cannot be clearly and confidently determined, the weed population should be tested for herbicide resistance (see *Assessing herbicide performance* in this section).

A positive test result confirms the need for alternative tactics or herbicides. An incorrect assumption about the herbicide resistance or cross-resistance status of a weed population can be very expensive and have a long-term consequence. Further application of an inappropriate herbicide will only lead to a build-up of the herbicide resistant weed seed levels in the seedbank, increasing the magnitude of the problem (see *Herbicide resistance testing* in this section and *Section 3: Herbicide resistance*).

Step 3 Identify weed management opportunities within the cropping system

Weed management tactics need to complement the farming system and business goals. Ensure that proposed changes to the system are suited to the land, infrastructure and management resources, and that including weed management tactics is practically, environmentally and economically sound. Be aware of likely constraints to implementing weed management tactics such as:

- enterprises within the business that limit the use of some tactics (e.g. canola and some soil residual herbicides)
- the farming system employed (e.g. cropping only)
- personal preferences (e.g. no-till, aversion to change, preference for livestock)
- financial situations or poor availability of contractors or markets
- soil types and/or environment.

Identification of constraints helps define opportunities for controlling weeds and the available weed control tactics. Discussing such issues with the grower will help ensure that later advice meets the needs of the farm business.

Using a weed management tactic might sometimes provide an opening for a new enterprise. For example, production of high-value legume silage might represent a profitable new enterprise as well as being a valuable tool to manage weed seedbanks.

Weed management plans should be flexible. Regular review ensures that tactics can be added or removed as needed.

Computer simulation and decision support tools

Computer simulation tools can be useful to run a sequence of 'what if' scenarios to investigate potential changes in management and the likely effect on weed numbers and crop yield. Four simulation tools being used are the Weed Seed Wizard, ryegrass integrated management (RIM) model, brome RIM model and barley grass RIM model.

Weed Seed Wizard

The Weed Seed Wizard is a computer simulation tool for use in cropping situations across Australia. It can be used to explore different weed management scenarios side by side and help users decide where a new practice (or tactic) or rotation may fit into their specific system and location.

The 'Wizard' uses farm-specific management inputs and modelled competition to predict grain yield and weed seed production. Changing management practices can alter crop or weed numbers. This will affect grain yield as well as the number of weed seeds produced and their subsequent return to the seedbank.

The process for inputting management practices into the model is very flexible. The model is based on a time line using specific management records and can be used to look at past or future years. Users can input:

- Crop types they have sown in the past or may sow in the future, specific sowing times and rates as well as the viability of the seed.
- Specific herbicides or mixtures can be added and their control percentages quickly adjusted to, for example, portray herbicide resistance or poor herbicide application.
- Particular harvest management strategies can be included and subsequently changed to suit the location, for example where a wet harvest affects the amount of weed seed dropped or where rain after haymaking may allow weeds to regrow and set seed.

The 'Wizard' fine-tunes to specific locations:

- Multiple weed species can be considered simultaneously for the same paddock and users can choose their particular weed species from the list available.
- Users choose their own weather file. Specific weather information predicts the loss of dormancy for each weed species and matches this with the rainfall to determine the timing of their emergence from the weed seedbank.
- Users also choose their soil type. The different soil types combine with the weather file to determine how much water is in the soil profile and when germination will occur.
- Different tillage practices can be added. The 'Wizard' matches where the weed seed is within the soil profile from the chosen tillage practice with the soil moisture of the chosen soil type to further predict the germination of each weed species.

The development of the Weed Seed Wizard was a collaborative investment between the Grains Research and Development Corporation, Department of Agriculture and Food Western Australia, University of Western Australia, New South Wales Department of Primary Industries, University of Adelaide and

Department of Agriculture, Fisheries and Forestry, Queensland.

Download the 'Wizard' for free from: https://www.agric.wa.gov.au/weed-seed-wizard/weed-seed-wizard-details

Ryegrass integrated management (RIM) model

RIM is a decision support tool that provides growers and consultants with insights into the long-term management of dryland broadacre winter cereals facing development of herbicide resistant annual ryegrass. RIM offers a convenient way to assess and compare the profitability of alternative strategic and tactical ryegrass management methods. The software's underlying model integrates biological, agronomic and economic considerations in a dynamic and user-friendly framework, at paddock scale and over and over the short and long-term.

The user first customises a paddock profile (yields, herbicides and other control methods, machinery, etc.), then builds a rotation and defines a management strategy over a 10-year timeframe. Rotation enterprises include wheat, barley, legumes and pastures, with over 40 field operations available. Ryegrass control methods include combinations of chemical, mechanical and cultural options. The tool tracks the changes through time with regard to the ryegrass seed germination, seed production and competition with the crop. Long-term effects over several seasons are accounted for through the carryover of ryegrass seeds into the next step of the rotation.

Additional features include settings for easy customisation as well as the ability to visually compare two different strategies or paddock profiles in terms of seed bank dynamics, ryegrass burden on yields, budget allocation for various weed control techniques, and overall profitability.

Download RIM for free, along with further information, from:

www.ahri.uwa.edu.au/RIM.

Brome RIM and barley grass RIM

The original RIM model was modified to develop brome and barley grass RIM models. These models allows users to quickly set up crop/pasture and management sequences and test of a full range of crop and brome and barley grass management options. The models provide expanded options for better planning, harvest weed seed control and changing crop rotation, herbicide usage pattern and non-chemical tactics for long-term brome and barley grass control. When continually maintained and updated these models can be a useful tool for farmers to combat herbicide resistance in weeds.

The brome and barley grass RIMs are free for download along with further information from:

https://ahri.uwa.edu.au/research-brome-rim/

https://ahri.uwa.edu.au/research/barley-grass-rim/

Step 4 **Match opportunities and weeds with suitable and effective tactics**

Tactic groups

Just as herbicides can be grouped by mode-of-action (MOA), tactics for weed control can also be assigned to one of five groups (*Table I1*). Each tactic group provides a key opportunity for weed control and is dependent on the management objectives and the target weed's stage of growth.

Two criteria must be met before tactic groups are accepted by the farming community. The components of an IWM system must be:

1. designed to work in a complementary manner
2. easy to integrate into existing crop-production practices.

Table I1 Tactic groups used to aid weed management planning.

Tactic group (TG)	Opportunity/ timing	Weed impact	Tactic	
Tactic Group 1 Deplete weed seed in the target area	Fallow Stubble Pre-sowing Pasture phase	Encourage germination of weeds – and subsequently kill them	Tactic 1.4 Tactic 1.5	Autumn tickle Delayed sowing (seeding)
		Reduce viability of weed seed in the seedbank	Tactic 1.1 Tactic 1.3 Tactic 4.2*	Burning residues Inversion ploughing Grazing crop residues
		Removal of weed seeds from the seedbank	Tactic 4.2* Tactic 3.5* Tactic 1.2	Grazing crop residues Grazing – actively managing weeds in pastures Encouraging insect predation of seed
Tactic Group 2 Kill weed(s) in the target area	Fallow Pre-sowing Early post-emergent herbicides Pasture phase	Kill weeds, particularly seedlings	Tactic 2.1 Tactic 1.1* Tactic 2.2a Tactic 2.2b Tactic 2.2c Tactic 2.2d Tactic 2.3a Tactic 2.3b Tactic 2.4 Tactic 2.6	Fallow and pre-sowing cultivation Burning residues Knockdown (non-selective) herbicides for fallow and pre-sowing control Double knockdown or 'double knock' Pre-emergent herbicides Selective post-emergent herbicides Inter-row shielded spraying and crop row band spraying Inter-row cultivation Spot spraying, chipping, hand roguing and wiper technologies Detect sprayer technologies
Tactic Group 3 Stop weed seedset	Pasture phase Late fallow Late stubble In-crop	Controlling weed seedset while maintaining yield	Tactic 3.1a Tactic 3.1b Tactic 3.1c Tactic 3.1d Tactic 3.2 Tactic 3.5 Tactic 2.4* Tactic 3.3	Spray-topping with selective herbicides Crop-topping with non-selective herbicides Wiper technology Crop desiccation and windrowing Pasture spray-topping Grazing - actively manage weeds Spot spraying, chipping, hand roguing and wiper technologies Silage and hay – crops and pastures
		Controlling weed seedset while sacrificing yield	Tactic 3.4	Green and brown manuring, mulching and hay freezing
Tactic Group 4 Prevent viable seeds within the target area being added to the soil seedbank	Pasture phase Late crop salvage Harvest	Physical removal of viable seed from paddock	Tactic 3.3* Tactic 4.1 Tactic 3.1d* Tactic 1.1* Tactic 4.2	Silage and hay – crops and pastures Weed seed collection at harvest Crop desiccation and windrowing Burning residues Grazing crop residues
Tactic Group 5 Prevent introduction of viable weed seed from external sources	Sowing Fallow Stubble In-crop Pasture phase Farm operations Livestock feeding Floods	Whole farm hygiene	Tactic 5.1a Tactic 5.1b Tactic 5.1c Tactic 5.1d Tactic 5.1e	Sow weed free seed Manage weeds in non-crop areas Clean farm machinery and vehicles Manage livestock feeding and movement, fodder incorporation including new weed species Monitor and control weeds introduced in flood water

Note: *Tactic used outside their main tactic group, supporting the primary ones within that group.

Step 5 **Combine ideas using a rotational planner**

A rotational planner is a useful and simple way to pull together an IWM plan. It needs to be drafted for each paddock and should include details such as:

- key weeds
- soil type(s)
- soil pH
- management issues and resistance issues (current and/or future)
- key weed management objectives that need addressing
- crop and pasture rotations
- selected weed management tactics from the different tactic groups
- plans for herbicide use (in-crop and fallow).

Review and improve the preliminary rotational planner, from both a weed management and an economic perspective, by asking questions such as:

- Will this plan be effective in reducing the weed seedbank of key target weeds?
- Is the plan likely to lead to economical and sustainable crop production?
- Are there significant areas of risk if aberrant seasonal conditions or other unexpected events occur?
- Is there flexibility within the plan?

Review the results

Review the plan to assess its impact on the target weed(s). Monitor outcomes to determine the effectiveness of each tactic and the combination of tactics for each paddock. Decide which tactics had the biggest effect on weed numbers (and why) and which tactics were disappointing (and why).

Adapt the rotational plan as needed depending on seasonal conditions and the results achieved. Always be open to new ideas and practices.

WeedSmart®

WeedSmart® is an initiative that promotes the long-term sustainability of herbicide use in Australian agriculture by being a herbicide resistance management focal point for farmers and agronomists.

WeedSmart® closely follows the principles laid out in this manual. These core principles help Australian agronomists fight herbicide resistance and start winning the battle against weeds.

The 'Big 6' of the WeedSmart plan

1. Rotate crops and pastures
2. Double knock – to preserve glyphosate
3. Mix and rotate herbicides
4. Stop weed seed set
5. Crop competition
6. Harvest weed seed control

and remember…

- Never cut the rate
- Spray well – choose correct nozzles, adjuvants and water rates
- Clean seed – don't seed resistant weeds
- Clean borders – avoid evolving resistance on the fence line
- Test – know your resistance levels

For more information on WeedSmart® go to www.weedsmart.org.au

Useful skills

Weed identification

Correct weed identification is critical to selecting appropriate control tactics. Resources to assist with weed identification include: the *Ute Guides*, websites, reference books, agronomists, local council weeds officers and herbaria located within each state. A weed identification course will help identify the key features of plants used to distinguish one from another.

Figure I1 An example of a good weed photograph, showing the whole plant, with good detail of leaves and stems to aid identification.
Photo: Andrew Storrie

Collecting and submitting plant samples for identification

A few basic collection principles need to be observed when collecting weed samples for identification. These are:

- Submit fresh samples. Collect samples as close to the time of identification as possible and store in a plastic bag in the refrigerator.
- Submit as much of the plant as possible including the underground parts. Dig up the plant and shake off the loose soil surrounding the root system. Gently washing the roots is also helpful but take care, as the original seed (point of germination) may still be attached and could assist with identification.
- Where possible provide flowers, seeds or fruit, as these are the most distinctive features for identification. Failure to provide these parts might prevent successful identification.
- If a range of growth stages or plant health states are present, it is essential to provide representative plants from each.
- Provide the following information:
  - name (with address and contact details)
  - the situation in which the plant is growing (location, soil type) and distribution (e.g. scattered, clumps, single specimens) and any information that may assist with identification. Such additional information could include:
    - whether the weed is growing where imported fodder has been fed out.
    - particular weed management tactics been used in the current season.
    - when the weed was first noticed.

Digital photos can sometimes be useful for weed identification. Useful features to include are:

- the whole plant, showing architecture: is it prostrate, erect, a bush, a vine, etc? Include an object such as a coin or ruler to indicate size.
- the key parts of the plant including leaf shape and colour, flowers, fruit, seeds and underground parts such as bulbs.

When taking digital photos be sure that the weed can be distinguished from the background (e.g. other plants, soil) and ensure that shadows do not conceal the weed, especially its key features. Fill-in flash can be useful, but do not submit over-exposed images. Check that the photos taken are in focus and not blurry.

Figure I2 Plants ready for pressing between sheets of dry newspaper before sending for identification.
Photo: John Hosking

Assess weed population density

The most accurate way to estimate weed population density in a paddock is to count the number of plants in an area of known size at a number of locations. Weed plant counts should be done using a quadrat, which may be square or circular. The number and location of counts needed to estimate the population will vary depending on the distribution pattern.

How big should the quadrat be?

The size of the quadrat will depend on the density of the weeds. Small quadrats (0.1 m^2) are adequate for weed populations greater than 200 plants/m^2. This would equate to counts above 20 plants per quadrat. For lower weed densities increase the quadrat size (up to 1 m^2) so that you are counting between five and 50 plants per count.

1. If the weed is in distinct patches across the paddock:
   - Conduct plant counts within the patches only.
   - Do at least five counts within each of at least four patches, giving 20 counts for the paddock. The more counts, the more accurate the assessment.
2. If weeds are relatively uniformly distributed across the paddock:
   - Conduct a transect. Walk in a line across the paddock taking a set number of steps, then do a plant count (e.g. walk in a 'W' path as in *Figure I3* and do a count at each 'x'). The most important thing is to do at least 20 counts ensuring you have covered the majority of the paddock. Do not simply concentrate your counts in one corner of the paddock.

Figure I3 An example weed assessment transect using a 'W' pattern and doing a count at each 'x'.

Record the plant count for each weed species being monitored. Plant counting is an opportune time to make notes on different aspects of the weeds and the crop. Consider whether plants appear small and stunted, or affected by insects or disease. Make observations on their distribution, such as whether they are all growing in the crop row with no weeds in the inter-row, or if the density is higher in the header trails.

Also take note of other weeds present. Records should be able to be examined to show changes in weed density and spectrum over time. These records can provide early warning of an emerging problem.

Estimating potential weed population density

Potential weed population density can be estimated in a number of ways:

- When weeds are setting seed, count the number of seed-heads or pods, and the number of seeds per pod or seed-head, from a given sample area. This will give an estimate of the total number of seeds produced.
- Take soil cores, sieve and wash them, and count the seeds in those samples. This technique, whilst more accurate, is often limited to research environments as it time consuming, complex, and dependent on seed identification skills.
- Water small areas in the paddock and identify and count the germinating weeds. This can be done in autumn but does not always provide a realistic guide to potential weediness due to the complex nature of seed dormancy.
- Use paddock records from past monitoring to give an estimate of aspects such as weed species, density, seed set and location. This allows the monitoring of changes through time.

Assessing herbicide performance

Understanding how different herbicides work helps when assessing herbicide performance. It is important to remember that the rate at which plants die after herbicide application depends on the product and rate applied as well as the weather conditions following application. For example, the effect of paraquat/diquat on weeds can be seen shortly after spraying, with initial effects visible within hours in bright sunlight and significant effects evident in a few days. Herbicides such as the sulfonylureas, however, are slower acting and it might take up to six weeks after application before a final assessment of their effectiveness can be made.

It is also important to understand claims made by the herbicide manufacturer. Some products registered for the control of weeds do not claim to kill the weed but, rather, 'suppress' growth, reducing seed set and competition against the crop.

Herbicide failures occur for numerous reasons including application error, adverse environmental conditions, plant stress and herbicide resistance. Spray and paddock records are key to effectively assessing herbicide performance.

Evaluate the likelihood of application error by asking:

- Has the target weed been accurately identified?
- What product was used, and was it a correct choice for the target weed?
- Was the correct product rate used for the weed growth stages present?
- Were appropriate adjuvants used at the correct rates?
- Did the product reach the target? Certain herbicides might be intercepted and bound to other plant material (e.g. stubble) or soil and not reach the target weed. Spray cards can be used to assess spray density, penetration and droplet patterns
- Was the product measured accurately when making up the spray tank mix?
- Was the water quality satisfactory? Herbicide performance can be affected by water quality characteristics such as hardness, pH, salinity and clay content.
- Was the water volume per hectare appropriate?
- Was the boomspray accurately calibrated?
- Were there equipment problems (e.g. blocked nozzles, erratic pump performance)?
- Were the correct nozzles, pressure settings, boom height and boom speed used to achieve uniform coverage?
- Were label directions regarding environmental spray conditions observed?
- What else was added to the tank mix? Some pesticide mixtures, while being physically compatible (i.e. they can be mixed together) might be biologically incompatible. Biological incompatibility can result in reduced weed control and/or increased crop damage. For example, the tank-mixing of glyphosate and 2,4-D are biologically incompatible with some plants of the family *Asteraceae*, such as sowthistle (*Sonchus* spp.). These herbicides should be applied sequentially for these weeds. Performance can also be reduced if insufficient time has been left between separate applications of antagonistic products.
- Was the tank solution mixed properly and was agitation adequate to keep it mixed? This is particularly important for 'dry' formulations.

Environmental factors or conditions at the time of spraying can affect the performance of herbicides. When assessing performance problems, good records of the conditions at the time of spraying are critical.

Herbicide labels provide guidance as to desired conditions or, alternatively, conditions to avoid when spraying weeds. Unfortunately, due to the nature of weather, the number of ideal spray opportunities in a season is limited. Critical environmental factors to consider include:

- the time of day
- the presence of heavy dew
- the temperature at time of application (high and low) and up to 10 days before or after application
- cloud cover: clear skies versus heavy clouds or overcast conditions
- rainfall (e.g. whether rainfall has occurred after application and before the rain-fast period of the post-emergent herbicide has elapsed). Heavy rain shortly after use of soil-applied herbicides can move them into the crop root zone, increasing crop damage but also possibly placing the herbicide within the weed seed zone in heavy soil types.
- stressed weeds due to many factors including too dry or wet, frosts before or after application, poor nutrition, disease or insect attack, and competition from other weeds or the crop
- soil properties: soil pH, organic matter and clay content affect herbicide availability to weeds or the crop
- whether the product leached or was otherwise destroyed, resulting in limited uptake by the target weed.

When trying to determine the reason for herbicide failure, the importance of good records cannot be overstated. If a reason cannot be found for a spray failure, herbicide application history could indicate that resistance is likely.

Herbicide resistance testing

The main reason for herbicide resistance testing is to determine which herbicides are still effective at controlling the weeds in a particular paddock. Whilst resistance to a particular herbicide MOA might be suspected, experience shows this assumption can be wrong. Besides, without testing it is hard to tell with any certainty which herbicides still work in certain paddocks.

Herbicide resistance can be different from paddock to paddock and farm to farm. When testing for resistance it is useful to understand the resistance profile of the weed population: ask which herbicides from which groups still work and at what rates? When conducting resistance tests use a range of products from different MOA groups and subgroups. This is of particular value when dealing with weed species known to develop cross-resistance (see *Section 3: Herbicide resistance*).

There are different methods of testing for herbicide resistance. Resistance testing can be conducted on-farm or by a commercial resistance testing service. Tests can be performed in situ (in the paddock during the growing season), on seed collected from the suspect areas, or on live plant samples sent to a testing service.

In situ testing

In situ testing can be performed following herbicide failure in a paddock. Testing should be done at the earliest opportunity, remembering that the weeds will be larger than when the initial herbicide was applied. Test strips should be applied using herbicide rates appropriate to the current crop growth stage and weed size, plus a double rate. The test strips should only be applied if the weeds are stress-free and actively growing. Conduct weed plant counts before and after application to more accurately assess the level of control. Measure green or dry plant weights before and after spraying for more accurate results.

When testing a number of herbicides in situ as part of field trials, a small motorbike boom or firebreak boom is more suitable than full sized spray equipment, provided it can be accurately calibrated. Owing to the often late timing of in situ testing, results must be carefully interpreted, preferably with the help of an experienced agronomist.

Herbicide resistance seed tests

Seed tests require collection of suspect weed seed from the paddock at the end of the season. This seed is generally submitted to a commercial testing service. It is possible to conduct these tests at home in pots, but this can be difficult due to the complex seed dormancy mechanisms of some weed species and practical difficulties associated with applying accurate rates of product and maintaining reasonable growing conditions for the weeds in pots.

The turn-around time for seed tests is generally several months due to the need to break dormancy. This can mean that results are received very close to the start of the following growing season, usually March to April.

Approximately 3,000 seeds of each weed (an A4-sized envelope full of good seed-heads) are required to test multiple herbicide MOAs. This equates to about one cup of annual ryegrass seed or six cups of wild radish pods.

Consult the testing service for more details on seed collection for herbicide resistance testing.

Syngenta herbicide resistance Quick-Test™

The Syngenta herbicide resistance Quick-Test™ uses whole plants collected from a paddock rather than seeds, eliminating the problem of seed dormancy and enabling a far more rapid turn-around time. In addition, the tests are conducted during the growing season rather than out of season over the summer. A resistance status result for a weed sample is possible within four to six weeks.

For each herbicide to be tested, 50 plants are required. To reduce postage costs, plants can be trimmed to remove excess roots and shoots.

> The Quick-Test™ is a whole-plant test. Weeds (ranging in size from 2-leaf stage to late-tillering or decimal codes 12 to 16 on the Zadoks scale for grasses and up to six leaves for broadleaf weeds) are collected and sent to the testing service by mail. In some cases plants at the early flowering stage can be tested using the Quick-Test™ methodology.

Once received by the testing service, plants are carefully trimmed and transplanted into pots. After new leaves appear (normally five to seven days), plants are treated with herbicide in a spray cabinet. The entire procedure, from paddock sampling to reporting results, takes between four and six weeks, depending on postage time and the herbicides to be tested.

Unlike paddock tests, the Quick-Test™ is performed under controlled conditions so it is not affected by adverse weather. Plant age is also less critical to the testing procedure. Trimming the plants prior to herbicide application means that herbicides are applied to actively growing leaves, thus mimicking chemical application to young seedlings. The Quick-Test™ has been used to test resistance in both grass and broadleaf weed species. During testing, both known sensitive and resistant biotypes are included for comparison.

Collecting seed and plant samples for resistance testing

The test area may be as large as a paddock or only a small problem spot. For large paddocks, consider submitting a few samples (e.g. from different management zones or soil types within the one paddock).

Before sampling, contact the particular testing service being used, or an agronomist experienced in herbicide resistance management, to determine how many herbicides need to tested. This will then determine the size of the sample required.

When sampling patches of weeds after a herbicide application failure, only collect seed or plants from these patches because this will help determine whether the cause of these patches is herbicide resistance and how strong the resistance is. Collecting seed or plants from across the paddock in a bulk sample will result in an underestimation of the level of herbicide resistance. The whole paddock should be managed based on the resistant patches within the paddock.

Draw a 'mud map' of the collection points or area, or use a GPS to record sampling locations.

It is often best to avoid headlands or areas where there may have been spray misses and/or overlaps or where the application rate is questionable.

Avoid producing a sample dominated by seed from only a few plants. It is best to collect one seed-head from many individual plants within the patch. The aim is to provide the most representative sample possible. Collect enough seed or sufficient plants to cover the range of herbicides to be tested.

Contributors

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Further reading

Boutsalis P 2012. How to sample plants for the Quick-Test. *Giving a RATS* email newsletter p. 6: https://www.agronomo.com.au/s/01-Newsletter-April-2012.pdf. Downloaded 9 December 2018

Cummins JA and Moerkerk M 1996. *Weeds the Ute Guide* – a TOPCROP publication. Primary Industries South Australia.

Dellow JJ 2005. *Broadleaf Weed Seedlings of Temperate Crops and Pastures.* New South Wales Department of Primary Industries, Orange.

Lacoste M 2013. RIM, Ryegrass Integrated Management – User guide. Australian Herbicide Resistance Initiative, University of Western Australia, Perth.

Pannell DJ, Stewart V, Bennett A, Monjardino M, Schmidt C and Powles SB 2004. RIM: a bioeconomic model for integrated weed management of *Lolium rigidum* in Western Australia. *Agricultural Systems*, vol. 79, pp. 305–325.

Storrie AM 2012. Know what herbicides still work!! *Giving a RATS* email newsletter p. 6: https://www.agronomo.com.au/s/01-Newsletter-April-2012.pdf. Downloaded 9 December 2018

Swanton CJ, Mahoney KJ, Chandler K and Gulden RH 2008. Integrated weed management: Knowledge-based weed management systems. *Weed Science*, vol. 56, pp.168–172.

Wood P, Cahill M, Marlow G and Douglas N 2000. *Weeds the Ute Guide, Northern Grain Belt Edition* – a TOPCROP publication. Farming Systems Institute, Queensland Department of Primary Industry.

Wilson B, Hawton D and Duff A 1995. *Crop Weeds of Northern Australia*. Queensland Department of Primary Industry.