Pasture Dieback in Queensland

A review of relevant literature

Contents

1. Introduction

1.1. Background

Australia's original grasslands were based on a range of native grasses, sedges and other low growing plants. These mingled with woody trees, creating an environment resilient to the extremes of drought and flood that typify the Australian environment. Some have suggested that this environment was created by the 'firestick ecology' practices of aborigines, based as it is on species that have evolved to thrive with regular burning.

However, the productivity of such environments is limited. The development of improved pastures using introduced species has greatly increased the carrying capacity of such areas. Fertiliser could be added to nutrient deficient soils, while clearing timber made more room for stock. Programs that seeded paddocks with introduced species were widely promoted, with both government and private businesses convinced of the major benefits from creating productive, perennial pastures.

Buffel grass is widely cultivated as pasture in dry tropical and sub-tropical regions around the world[1]. It was introduced from Eastern Africa into Northern Australia in the 1920's. The species has many qualities that make it ideal for stock. It is highly palatable, easily digested, produces large quantities of wind dispersed seeds, and forms rhizomes which allow it to spread rapidly, even under semi-arid conditions. It is also highly resistant to drought, fire, and heavy grazing[2].

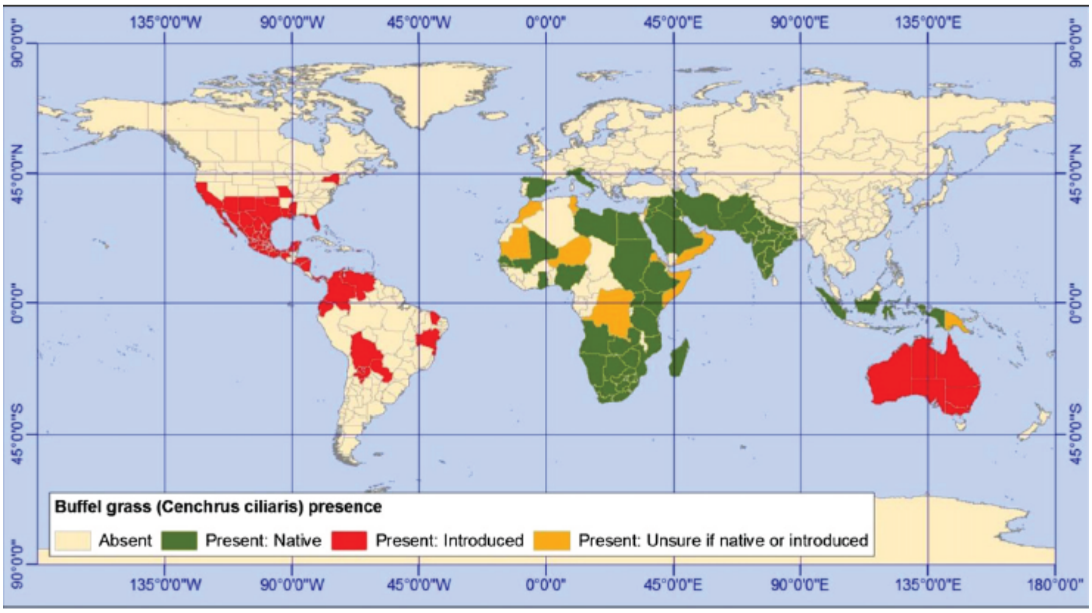

Figure 1. The native and exotic distribution of buffel grass to state or country level. From Marshall et al, 2012.

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[1] Marshall VM, Lewis MM, Ostendorf B. 2012. Buffel grass (*Cenchrus ciliaris*) as an invader and threat to biodiversity in arid environments: a review. J. Arid Environ. 78:1-12.

[2] Eyre TJ et al. 2009. Buffel grass in Queensland's semi-arid woodlands: response to local and landscape variables, and relationship with grass, forb and reptile species. Rangeland J. 31:293-305.

The adaptive capacity and invasive ability of buffel grass mean that in many parts of the world it is considered a weed. So, for example, buffel grass now dominates 90% of the rangelands in Texas[3] and 33% of the native grasslands in Hawaii[4]. Similar impacts have been observed in Australia, as buffel grass pastures can displace native vegetation[5], reducing biodiversity of vertebrates and invertebrates alike[6].

Buffel grass is clearly a highly resilient species well suited to hot, arid regions. This makes the current major dieback issues all the more mystifying. However, as with other crops, the creation of more uniform environments can also increase susceptibility to diseases[7], pests, and extremes of climate.

1.2. What is dieback?

Dieback occurs when a large area of plants dies without an obvious cause. This is certainly not unique to pasture, but has been reported in plants ranging from Eucalypts to salt marshes, and orchard trees to turf grass.

Dieback is considered quite differently to pasture decline or ‘rundown’, although this condition can also affect pastures in northern Australia. Pasture decline involves gradual loss of productivity over time, whether due to over grazing, nutrient loss, soil compaction, lack of seedling establishment, climate change or all of these factors combined.

Areas in Queensland currently affected by dieback may also be affected by pasture rundown, with losses of 50% productivity in buffel pasture reported compared to when the pasture was first established[8]. In 2011 it was estimated that the economic impacts of pasture rundown would be >17billion over the next 30 years[9].

1.3. Buffel grass dieback

1.3.1. Symptoms

The symptoms of dieback in buffel grass are quite specific. Makiela[10] describes these as reddening or bronzing of the leaves, starting from the tip and progressing down towards the ligule. The symptoms develop first on the oldest leaves, but eventually spread to the whole plant. If the plant is watered and fertilized then it can grow faster than the symptoms progress. However, once water stress occurs, the plant quickly succumbs.

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[3] Mayeaux HS, Hamilton WT. 1983. Response of common goldenweed (*Isocoma coronopifolia*) and buffel grass (*Cenchrus ciliaris*) to fire and soil. Weed Sci. 31:337-343.

[4] Daehler CC, Carino DA. 1998. Recent replacement of native pili grass (*Heteropogon contortus*) by invasive African grasses in the Hawaiin islands. Pacific Sci. 53:220-227.

[5] Clarke PJ, Latz PK, Albrecht DE. 2009. Long-term changes in semi-arid vegetation: Invasion of an exotic perennial grass has larger effects than rainfall variability. J. Veg. Sci. 16:

[6] Smyth A, Friedel M, O’Malley C. 2009. The influence of buffel grass (*Cenchrus ciliaris*) on biodiversity in an arid Australian landscape. Rangeland J. 31:307-320.

[7] Clarke RG, Eagling DR. 1994. Effects of pathogens on perennial pasture grasses. NZ J. Agric. Res. 37:319-327.

[8] Peck G et al. 2012. Graziers, pasture seed industry and researchers are concerned about pasture productivity decline. Proc. 16th ASA Conf. 14-18 Oct 2012, Armidale, Australia.

[9] Peck G et al. 2011. Review of productivity decline in sown grass pastures. MLA final Report B.NBP.0624.

[10] Makiela S. 2008. Studies on dieback of buffel grass (*Cenchrus ciliaris*) in Central Queensland. PhD thesis, Central Qld University.

Figure 2. Symptoms of buffel grass dieback. The leaf tips redden, initially on the older leaves (left). Symptoms progress (centre) until the whole plant is affected and dies, turning grey and disintegrating (right).

Patches of dieback are initially roughly circular, ranging from 2 to 60m diameter. These grow irregularly by approximately 5cm/week, with multiple patches coalescing to form large, dead areas[10]. This spread occurs both up and down sloping areas although with a slight tendency to increase downhill. It can occur on a wide range of soil types and appears unrelated to soil compaction[11].

Whereas dry, dormant pasture is golden, buffel grass plants affected by dieback become grey and disintegrate. Cattle avoid eating affected plants, further decreasing the productivity of affected areas.

1.3.2. Spread

Buffel grass dieback was first observed in Queensland in the early 1990's. Patches of dead buffel grass were first observed in the Baralba district, south west of Rockhampton, during the drought years of 1993-4. However, the dead areas did not recover after the following wet seasons, but continued to expand[12]. By 1997 patches of dead grass were appearing over wide areas.

Several research projects attempted to resolve the issue. These included a major investigation conducted by Graham and Conway using a producer demonstration site and a PhD study conducted by Sandrine Makiela.

Both of these projects conducted extensive testing of soil and plants, examined how the condition spread, and attempted to isolate causal organisms from affected plant tissue. Neither was able to consistently isolate and re-inoculate a single pathogen in order to trigger the observed symptoms; Koch's postulates of causation remained unsatisfied.

Reports suggest that the rate of spread of dieback slowed following the initial outbreak. However, this changed in 2012, when pasture dieback again became a major issue. Since this time there have been numerous and increasing reports of buffel grass dieback on grazing properties.

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[11] Makiela S, Harrower KM. 2008. Overview of the current status of buffel grass dieback. Aust. Plant Dis. 3:12-16.

[12] Graham TWG, Conway M. 2000. Sustainable production from sown pastures. PDS Annual Report. DPI Brisbane.

1.4. Dieback of other pastures

1.4.1. Species

While initial reports focused on buffel grass, a number of other grass species are now also suffering dieback. A 2017 review by Buck[13] listed a number of species potentially affected by dieback, in addition to buffel grass. While most are introduced pasture species, the list even includes three native grasses (Table 1).

Table 1. Grasses reported as potentially affected by dieback in Queensland. From Buck, 2017.

Species	Common name	Cultivar	When affected
Cenchrus ciliaris	Buffel grass	American, Gayndah	Since approx. 1990
Urochloa mosambicensis	Sabi grass	Nixon	Since approx. 1990
Bothriochloa insculpta	Creeping blue grass	Bisset	~5 years
Chloris gayana	Rhodes grass		~5 years
Panicum maximum	Panic	Petrie, Gatton	~5 years
Panicum coloratum	Panic	Bambatsi	~5 years
Paspalum dilatum	Paspalum		~5 years
Paspalum dilitatum	Signal grass	Basilisk	~5 years
Brachiaria mutica	Para grass		~5 years
Digitaria eriantha	Pangola grass	Pangola	~5 years
Setaria sphacelata	Setaria	Kazungula	~5 years
Heteropogon contortus	Black spear grass	(Native)	~5 years
Bothriochloa bladhii	Forest blue grass	(Native)	~5 years
Chrysopogon fallax	Golden beard grass	(Native)	~5 years

1.4.2. Symptoms

Graziers have observed that dieback is most severe in patches under fences, under trees, and other areas of long grass with a large amount of thatching. Rain, like shading and protection from grazing, may allow the tussocks to become long, thick and thatched.

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[13] Buck, S. 2017. Pasture dieback: Past activities and current situation across Queensland (2017). Report by Agri-Science Queensland.

Figure 3. Dieback under trees and along a fence line.

Figure 4 shows dieback in the fenced off area around a dam, an area which would normally be expected to have much better growth than the clearly green and unaffected area surrounding it.

Figure 4. Dieback in the fenced off area surrounding a dam. Note the lush growth in the paddock below.

Conversely, however, dieback may occur **less** frequently in recently sown pastures, areas where fertiliser has been added, and areas where grass is kept short by heavy grazing[13]. These observations appear contradictory – dieback can appear where grass is growing well, but also where grass is old and lacking nutrients and vigour.

This report discusses the potential role of pests, diseases, nutrition and the environment in both dieback and improved resilience of pastures, with reference to the existing literature. A number of relevant case studies are also presented. These may provide some insight into methods of approaching this issue as well as the complex web of factors that can result in catastrophic plant dieback.

1.4.3. Spread

According to Buck[13], more than 120 landholders have reported pastures with dieback symptoms, with areas affected ranging from less than one to more than 35,000 ha. Now that symptoms have been observed in a range of pasture species, dieback can now be found in southern pasture areas, which includes regions less dominated by buffel grass.

Affected areas range from Warwick in the south to Malanda in the north. In total, this equates to a total potential affected area of nearly 35 million ha.[13].

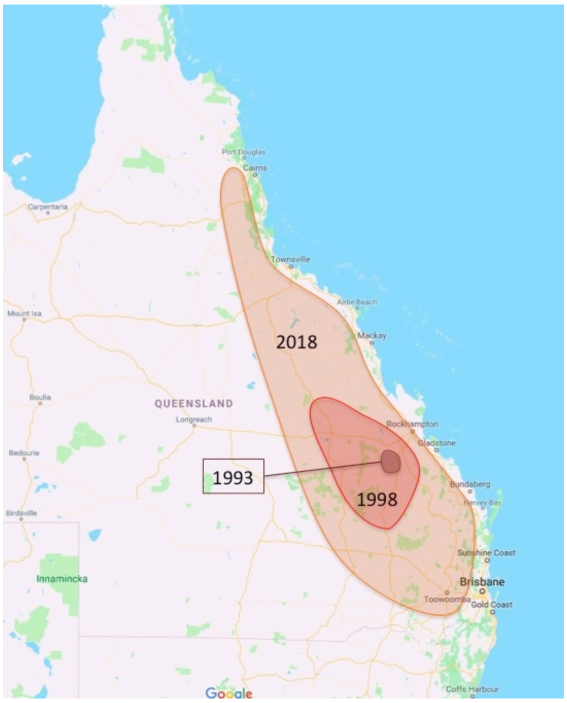


Figure 5. Expansion of areas affected by pasture dieback

Table 2. Queensland regions affected by pasture dieback at June 2017 (from Buck, 2017).

Region	**Area affected (Ha)**	**Main grass (and cultivar) affected**
Nth Queensland (Atherton tablelands)	81	Signal (cv. Basilisk)
Mackay/Whitsunday	460	Digitaria sp. (cv. Pangola)
Central Highlands	6,345	Buffel (cvv. American, Gayndah)
Dawson and Callide Valleys	26,787	Buffel (cvv. American, Gayndah)
Coastal Fitzroy	481	Creeping blue (cv. Bisset)
Burnett	423	Creeping blue (cv. Bisset)
Brisbane and Lockyer Valleys	44	Creeping blue (cv. Bisset)
Total	**34,621**	

2. Environment and physiology

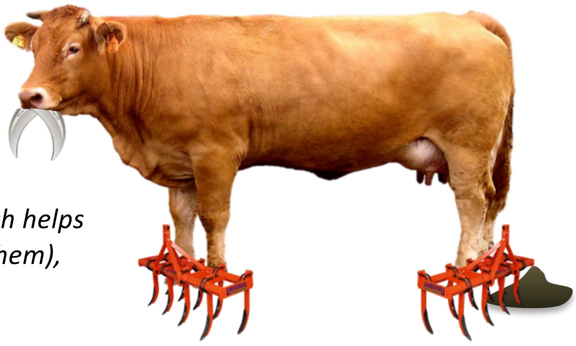
2.1. Grazing management

Key point

Cattle can be used as tools to manage the landscape. Rotational or 'crash' grazing can be used to improve sedentary pest and weed management, pasture health and productivity. Managing where cattle move and rest can help improve redistribution of nutrients through manure and urine.

- It has already been observed that dieback is often most severe in areas protected from cattle grazing, such as underneath fencelines, inside fenced off areas, and under trees (where cattle tend to sit rather than graze).
- According to Prof. RDB Whalley of the University of New England;

> *"We need to think of cattle as a tool with a slasher at the front, four cultivators underneath, and a manure spreader at the rear.*
>
> *If there are a small number of cattle grazing a large area then the slasher is selective, the soil becomes compacted, and the manure is spread mostly under trees. However, if a large number of cattle graze a small area the slasher is non-selective, the soil gets kicked up (which helps to bury grass seeds and stop ants eating them), and the manure is spread widely over the paddock."* (pers. com)



- Manipulating where and how cattle graze can have major benefits in terms of pasture health, weed control, nutrient distribution and pest management. Repeatedly grazed perennial grasses may be unable to recover and set seed, so will be replaced over time by less palatable plants[14]. So, for example,
  - Trials in Orange NSW have shown that rotational grazing can increase pasture growth and stocking rate by approximately 20%. This system increased perennial grasses and pasture stability. However, it is also noted that infrastructure costs are significant[15].
  - Similar results were reported in western Botswana[16]. Rotational grazing increased cover by perennial grass species as well as pasture productivity and stocking rates (Figure 6).
  - Intense grazing (four times normal pressure) by sheep has been demonstrated to be highly effective in reducing populations of red legged

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[14] Teague R et al. 2013. Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? J. Environ. Management. 128:699-717.

[15] Badgery WB, Michalk DL. 2017. Synthesis of system outcomes for a grazing-management experiment in temperate native pastures. An. Prod. Sci. 57:1869-1876.

[16] Mudongo EI et al. 2016. The role of cattle grazing management on perennial grass and woody vegetation cover in semiarid rangelands: insights from two case studies in the Botswana Kalahari. Rangelands J. 285-291.

earth mite (46,000/m^2 to 27/m^2) due reduced food availability as well as lower RH compared to dense pasture[17].

  - Outcomes from rotational grazing studies can be highly variable, with results varying widely depending on climate, timing, rainfall and other factors. However, there is strong evidence for the importance of resting pasture after rains to allow it to develop new leaves, and timing grazing so as to encourage seed development and dispersal [18].

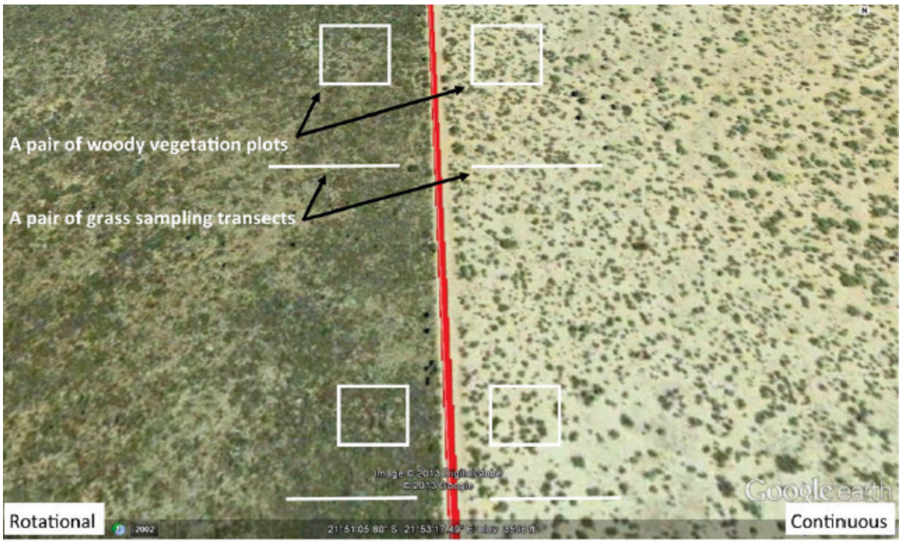

Figure 6. Rotationally (left) and continuously (right) grazed ranches in Gantsi district, western Botswana. From Mudongo, 2016.

- Manure from livestock is a major pathway for nutrients to return to the soil. However, manure spreading is often concentrated under trees and along fencelines. Stocking method, portable shade, mobile watering and strategic fencing can all help improve manure distribution back onto pasture[19].
- Allan Savory, previously a Zimbabwean rancher and now agricultural consultant in the USA, is internationally renowned for his theories on manipulation of cattle grazing patterns. He has become well known since his 2013 TED conference presentation on “How to fight desertification and reverse climate change”, and some groups of Australian graziers now follow his “holistic management and planned grazing” methods. These are based on his observations of grazing in Africa, where he suggests grasslands co-evolved with herds of grazing animals. The objective is to concentrate herds but move them often. Savory claims that churning the soil with hooves while fertilising it with dung or urine incorporates carbon into the soil and stimulates plant growth.
- Two key ecological principles were laid out in Savory and Parsons[20];

    1. *Animal impact does not degrade rangelands but rather expedites plant succession by improving water penetration as a result of “hoof action”*

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[17] Ridsdill-Smith TJ et al. 2008. Strategies for control of the redlegged earth mite in Australia. Aust. J. Exp. Agric.

[18] Waller RA, Sale PWG. 2001. Persistence and productivity of perennial ryegrass in sheep pastures in south-western Victoria: a review. Aust. J. Exp. Agric. 41:117-144.

[19] Vendramini JMB, Dubeux JCB, Silveira ML. 2014. Nutrient cycling in tropical pasture ecosystems. Rev. Bras. Ciencias Agrarias. 9:308-315.

[20] Savory A, Parsons SD. 1098. The Savory grazing method. Rangelands 2:234-237.

2. *Carefully controlling the time that animals are grazing an area, and leaving time for pasture recovery, is what avoids plant stress and thus degradation.*

Followed by seven applied principles:

1. ***Versatility** – no prescribed grazing system can have success in varying conditions*
2. ***Herds** – stock must be grouped and run together to achieve and control impact.*
3. ***Movement** – stock should only be left on pasture for a short time (e.g. 1-5 days), before resting, which generally means smaller field units and more fencing. Slower pace is possible in non-growing seasons.*
4. ***Rest** – native pasture should be rested from one to two months after grazing, shorter for improved.*
5. ***Increase stocking** – carefully raise stocking rate to match land base.*
6. ***Fencing** – fencing designs such as wheel-like 'cells' (in flat country) can be used to make rotation efficient and ensure access to water, though is optional.*
7. ***Whole-ranch planning** – the above must be carried out as appropriate to planning that includes all farm aspects, including business management.*

- Various attempts have been made to scientifically evaluate Savory's methods, and his claims have been reviewed. Many of these have failed to find scientific basis for the claimed benefits. For example, a review by Prof. D.D. Briske states that holistic farming "can not green deserts or reverse climate change" as claimed, and that moreover they "are not only unsupported by scientific information, but they are in direct conflict with it"[21].

- Science is generally divided on the benefits or otherwise of this method: while experimental scientists have failed to find benefits from controlled experiments (especially not at the scale promised), management oriented agricultural, ecological and social scientists report (subjective) benefits at the farm scale[22]. A recent review found that while 75% of social science related papers were positive, a similar percentage of experimental agriculture papers were either neutral or negative[23].

- It should also be clearly noted that Australian soils and grasslands, unlike those in Africa, have not previously been grazed by large herds of hoofed herbivores.

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[21] Ketcham C. 2017. Allan Savory's holistic management theory falls short on science. Sierra Magazine. Accessed online https://www.sierraclub.org/sierra/2017-2-march-april/feature/allan-savory-says-more-cows-land-will-reverse-climate-change

[22] Nordborg M, Roos E. 2016. Holistic managmeent – a critical review of Allan Savory's grazing method.

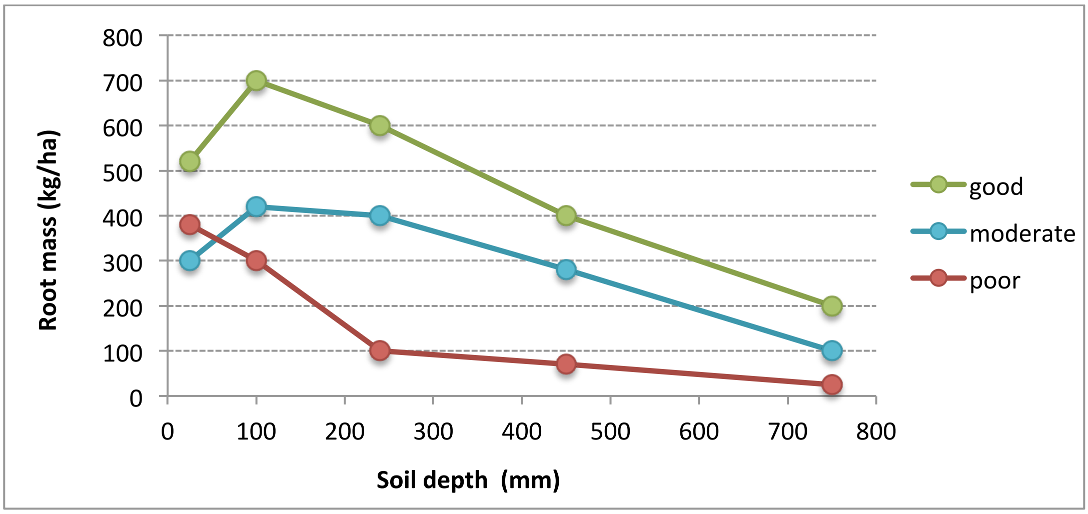
[23] Sherren K, Kent C. 2019. Who's afraid of Allan Savory? Scientometric polarisation on holistic management as competing understandings. Renewable Agricultur and Food Systems. In Press.

2.2. Climate and soil

Key point

Buffel grass can tolerate a wide range of temperatures, and it's deep, penetrating roots provide it with excellent drought tolerance. However, root mass and plant resilience is greatly reduced if soils are in poor condition.

- Buffel grass can tolerate a wide range of soils and climates, including temperatures from 5 to 50°C[24]. However, it is limited by low minimum temperatures and is frost sensitive.
- Annual rainfall of only 180mm is sufficient for survival. There are reports of buffel grass roots penetrating up to 2.4m into the soil, providing it with excellent drought tolerance[1]. While generally intolerant of waterlogging, buffel grass is able to respond rapidly to summer rainfall[25], and has been shown to be able to adapt to wetter conditions.
- As a C4 grass, buffel grass could potentially benefit from climate change. Although higher temperatures and increased rainfall variability reduce pasture productivity, it is anticipated that these losses will be partly offset by the beneficial effects of heightened CO_2, which increases photosynthesis and water use efficiency[26].
- Soil health plays a large role in the capacity of pasture species to survive water stress. Conversion of mulga to pasture grasses decreased soil organic carbon in the top 30cm by 2.7t/ha, with losses greatest (28%) in the top 5cm of soil. This has reduced soil fertility and plant growth overall[31].
- A series of studies by Snyman[27] examined root growth and water uptake in rangeland areas categorised as poor, moderate or good condition according to management practices. Pasture species in areas in poor condition areas developed less root mass and had a greater percentage of their roots in the top 200mm of soil compared to those in better managed sites, irrespective of whether rainfall was high or low (Figure 7).



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[24] DeLa Barrera E. 2008. Recent invasion of buffel grass (*Cenchrus ciliaris*) of a natural protected area from the southern Sonoran desert. Rev. Mex. Biodivers. 79:385-392.

[25] NSW DPI Agnote, Buffel grass. Accessed October 2018 https://www.dpi.nsw.gov.au/agriculture/pastures-and-rangelands/species-varieties/pf/factsheets/buffel-grass

[26] McKeon GM et al. 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. Rangeland J. 31:1-29.

[27] Snyman HA. 2009. Root studies on grass species in semi-arid South Africa along a soil-water gradient. Agric. Ecosys. Environ. 131:247-254.

Figure 7. Development of grass roots in rangeland areas classified as being in poor, medium or good condition. Derived from Snyman, 2009.

- There seems to be a strong association between dieback and wetter conditions, with outbreaks appearing to mainly occur in the months or even years following heavy rain events – such as a cyclone, or other extreme weather event.

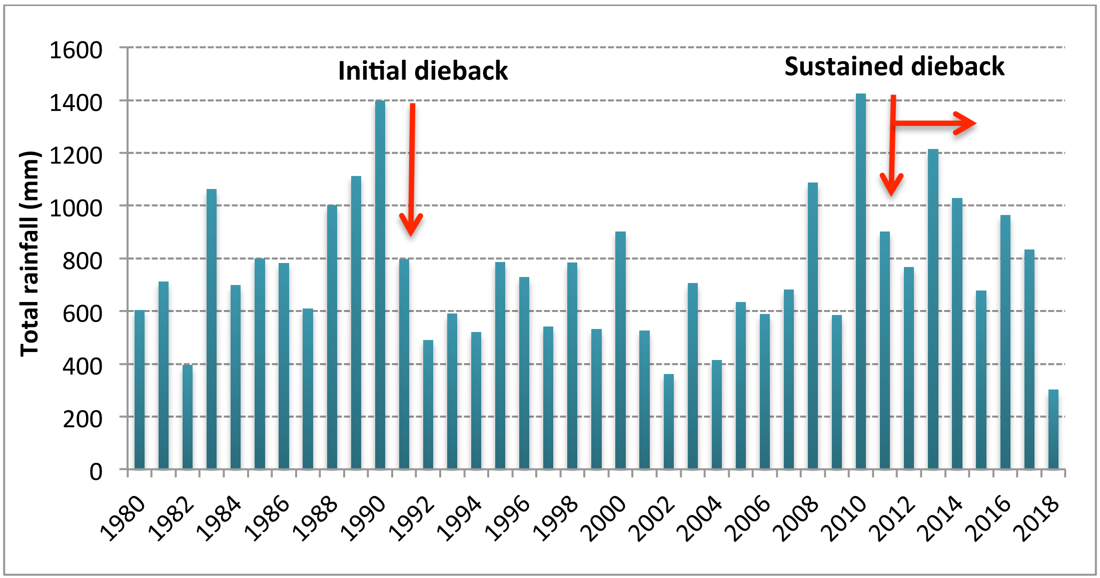

Figure 8. Annual rainfall in Rockhampton from 1980 to present. Data downloaded from the Bureau of Meteorology historical records.

2.3. Nutrition

2.3.1. Nitrogen

Key points

Buffel grass responds strongly to fertiliser in nutrient deficient soils so long as there is sufficient water to support growth. Nitrogen needs to be replaced due to loss from the system, as well as slow rates of decomposition of C4 grasses.

Fertilisers have been shown to increase pasture yield in dieback-affected areas. However initial benefits reduce over time. More work is needed to determine longer-term impacts.

- Much of the area now sown to perennial pasture was originally "brigalow scrub", dominated by *Acacia harpophylla* – a hardy, suckering, leguminous tree. Clearing, burning and fallowing initially release nutrients into soils, increasing the N available for freshly sown pastures;
    - Clearing and burning brigalow scrub initially increased available N from 9kg/ha to 67kg/ha[28].
    - However, available N declines as the pasture matures. In St George, available N increased from 12.5kg/ha to 20.2kg/ha under buffel grass pasture, but subsequently declined to 5.6kg/ha[29].
- The 23 year Brigalow Catchment Study examining productivity of the region found that approximately 1.6kg N/ha/year is lost from buffel grass pastures. As a result, productivity fell by 30% after 8 years of grazing[30].
- Dalal et al[31], estimated even higher losses, with 12kg N/ha/year removed from the system after Mulga (*Acacia aneura*) woodlands were converted to buffel grass pasture.
- Runoff from cleared areas can be double that from native bush. This may remove an additional 3.4kg N/ha/year[32].
- Grasses that are C4, such as buffel grass, produce large amounts of litter with a high C:N ratio. This is resistant to decomposition, an issue that becomes worse as the pasture ages, and reduces re-deposition of N into the soil[33].
- Manure and urine from livestock return significant amounts of N to soils. However, as previously noted, this is not evenly distributed around the paddock. Excretion sites are essentially 'hot spots' due to the high concentration of nutrients that occur. A single urination from cattle adds N to soil at a rate of 400-500kg/ha[34]. As plants are unable to

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[28] Lawrence DN et al. 1994. Fertility decline. In "Sown pastures for the brigalow lands". Qld DPI.

[29] Mathers NJ, Dalal RC. 2004. Predicted and actual changes in nitrogen mineralization in the Mulga soils of southern Queensland. In 'SuperSoil 2004: 3rd Aust. NZ Soils Conf. Sydney.

[30] Radford BJ et al. 2007. The Brigalow Catchment Study: III. Productivity changes on brigalow land cleared for long-term cropping and for grazing. Aust. J. Soil Res. 45:512-523.

[31] Dalal RC et al. 2005. Total soil organic matter and its labile pools following mulga (Acacia aneura) clearing for pasture development and cropping. 2. Total and labile nitrogen. Aust. J. Soil Res. 43:179-187.

[32] Thornton CM et al. 2007. The Brigalow Catchment Study: II. Clearing brigalow (Acacia harpophylla) for cropping or pasture increases runoff. Aust. J. Soil res. 45:496-511.

[33] Dubeux JCB et al. 2007. Nutrient cycling in warm climate grasslands. Crop Sci. 47:915-928.

[34] Haynes RJ, Williams PH. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49:119-199.

absorb such large amounts, significant losses of this additional N occur by volatilization or leaching[33].

2.3.2. Phosphorus

Key points

Buffel grass has a relatively high requirement for phosphorous, which is often the key nutrient limiting productivity in Australian soils. Phosphorous can increase seedling germination and growth as well as improve drought tolerance. Buffel grass with dieback tends to have low leaf phosphorous, and initial dieback symptoms resemble phosphorous deficiency.

- Phosphorus (P) is often cited as the main nutrient limiting establishment and growth of buffel grass[35,36]. Marshall et al[1] consider the availability of phosphorous one of the key factors restricting invasion of buffel grass into arid areas.
- Most Australian soils are low in P due to extensive weathering. Many native species (particularly Proteaceae, but also other families) develop specialised proteoid roots, which have a high affinity for P. Moreover, it has been estimated that grazing removes approximately 0.8kg P/ha/year, particularly extractable P, further reducing soil availability[37].
- It is interesting to note that the early symptoms of dieback superficially resemble phosphorus deficiency (Figure 9).

Figure 9. Phosphorus deficiency in oats (DAFWA) and rice (Plant Nutrition Manual, CRC Press)

- Giongo et al[36] suggest that lack of phosphorous is a key reason for the sharp decline in buffel pasture productivity that has been observed in Brazil since the 1980's;

> *"The degradation of cultivated pastures in the Brazilian semiarid region is associated with chemical fertility, physical and biological,*

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[35] Faria CMB, Alburquerque SG. 1988. Availability and amendment of phosphorous level in a soil of the Sao francisco region in relation to buffel grass yield. Pesquisa Agropecuaria Brasileira 23:555-561.

[36] Giongo V et al. 2015. Phosphorus fertilization and growth of buffel grass (*Cenchrus ciliaris* L.) cultivars. Rev. Brasil. Engenharia Agric Ambient. 19:34-38.

[37] Cowie BA, Thornton CM, Radford BJ. 2007. The Brigalow Catchment Study. I. Overview of a 40 year study of the effects of land clearing in the Brigalow bioregion. Aust. J. Soil Res. 45:479-195.

> *highlighting mainly to low phosphorus soil content associated with adoption of the same animal stocking rate during the year."*

- Phosphorus improves the capacity of pasture grass seedlings to survive drought, as fertilised plants develop a deeper and more extensive root system[38]. This appears confirmed by Makiela[10], who demonstrated that depriving buffel plants of phosphorous greatly reduced shoot growth, mainly because these plants had virtually no root system.
- A study on productivity of buffel grass near Charleville and Yalleroi found that buffel grass established well under the canopies of poplar box trees (*Eucalyptus populnea*). As a result dry matter yield under the trees was about 300g.m^2, compared to 89 to 107g.m^2 for native pasture in the inter-tree area. The authors suggest that this is because soil phosphorus availability increased from 10ppm in the inter-tree area to 27 – 65ppm under the poplar box canopy[39].
- Eyre[2] also noted that buffel grass frequently occurs in conjunction with poplar box trees. Unfortunately phosphorus was not measured, but it was recorded that no relationship was found between soil nitrogen and buffel grass growth.
- Similar results have been reported from Brazil, with soil phosphorus higher under remnant native 'joazeiro' trees than when the same land was converted to pure buffel grass pasture[40].
- According to Silcock[41], phosphorus is particularly important for buffel grass seed germination and growth. Even a few mg, provided as a seed coating, significantly improves establishment. The strongest responses are likely to occur on acid red earths and loose sandy soils, as cracking clays and alluvial soils are higher in phosphorus[42].
- Recent analysis of buffel grass leaves from matched populations of healthy and dieback-affected plants indicates that phosphorous is often low in the latter, averaging 0.16% compared to 0.24% in green plants (Figure 10). This result is supported by an analysis of buffel grass leaves classified as green, yellow or red. Red leaves contained less of all nutrients, with phosphorous only 0.11% compared to 0.29% in healthy leaves.
- This result is consistent with those reported by Graham and Conway[12], who also found that phosphorous and potassium were lower in the leaves of buffel grass with dieback compared to healthy plants.

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[38] Christie EK. 1975. A study of phosphorous nutrition and water supply on the early growth and survival of buffel grass grown on a sandy red earth from south-west Queensland. Aust J. Exp. Agric An. Husbandry. 15:239-249.

[39] Christie EK. 1975. A note on the significance of *Eucalyptus populnea* for buffel grass production in infertile semi-arid rangelands. Trop. Grasslands. 9:243-246.

[40] Wick B, Tiessen H, Menezes RSC. 2000. Land quality changes following the conversion of the natural vegetation into silvo-pastoral systems in semi-arid Brazil. Plant Soil. 222:59-70.

[41] Silcock RG, Smith, FT. 1982. Seed coating and localised application of phosphate for improving seedling growth of grasses on acid, sandy red earth soils. Aust. J. Agric. res. 33:785-802.

[42] Silcock RG, Smith FT. 1984. Soils on which buffel grass seedlings respond to phosphate fertiliser. Qld. J. Agric. Anim. Sci. 41:49-55.

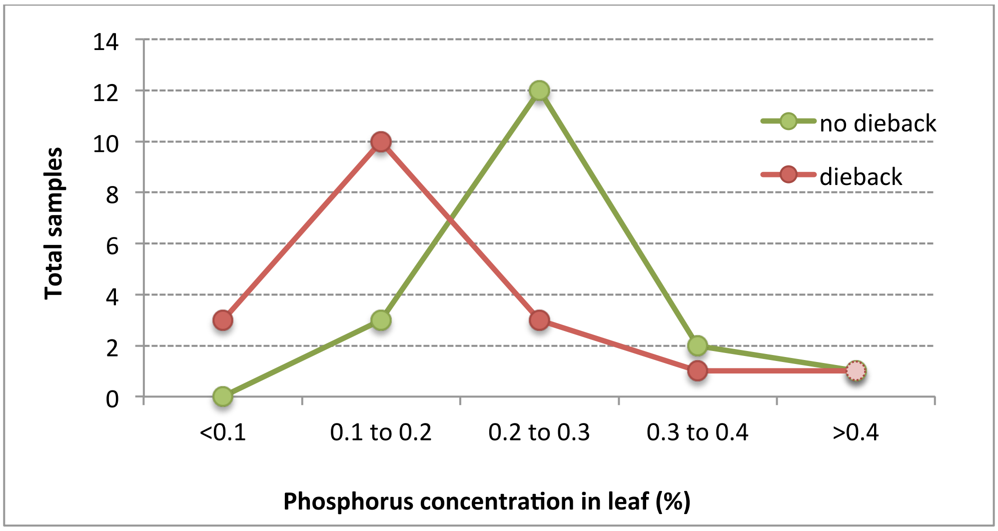

Figure 10. Number of foliage samples with extremely low (<0.1%) to high (>0.4%) phosphorous content. A total of 36 samples were analysed from 18 sites, each of which had areas of dieback as well as apparently healthy plants. AHR data.

- Makiela[10] induced a range of nutrient deficiencies in buffel grass plants. Phosphorous deficiency resulted in red leaf margins and red leaf tips. However, deficiencies in sulfur and zinc also induced leaf reddening.

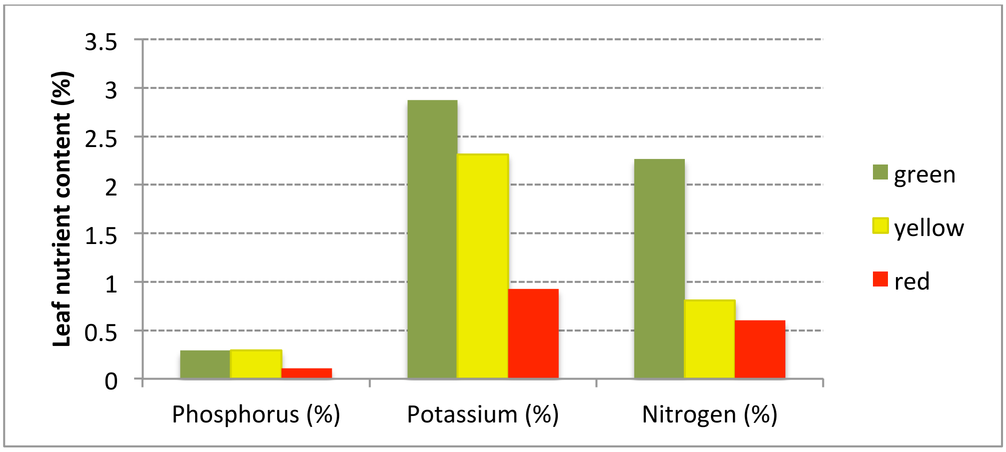

Figure 11. Nutrient content in green, yellowing and red buffel grass leaves. From Graham and Conway, 2000

2.3.3. Fertilisers

Key point

Australian soils are generally rather nutrient poor. Fertilisers can greatly increase yield and water use efficiency of pasture grasses, so long as there is enough rainfall to support growth. Field trials have demonstrated positive effects of fertiliser on yield in dieback-affected areas. However, biomass increases in fertilised vs unfertilised areas had slowed after 6 months, with only the highest rate (150kg DAO/ha) continuing to show major gains.

- If N, P and other nutrients lost from grazing areas are not replaced, pasture quality will inevitably decline.
- Many studies have demonstrated strong increases in pasture grass growth in response to nitrogen fertilisers[43]. However, these responses are dependent on rainfall. For example, buffel grass grown with 168kg/ha N produced more than four times as much biomass as unfertilised areas when 100mm of rain fell. However, in a dry season there was no response to fertilisation[44]. Peake et al estimated that at least 25 to 75mm of rainfall per growing season is required before buffel grass will respond positively to N fertiliser[45].
- Pot trials in Brazil indicate that N fertilisation increases water use efficiency of buffel grass, which helps account for some of the strong positive responses that have been observed[46].

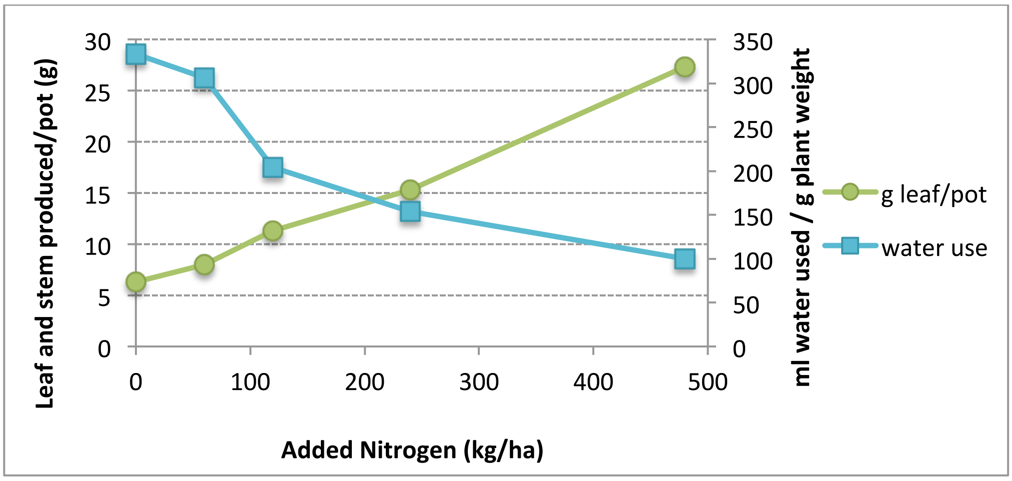

Figure 12. Effect of N fertilisation on buffel grass productivity (●) and water used per g plant growth(■). Derived from pot trials by de Medeiros et al., 2007.

- Recent trials in areas affected by dieback in central Qld initially found a positive response in pasture yield following addition of fertilizer for 35 of 36 treated plots evaluated on four different properties (Figure 13). However, only 7-9 months after application, the boost provided by the fertilizer relative to unfertilized areas had fallen, particularly at sites that had received lower fertilizer rates. At the first assessment fertilizer produced

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[43] Peake DCI, Myers RJK, Henzell EF. 1990. Sown pasture production in relation to nitrogen fertiliser and rainfall in southern Queensland. Trop Grass. 24:291-298.

[44] Henzell EF et al. 1975. Nitrogen response of pasture grasses on duplex soils formed from granite in southern Queensland. Aust. J. Exp. Agric. Anim. Husb.. 15:498-507.

[45] Peake DCI et al. 1979. Simulation of changes in herbage biomass and drought response of a buffel grass (*Cenchrus ciliaris* cv. Biloela) in Southern Queensland. Agro-Ecosys. 5:23-40.

[46] De Medeiros HR, Dubeux JCB, Sobral Neto E. 2007. Effects of nitrogen fertilisation on buffel grass productivity and water efficience use. Trop. Grass. 29:79-81

yield gains of 36 to 100% per property compared to unfertilized areas. However, by the second assessment a larger range of responses was evident, ranging from 25 to 100%. It is interesting to note that the 150kg DAP/ha treatment was still providing a significant benefit to pasture growth, whereas lower rates of DAP, Urea or MAP were no longer as effective (Figure 14).

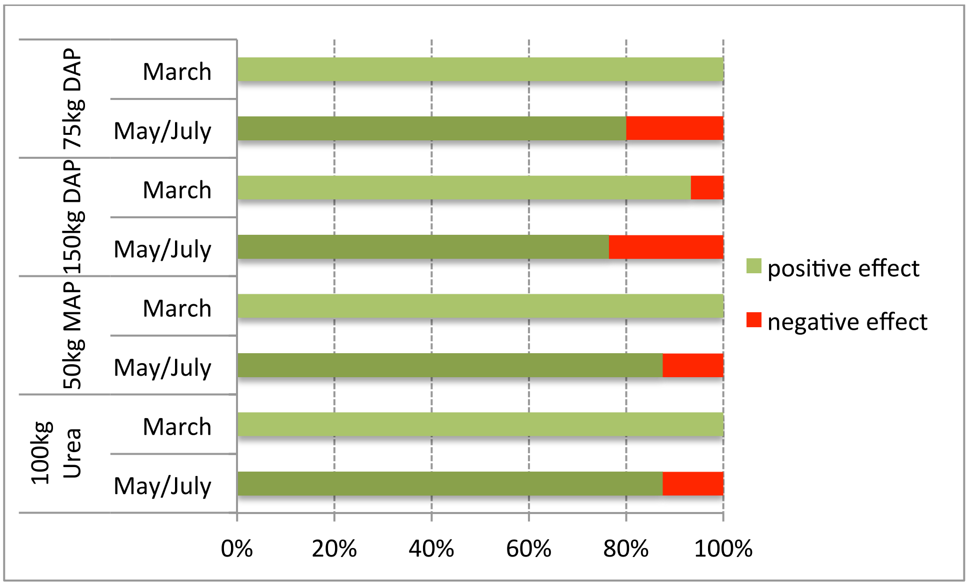

Figure 13. Number of trial plots in central Qld where fertiliser had a positive effect on pasture yield compared to those where treatment reduced yield, as assessed approximately 4 and 7 months after application. AHR data.

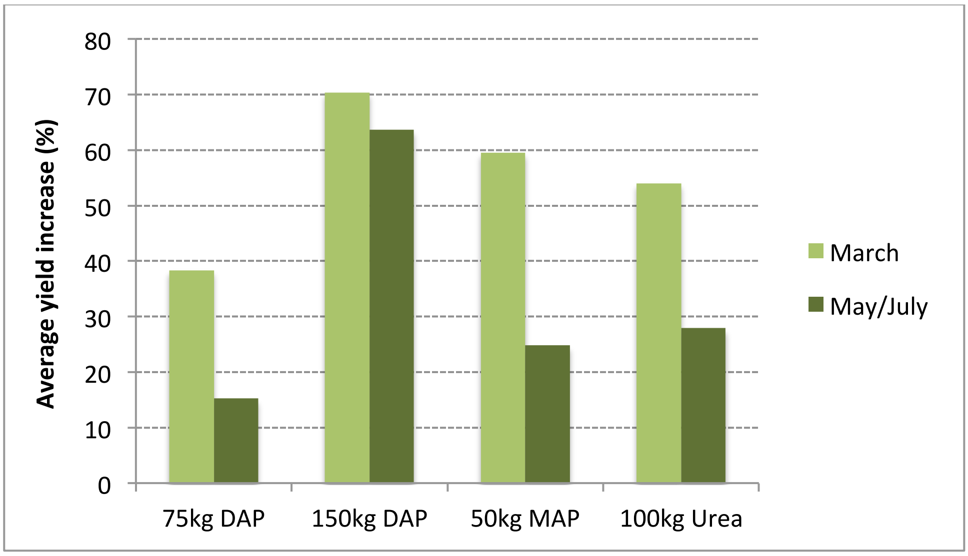

Figure 14. Average change in pasture yield in March and May/July 2018 for plots fertilised with 75kg/ha (n=5) or 150kg/ha DAP (n=17, 3 properties); 50kg/ha MAP (n=8) or 100kg/ha urea (n=8, 1 property) compared to plots managed the same way but without added fertiliser. AHR data.

2.3.4. Interactions between nutrition and disease

Key point

The effect of changing soil nutrition can either increase or decrease the severity of disease. Effects are heavily reliant on soil type, pH and existing nutrients and specific to each disease. In general, a nutritionally well-balanced plant is least likely to be affected by disease, as either high or low nutrient levels can increase susceptibility. Adding a specific nutrient is only likely to reduce disease if plants are deficient.

- Plant nutrition can have a major impact on disease development. However, effects are variable, and often contradictory, with high levels of a particular nutrient potentially inhibiting one disease but stimulating another (Table 3). For example, high levels of N increase several diseases in wheat, including *Fusarium* spp, powdery mildew and septoria leaf spot. However, plants that are N deficient are less able to defend themselves, so may also express more disease symptoms[47].

Table 3. Effect of N level on the severity of some plant diseases. From Dordas, 2008.

Disease	**Proper name**	**Disease severity**	
		Low N	**High N**
Bacterial leaf spot	*Xanthomonas vesicatoria*	↑	↓
Bacterial spot	*Pseudomonas syringae*	↓	↑
Clubroot	*Plasmodiophora brassicae*	↓	↑
Early blight	*Alternaria solani*	↑	↓
Fusarium	*Fusarium oxysporum*	↑	↓
Powdery mildew	*Erisyphe graminis*	↓	↑
Powdery mildew	*Oidium lycopersicon*	↓	↑
Stem rust	*Puccinia graminis*	↓	↑
Tobacco mosaic virus		↓	↑

- Phosphorous (P) has variable effects on susceptibility to disease. However, adding this nutrient to soils deficient in P can have significant benefits, particularly for reducing root rots such as Pythium[48].
- Potassium (K) decreases the incidence of disease up to the optimal level for plant growth, after which no further gains can be achieved[49].
- Calcium (Ca) is important for stabilising plant membranes and building cell walls. Low levels of Ca increase susceptibility to a range of soilborne fungal infections, including *Pythium*, *Sclerotinia*, *Botrytis* and *Fusarium*[50].
- Although silicon (Si) is not considered essential for plant health, adding silicon to soils is often beneficial. Plants may show improved growth and yield, reduced mineral toxicities and improved resistance to diseases. It is believed that silicon stimulates plant defenses,

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[47] Walters DR, Bingham IJ. 2007. Influence of nutrition on disease development caused by fungal pathogens: implications for plant disease control. Ann Appl. Biol. 151:307-324.

[48] Huber, DM. 1980. The role of mineral nutrition in defense. In "Plant Disease, an Advanced Treatise". Ch.5 381-406. Academic Press NY.

[49] Dordas C. 2008. Role of nutrients in controlling plant diseases in sustainable agriculture. A review. Agron. Sustain. Dev. 28:33-46.

[50] Graham DR. 1983. Effects of nutrient stress on susceptibility of plants to disease with particular reference to the trace elements. Adv. Bot. res. 10:221-276.

allowing plants to respond more quickly to pathogen attack as well as stresses such as drought[51].

- The role of manganese (Mn) in plant defense responses against disease has been widely studied. Application of manganese has been shown to reduce root rot development[52] and diseases such as take-all. However, increasing Mn reduces Ca uptake. Moreover, adding Mn to soils is often ineffective as it rapidly (<1 week) binds to the soil, becoming unavailable to plants[49]. Buffel grass and Rhodes grass are relatively sensitive to elevated levels of Mn and can develop toxicity symptoms[53].
- Sulphur has been recommended for management of plant diseases since the 1800's. Until legislation controlled pollution, sulphur was mainly deposited from the air. It has been shown that, in Europe, changes in abundance of certain wheat diseases over a 160 year period are closely linked with changes in sulphur pollution. However, effects are variable; in this case one pathogen increased with rising levels of pollutants while the other decreased[47].
- Other micronutrients, such as boron, iron, sulphur and chlorine, have highly variable effects on disease levels.
- Soil pH has a major impact on the ability of plants to extract nutrients from the soil. Even small changes in pH can have significant effects on the availability of minor nutrients. Soil pH also has a significant effect on many diseases. For example:
    - Application of ammonium and thiosulphate N sources acidifies the soil, lowering pH. When soil pH is below 6.2, the availability of Mn is increased. Acidifying the soil by adding nitrogenous fertilisers can greatly reduce the incidence of take-all disease (*Magnaporthe poae*) in various grass species[54,55].
    - However, this same treatment increases symptoms of anthracnose (*Colletotrichum cereale*) in bluegrass[56]. In this case, the disease is best managed by fertilising with potassium nitrate, which maintains neutral pH and increases availability of K.
- Walters[47] suggests that, in general, there is limited scope for using fertilisers to aid disease management unless plants are in some way deficient. Moreover, it is difficult to predict the effects of adding particular nutrients due to uncertainties in how they will interact with the soil, the effects of climate and other variables.

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[51] Keeping MG, Reynolds OL. 2008. Silicon in agriculture: new insights, new significance and growing application. Ann. Appl. Biol. 155:153-154.

[52] Stoltz E, Wallenhammar AC. 2012. Micronutrients reduce root rot in clover (Trifolium pratense). J Plant Dis. Prot. 119:92-99.

[53] Smith FW. 1979. Tolerance of seven tropical pasture grasses to excess manganese. Comm. Soil Sci. Plant Anal. 10:853-857.

[54] Hill WJ et al. 2003. Summer patch disease severity on Kentucky bluegrass in response to fertiliser source. J. Plant Nutr. 26:1499-1512.

[55] Heckman JR, Clarke BB, Murphy JA. 2003. Optimizing manganese fertilization for the suppression of take-all patch disease on creeping bentgrass. Crop Sci. 43:1395-1398.

[56] Schmid CJ, Clarke BB, Murphy JA. 2017. Anthracnose severity and annual bluegrass quality as influenced by nitrogen source. Plant Genome 10:S-285-Sbuffel-292.

2.3.5. Interactions between nutrition and insect damage

Key points

Plants grown with high levels of nitrogen are more nutritious, and therefore generally attract and support larger populations of insect pests. The effects of other nutrients are more variable and likely to be species specific.

Root mealybugs may contribute to nutrient deficiencies by feeding on the contents of the plant vascular system, reducing transport of nutrients to the upper parts of the plant. This could explain the observed low levels of phosphorous in dieback-affected grasses.

- It is well established that increases in nitrogen can also increase attractiveness of plants to insects as it is a key nutrient needed for their survival[61]. This is believed to be a key factor in insect-mediated dieback of eucalypts[170,172].
- Wyckhuys et al[57] studied the effects of soil fertility on growth and development of three species of mealybugs infesting cassava. Pot trials showed that high N and medium K fertilisation increased the rate of mealybug development and growth. Female mealybugs deposited more eggs and sooner when plants had added N. However, work from the field found differences between species;
    - *Phenacoccus manihoti* was most numerous in fertilised crops, preferring nutrient rich, actively growing tissues. It was also more common in sandy soils compared to those containing silt.
    - *Paracoccus marginatus* were more abundant in soils with low fertility, populations being negatively correlated with soil Ca, Mg, N and P.
    - *Pseudococcus jackbeardsleyi* tended to feed on older, decaying plant tissues, and was often found on plants with cassava witches broom disease. This species prospered in non-acidic soils with high soil carbon and phosphorous.
- Similar results have been found for other insects. Noma et al[58] found that soybean aphid populations increased with high leaf N, whereas leaf K had more variable effects. In African grassland areas, both chewing and sucking insects increased where pasture was higher in N, but relationships with P and K were not significant[59].
- Insects have a high demand for nutrients such as nitrogen and phosphorous. By feeding, they further reduce availability of nutrients to the plant.
    - Mealybugs, like aphids and whiteflies, are generally regarded as phloem feeders. However, new research has demonstrated that most also feed on the xylem vessels, which carry water and minerals from the roots to the plant leaves[60].

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[57] Wyckhuys KAG et al. 2017. Soil fertility regulates invasive herbivore performance and top-down control in tropical agroecosystems of Southeast Asia. Agric. Ecosys. Environ. 249:38-49.

[58] Noma T. 2010. Relationship of soybean aphid to soybean nutrients, landscape structure and natural enemies. Env. Entomol. 39:31-41.

[59] LaPierra KJ, Smith MD. 2016. Soil nutrient additions increase invertebrate herbivore abundances, but not herbivory, across three grassland systems. Oecol. 180:485-497.

[60] Cid M, Fereres A. 2010. Characterisation of the probing and feeding behavior of Planococcus citri (Hemiptera: Pseudococcidae) on grapevine. Arth

  - The low nutritional content of both xylem and phloem means sucking insects need to extract large volumes of liquid in order to obtain sufficient nutrients to survive[61].
  - If plants are already limited by phosphorous availability, further reduction in phosphorous supply due to mealybug feeding could result in the previously noted low levels of phosphorous and symptoms of phosphorous deficiency in plant leaves.
- Using Brix readings of leaf sap to predict plant health as well as resistance to insectswas popularised in the book "Mainland Farming for Century 21" by Dan Skow and Charles Waters. High brix farming has since gained popularity among some organic group, and lead to development of fertilisers specific formulated to raise brix in plant sap.
  - Refractometer readings of plant sap are a measure of the concentration of dissolved solutes. These include carbohydrates, but also minerals and other phytochemicals
  - Brix readings will clearly be affected by the hydration of the plant
  - In the book it is suggested that "*if brix levels are above 12, the plants are not bothered by insects*"[62]
  - The book also links prostate and breast cancer with low manganese in food, and suggests that magnetic forces reduce soil erosion and govern plant growth
  - E.S Cropconsult[63] conducted a thorough review of the evidence around these claims in 2010. This concluded many of the individual nutrients manipulated in "high Brix" programs have been shown to have impacts on pest levels. However, there is no support for the idea that simplistic Brix measurements relate to pest pressure.
  - Conversely, more nutritious foliage has unsurprisingly been shown to be more – not less – attractive to some leaf eaters[170].

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[61] Anon. 2005. Why and how insects and mites feed on your plants and flowers. University of Illinois Extension Newsletter April 2005.

[62] Skow D, Walters C. http://bionutrient.org/site/library/reviews/mainline-farming-century-21

[63] Syrovy L, Prasad R. 2010. Brix manipulation for reducing pest pressure: Literature review. Accessed online https://www.certifiedorganic.bc.ca/programs/osdp/I-101%20Brix%20Final%20Report.pdf

2.4. Fire

Key points

Buffel grass is often a beneficiary of fire, as its deep root system allows it to re-shoot even after relatively intense burns. Fire produces a temporary increase in phosphorous, which helps fuel this new growth, as well as reducing competition from woody plants and controlling some insect pests. Regular low intensity burning has been demonstrated to increase buffel grass pasture growth and productivity. Although low intensity burning will eliminate mealybugs on leaves, it is unlikely to affect insects deep in the soil.

- Buffel grass' deep roots and long-lived tussocks mean it is well adapted to survive fire. It has been observed that it is one of the first species to re-sprout after fires, especially higher intensity burns.
- Areas with buffel grass burn more intensely than areas with native grasses or open woodland communities due to the large fuel load the species generates. Two unplanned burns affecting replicated trial sites in the West MacDonnell National Park provide a clear demonstration of this effect[64]. The sites cleared of buffel grass burned patchily, if at all, whereas those with established buffel grass burned completely. The high intensity of the fire killed woody shrubs such as hakeas, whereas buffel grass regenerated almost immediately. The result was a shift to buffel grass at the expense of native vegetation.
- There is strong evidence that burning advantages buffel grass against other plants, particularly small native shrubs and young trees[65]. As a result, it has been demonstrated that area covered by buffel grass cover can more than double after a fire[66].
- Fire also provides a temporary but potentially important boost of phosphorous to the soil[67]. As available phosphorous is a key limiting factor to buffel grass growth in Australia, this may explain why it responds so positively to burning.
- In Mexico, annual burning in spring and early summer significantly increased both yield and quality of buffel grass pastures. The authors state that fire eliminated dead areas, reduced weeds and controlled some insect pests[68].
- Regular burning is also proposed as a management tool for buffel grass pastures in Texas. In this case burning is conducted at the end of winter to control woody plants. Best results were obtained when there was sufficient rainfall during spring to support the growth flush that occurs after burning[69].
- Some Australian graziers have previously strongly supported regular burning of buffel pastures as it leads to a flush of new green growth. However others are just as strongly opposed, suggesting an overall negative response[9].

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[64] Schlesinger C, White S, Muldoon S. 2013. Spatial pattern and severity of fire in areas with and without buffel grass (*Cenchrus ciliaris*) and effects on native vegetation in central Australia. Austral. Ecol. 38:831-840.

[65] Miller G et al. 2010. Ecological impacts of buffel grass (*Cenchrus ciliaris*) invasion in central Australia – does field evidence support a fire invasion feedback? Rangeland J. 32:353-365.

[66] Butler DW, Fairfax RJ. 2003. Buffel grass and fire in a gidgee and brigalow woodland: a case study from central Queensland. Ecol. Manage. Restor. 4:120-125.

[67] Bennett LT, Judd TS, Adams MA. 2003. Growth and nutrient content of perennial grasslands following burning in semi-arid, sub-tropical Australia. Plant Ecol. 164:185-199.

[68] Avalos V et al. 2008. Response of six tropical grasses to prescribed burning in the west coast of Mexico. Tec. Pec. Mex. 46:397-411.

[69] Hamilton WT, Scifres CJ. 1982. Prescribed burning during winter for maintenance of buffelgrass. J. Range Manage. 35:9-12.

2.5. Legumes in pastures

Key points

Previous research has identified that establishing legumes in mixed pastures greatly improves productivity and reduces 'pasture rundown'. Recent trials in dieback affected pastures in Qld found that establishment of legumes provided excellent biomass improvement. Gains were greater than those from fertilisers, burning or cultivation, and continued to increase over time.

- According to Bowen et al.[70], approximately ¾ of the perennial pasture areas in the region west of Rockhampton are suitable for sown forages or grain. They could therefore support more intensive cattle production if planted with alternative feed sources.
- A 2011 report by Peck et al[9] states

> *"The only long-term solution* (to pasture rundown) *that provides good economic returns for the beef industry and individual graziers is to establish a range of adapted legumes into the existing grass-only pastures. Establishing legumes into a grass pasture can reclaim 30-50% of the lost production from pasture rundown and improve economic returns."*

- While the report found that legumes are the most promising mitigation strategy for unproductive buffel pastures, the report also notes their variability in establishment, growth and resilience.
- Legume cultivars need to be selected carefully for their suitability to the site and climate. More than 70 tropical legume cultivars are available, including *Desmanthus* spp., Caatingo stylo (*Stylosanthes seabrana*), burgundy bean (*Macroptilium bracteatum*), annual medics (*Medicago* spp.) and winter vetches (*Vicia* spp.).
- Improving legume establishment within existing pastures is identified as a key research need, particularly focusing on the use of different cultivation methods and direct drilling. Legume seedlings are unable to compete for moisture and nutrients with established grasses, especially those with large root systems. Strips 5m wide, combined with fallowing, result in the best legume establishment[71].

Table 4. Legume establishment timeline proposed by Peck et al[71].

Planning		Fallow		Sowing		Early growth
Which paddock, method and legume	KILL GRASS	Control weeds to reduce soil seed bank, fertilise and store soil moisture	SOW LEGUME	Consider timing, seed quality and rate, rhizobia and seed placement	SEED EMERGENCE	Aim for large plants before frost or drought, control weeds, grazing and insects

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[70] Bowen MK et al. 2018. Productivity and profitability of forage options for beef production in the subtropics of northern Australia. Anim. Prod. Sci. 58:332-342.

[71] Peck G, Buck S, Johnson B. 2015. Establishing small seeded pasture legumes into existing grass pastures. Presentation to MLA. Qld DAF.

- Mixed perennial legume/grass pastures, particularly leucaena/grass pastures, have been found to result in higher gross margins/ ($181/ha) than perennial grass alone ($96/ha) or annual forage crops such as oats ($102/ha) or lablab ($18/ha)[70]. Note that this study was conducted during a period of relatively high rainfall.
- Legumes not only fix N directly into soils, they increase the rate of decomposition and therefore nutrient cycling[33]. The 'half life' for decomposition of some common legumes ranges from 50 to 111 days, whereas for common grasses the range is 75 to 277 days. This suggests that – in general – legumes decompose twice as quickly as grasses[72].
- Lack of persistence of legumes can be an issue, especially if grazing practices favour the grass component of pastures. This can result in one or other species being lost, reducing the resilience of the system to climate extremes[73]. Peck et al[9] note numerous instances where legumes have not established, been killed by frost, or otherwise failed, resulting in reduced, rather than increased yield.
- Despite these reservations, recent trials conducted by AHR in central Queensland have found that adding a legume to pastures consistently and significantly increased pasture yield compared to cultivation or burning. In total, 23 of 27 plot assessments found an increase in yield where a legume had been sown with pasture (Figure 15) At some sites productivity increased more than four-fold, with many recording >200% increase in pasture cover (Figure 16).

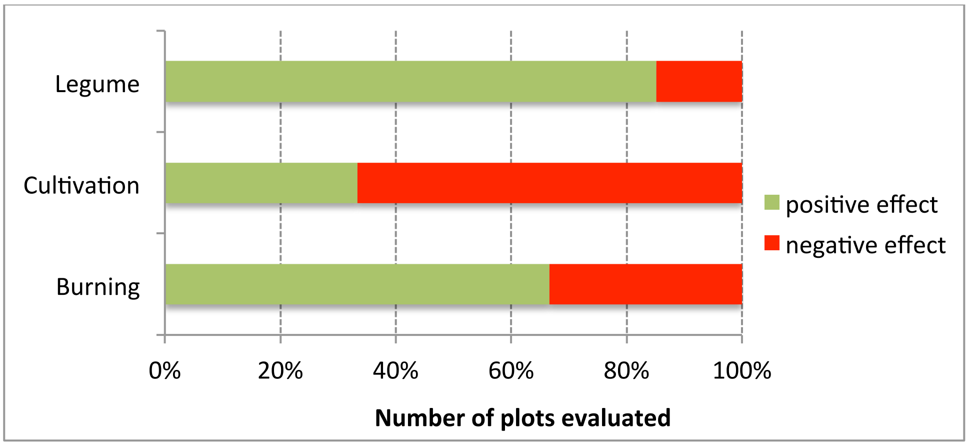

Figure 15. Number of trial plots in central Qld where adding a legume, cultivating, or burning had a positive effect on pasture yield compared to those where treatment reduced yield. AHR data.

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[72] Thomas RJ, Asakawa NM. 1993. Decomposition of leaf litter from tropical grasses and legumes. Soil Biol. Biochem. 25:1351-1361.

[73] Clarkson N et al. 1991. Sustaining productive pastures in the tropics. 8. Persistence and productivity of temperature legumes with tropical grasses. Trop. Grass. 25:129-136.

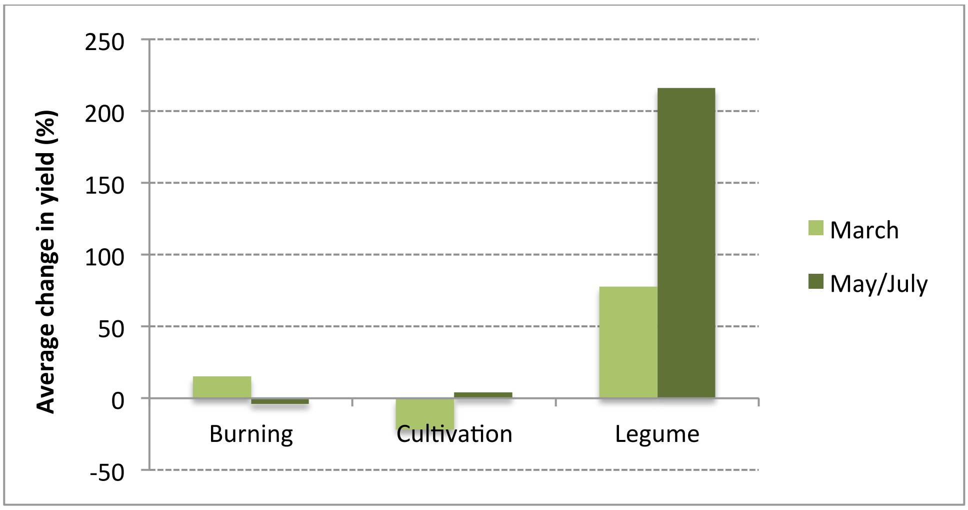

Figure 16. Average change in pasture yield in March and May/July 2018 for plots that were burned (n=16,20); cultivated (n=12,15) or sown with a legume (n=12,15) compared to plots managed the same way but without those specific treatments. Data collected from four different properties. AHR data.

2.6. Plant density

Key points

It has been observed that dieback often occurs in areas where grass was previously growing well, such as under fence-lines and around dams. Dense, lush growth increases demands for soil water and nutrients; when these are no longer available it is possible that the plant population may crash. Dieback of English cordgrass in China is thought to be due to a combination of excess plant density and ongoing clonal reproduction. This reduces the ability to adapt to changing conditions. This is similar to buffel grass, which also mainly reproduces asexually.

- One of the most puzzling aspects of pasture grass dieback is that areas with luxuriant growth are often the first to suffer dieback. It has also been observed that dieback can occur following heavy rain events that promote such growth.
- It is possible that plants grown with adequate water are unable to adapt as the soil dries out. This has been demonstrated with the perennial grass *Molinia caerulea*; although N fertilisation greatly increased productivity, it also meant the plant was less resistant to drought stress[74]. However, it should be observed that *Molinia* is adapted to wet areas, so likely to have limited drought tolerance.
- Density appears to have impacted on dieback of cordgrass:
    - Like buffel grass, English cordgrass (*Spartina anglica*) was introduced into China as a useful pasture species. It tolerates a wide range of habitats, grows rapidly, can stabilise degraded areas and is palatable to stock.

Figure 17. English cordgrass, *Spartina anglica* (J. Howaldt)

    - *S. anglica* has gone through five stages in China;
        1. Laboratory propagation and planting (1963-1966)
        2. Slow spread (1966-1973)
        3. Rapid spread (1973-1985)
        4. Stable (1985-1995)
        5. Dieback (1995–)

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[74] Friedrich U et al. 2011. Nitrogen deposition increases susceptibility to drought – experimental evidence with the perennial grass *Molinia caerulea* (L.) Moench. Plant soil. 353:59-71.

  - Acreage of *S. anglica* in China declined from 36,000 ha to only 50 ha in less than 25 years. Yet, the plant is still considered an invasive species in the USA, parts of Europe and Australia.
  - While the causes of this dieback in China are unclear, plant density appears to be one factor. In effect, plants growing extremely densely exhaust soil resources, causing the population to crash.
  - It is also noted that *S. anglica* has changed from primarily sexual to clonal reproduction. Although this initially allowed rapid expansion, it has reduced its ability to adapt to changing conditions[75]. Buffel grass is classified as apomictic. That is, it also primarily reproduces asexually, producing seedlings genetically identical to the parent plant. However some genetic mixing can occasionally occur[1].

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[75] Li H et al. 2009. Density dependant effects on the dieback of exotic species Spartina anglica in coastal China. Ecol. Eng. 35:544-552.

2.7. Biodiversity

Key point

Pastures dominated by a single species lack biodiversity. They may therefore be less resilient to plant stresses than natural areas, and have poorer soil health. Plants growing in soils with high microbial activity have improved resistance to disease, drought and other stresses compared to plants growing in areas with poor soil health.

- Although buffel grass is a valuable and important pasture species, much of the recent literature has focused on its invasive potential with regard to native landscapes.
- Widespread clearing, followed by establishment of buffel grass, has been demonstrated to substantially reduce biodiversity[76]. Environments lacking biodiversity have less resilience to stresses such as drought, flood and changing climate so may be less sustainable in the long term.
- However, as noted previously, remnant trees under-planted with buffel grass form patches with higher soil nutrients, as well as organic matter and moisture. These 'resource islands' are aided by improved capture of nutrients, inputs from animals and litter and reduced temperatures[77].
- This effect may partly explain why soil microbial activity and organic matter was improved where carob trees (a legume, hence nitrogen fixing) were inter-planted with buffel grass, compared to buffel grass alone[40].
- Increased microbial activity in soil can have many benefits for plant health. For example, the presence of earthworms in soil has been shown to reduce the disease symptoms of perennial ryegrass and clover growing in soils artificially inoculated with *Rhizoctonia solani*[78].

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[76] Fensham RJ, Wang J, Kilgour C. 2015. The relative impacts of grazing, fire and invasion by buffel grass (*Cenchrus ciliaris*) on the floristic composition of a rangeland savanna ecosystem. Rangeland J. 37:227-237.

[77] Menezes RSC, Salcedo IH, Elliott ET. 2002. Microclimate and nutrient dynamics in a silvopastoral system of semiarid northeastern Brazil. Agrofor. Sys. 56:27-38.

[78] Stephens PM, Davoren CW. 1997. Influence of the earthworms *Aporrectodea trapezoides* and *A. rosea* on the disease severeity of *Rhizoctonia solani* on subterranean clover and ryegrass. Soil Biol. Biochem. 29:511-516.

3. Pests

3.1. Mealybugs

Key points

Mealybugs are highly polyphagous and adaptable, and are common pests on many Australian grasses. Outbreaks have caused dieback of paspalum and severely affected sugar cane, turfgrass, rhodes-grass, sorghum and rice. Symptoms of mealybug infestation on sugar cane can resemble disease, as can other insect damage on plants.

In New Zealand, mealybugs are a poorly recognised, but significant, pest of ryegrass. However, damage is reduced in ryegrass pastures infected with *Neotyphodium* spp fungal endophytes. Similar results have been reported for Australian pastures.

Fungal endophytes have been widely shown to increase pasture productivity and protect against insects. **However, published research is overwhelmingly focused on ryegrass and tall fescue, both cool climate species.** Moreover, endophytes can reduce pasture palatability, and grazing may reduce production of protective compounds.

In Australia, mealybugs have been found infesting grass in areas suffering dieback. Previously reported root damage on plants suffering dieback appears to be consistent with mealybug feeding. Initial dieback symptoms of leaf reddening may be a stress response to mealybug damage.

3.1.1. Mealybugs on grasses

- Mealybugs are highly polyphagous, with many species able to feed on a wide range of grasses. There are reports dating to the early 1900's of mealy bugs on grass blades, concealed between the grass sheath and the stem, and living under the soil on the grass' roots[79].
- In 1928, a mealy bug was reported attacking paspalum in Queensland[80], resulting in destruction of large areas of pasture:

> *"In all cases the outbreaks were observed in isolated patches of a few acres, and were confined to the northern slopes of ridges, protected from the strong south-east winds and more exposed to the sun…. The insects…are usually found six to thirty or more clustered together as near the base of the leaf stalk as possible. The attack is always most severe in thick matted grass."*

- The mealybug was subsequently identified as *Heliococcus summervillei*. The author suggests that it may have been introduced to Australia from Pakistan, where the same species infests sugar cane[81].
- The same species was subsequently found in New Caledonia, where it produced "*a very spectacular attack on grasses in pastures*"[82].

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[79] Cockerill, TDA. 1916. Some grass-feeding mealy-bugs (Coccidae). J. Econ. Entomol. 9:312-315.

[80] Summerville WAT. 1928. Mealy bug attacking paspalum grass in the Cooray district. Qld. Agric. J. 30:2019-209.

[81] Brookes HM. 1978. A new species of *Heliococcus* Sulc from Australia and Pakistan and a redescription of *Heliococcus glacialis* (Newstead) Comb.N. (Homoptera: Pseudococcidae). J. Aust. Ent. Soc. 17:241-245.

[82] Brinon L, Matile-Ferrero D, Chazeau J. 2004. Outbreak and regression of a grass infesting mealybug, introduced into New Caledonia, *Heliococcus summervillei* Brookes (Hemiptera, Pseudococcidae). Bull. Soc. Entomol. Fr.

- Other reports of mealybugs causing severe damage to grasses include:
    - Rice mealybugs (*Brevennia rehi*) have been reported infesting turf grass in Darwin[83]. The species is a widespread pest of sorghum and rice (including in Australia), which it causes to yellow and wither without forming seeds[84].
    - The Rhodes-grass mealybugs *Antonina graminis*, *Tridiscus sporoboli* and *Trionymus* sp. are considered major pests of many subtropical pasture and turfgrass species in the USA, including buffalograss, kikuyu and other species. Leaf morphology affects susceptibility to attack[85].
    - *A graminis* can occur at densities >3,000/0.1m^2 and is considered a major pest across Texas and southern California. Although brought under biological control with an introduced parasitoid in the 1960's, its mutualistic relationship with red imported fire ants (*Solenopsis invicta*) has allowed populations to increase in the last decade[86].

3.1.2. Mealybugs on sugar cane

- Several mealybugs affect sugar cane, including *Saccharicoccus sacchari*. Infestation by mealybugs limits growth and sett development (Figure 18). These mealybugs can live below the soil surface, but spread onto the upper parts as crawlers as new leaves emerge. There are significant differences between cultivars in terms of their susceptibility to the mealybugs[87]. Damage can be severe; a study in China found that this pest was present in all of their main sugar production areas, with up to 80% of plants damaged[88].

109:425-428.

[83] Williams DJ, Radunz LAJ, Brookes HM. 1981. The rice mealybug *Brevennia rehi* (Lindinger) now recorded from Australia and Papua New Guinea (Hemiptera: Coccoidea: Pseudococcidae). J. Aust. Ent. Soc. 20:46.

[84] Williams DJ. 1970. The mealybugs (Homoptera; Coccoidea; Pseudococcidae) of sugar-cane, rice and sorghum. Bull. Ent. Res. 60:109-188.

[85] Johnson-Cicalese J et al. 2011. Evaluation of buffalograss leaf pubescence and its effect on resistance to mealybugs (Hemiptera: Pseudococcidae). J. Kansas Entomol. Soc. 84:71-77.

[86] Reinart JA, Bradleigh Vinson S. 2010. Preference among turfgrass genera and cultivars for colonization by rhodesgrass mealybug Antonina graminis (Hemiptera:Pseudococcidae). Southwestern Entomol. 35:121-128.

[87] Dick, J. 1953. Mealybug and its effect on sugarcane. Differences 31:23.

[88] ZhenQuiang Q et al. 2013. Investigation on occurrence and damage of pink sugarcane mealybug *Saccharicoccus saccharin* Guanxi sugarcane growing area. J. Sthrn. Agric. 44:1277-1281.

Figure 18. Six month old sugar cane plants. The plant on the right was grown from setts infested by mealybugs, that on the left from clean setts. From Dick, 1953.

- Dick[87] notes that the symptoms of mealybug infestation on sugar cane resemble those of a disease. There are many examples of where insect damage can appear more like a disease, as may possibly be the case with pasture dieback.
    - For example, Costa et al.[89] describe disease-like symptoms in gai choy and lettuce that include mid-vein blanching, leaf curling and yellowing.
    - Although associated with whiteflies, these symptoms are not caused directly by the insect. Instead, they are due to toxins introduced into the plants by whitefly feeding.

3.1.3. Mealybugs and endophytic fungi

- Fungal endophytes are extremely common and highly diverse. They mainly live within above ground plant tissues but do not usually cause any negative symptoms within the plant itself. In many cases they have the opposite effect. Systemic endophytes in pasture grasses have been reported to increase germination, and act as defenses against seed predators, herbivores and pathogens[90]. Some have also been reported to improve drought resistance[91], although the opposite effect can also occur[92].
- While most endophytes are harmless to livestock, a number in the genus' *Epichloe* and *Neotyphodium* can be toxic. However, it is these same endophytes that can also protect pasture species from invertebrate pests and microbial pathogens[93,94].

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[89] Costa HS et al. 1993. Association between *Bemisia tabaci* density and reduced growth, yellowing and stem blanching of lettuce and gai choy. Plant Dis. 77:969-972.

[90] Faeth SH, Fagan WF. 2002. Fungal endophytes: Common host plant symbionts but uncommon mutualists. Integ. Compar. Biol. 42:360-368.

[91] Bacon CW. 1993. Abiotic stress tolerances (moisture, nutrients) and photosynthesis in endophyte infected tall fescue. Ag. Ecosys. Environ. 44:123-141.

[92] He L. et al. 2017. Productivity in simulated drought and post-drought recovery of eight ryegrass cultivars and atall fescue cultivar with and without Epichloe endophyte

[93] Clay K. 1988. Fungal endophytes of grasses: A defensive mutualism between plants and fungi. Ecol. 69:10-16.

[94] Breen JP. 1994. Acremonium endophyte interactions with enhanced resistance to insects. Ann. Rev. Entomol. 39:401-423.

  - *Neotyphodium*-linked alkaloids in ryegrass can produce 'staggers' in sheep and cattle
  - Endophytes in tall fescue can produce pyrrolizidine and ergot-type alkaloids, which cause gangrene of extremities, low conception and poor health[95]
  - Resistance to insects in ryegrass and fescue is primarily due to the presence of peramine and pyrrolizidine alkaloids.
- The pasture mealybug *Balanococcus poae* is found in certain New Zealand ryegrass pastures[96]. The researchers state that:

> *"…the pasture mealybug could be an important factor in pasture deterioration in certain areas of New Zealand. Pastures under stress from low fertility, drought, insect attack or undue grazing management may be more susceptible."*

- It is noted that there had previously been little importance attributed to mealybug affecting ryegrass pasture in New Zealand, even though it can cause significant damage. They suggest that this is because damage is greatest, and populations highest, during dry spells – when the death of pasture is likely to be attributed to drought[97].
- These pastures are also widely infected by endophytic fungi from the genus *Neotyphodium*. However, mealybugs and endophyte rarely occur together, as the fungi produce alkaloids which protect it (and the grass) from mealybugs. Strains of *Neotyphodium* have been identified which are active against insects (Figure 19, Figure 20) but do not affect mammals. Certain of these endophyte strains may also be effective against black beetle and/or the root aphid *Aploneura lentisci*, also pests of ryegrass pastures[97].

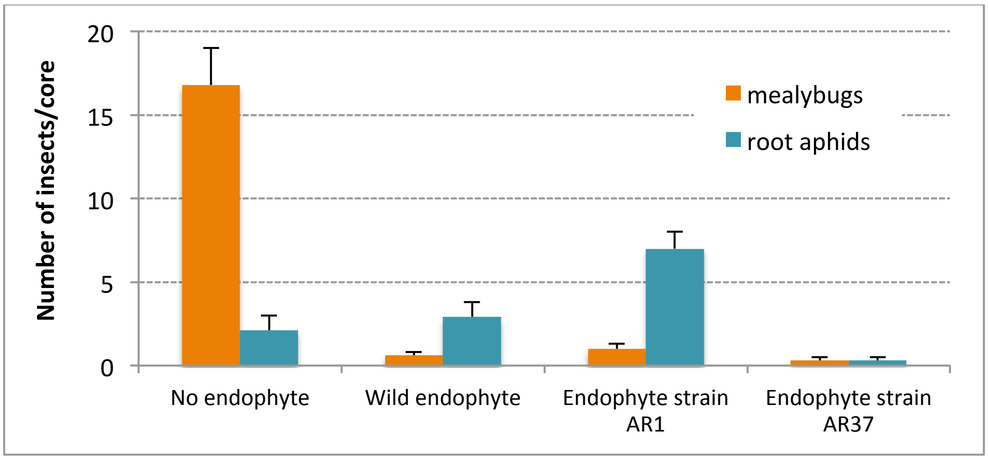

Figure 19. The number of insects on ryegrass plants that were uninfected, or were inoculated with one of three different strains of the endophytic fungus *Neotyphodium* sp. Derived from Pennell et al., 2005.

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[95] Schardl CL, Phillips TD. 1997. Protective grass endophytes. Where are they from and where are they going? Plant Dis. 81:430-438.

[96] Pennell C, Ball OJ-P. 1999. The effects of *Neotyphodium* endophytes in tall fescue on pasture mealybug (*Balanococcus poae*). Proc. 52nd NZ Plant Prot. Conf. 259-263.

[97] Pennell CGL et al. 2005. Occurrence and impact of pasture mealybug (*Balanococcus poae*) and root aphid (*Aploneura lentisci*) on ryegrass (*Lolium* spp.) with and without infection by *Neotyphodium* fungal endophytes. NZ J. Agric. Res. 48:329-337.

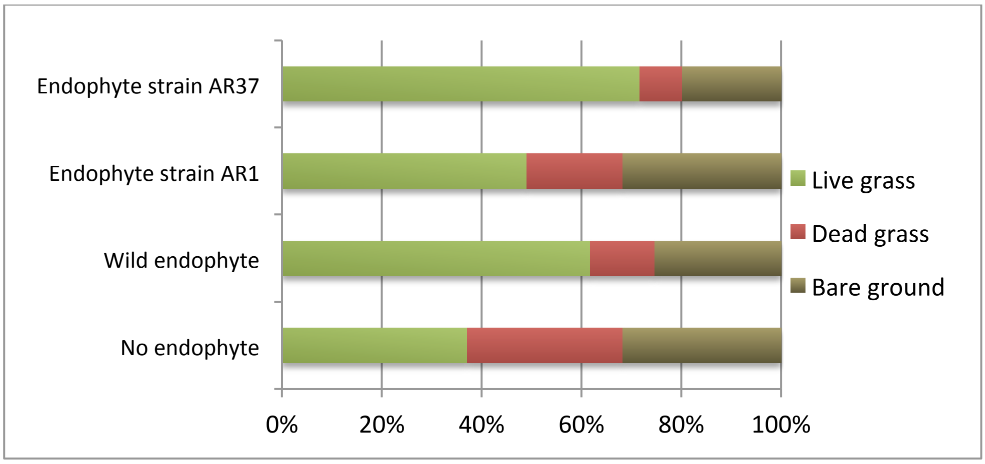

Figure 20. Productivity of ryegrass plots that were uninfected, or were inoculated with one of three different strains of the endophytic fungus *Neotyphodium* sp. Derived from Pennell et al., 2005.

- As well as mealybugs, fungal endophytes have been reported to increase pasture resistance to black cutworm, Argentine stem weevil, root aphids, Japanese beetle and soil inhabiting grubs including African black beetle larvae. However, toxins produced are endophyte and host specific, so it is important to thoroughly test strains for toxicity to livestock as well as insects[98].
- While mealybugs are important, the most damaging pest of perennial ryegrass in New Zealand is the Argentine stem weevil. Infection with the AR37 fungal endophyte strain significantly reduced feeding by weevils, reducing the number of tillers with damage and increasing yield. This strain also reduced the number of black beetle larvae and root aphids around the grass roots[99].
- It was recently shown that clipping endophyte infected ryegrass promoted production of the protective alkaloid perloline, further enhancing its resistance to weevils. However, this effect was negated when sheep grazed the grass. Artificially applying sheep saliva to cut grass produced the same effect, suggesting components in the sheep saliva de-activated perloline. While this adaptation ensures that the sheep are unaffected by alkaloids in the grass, it also reduces plant defenses against insect feeding[100].
- In Australia, both perennial ryegrass and tall fescue are widely infected (42 to 100%) with fungal endophytes. A large number of studies have found increases in density and yield in endophyte-infected pastures[101,102]. Much of the positive effects of endophytes on pasture productivity are believed to be due to their effects on insects.
    - A study by Moate et al[103] showed that the number of mealybugs and root aphids were significantly reduced in ryegrass grazed by dairy cattle if it was

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[98] Esqueda MK et al. 2017. A review of perennial ryegrass endophytes and their potential use in the management of African black beetle in perennial grazing systems in Australia. Frontiers P. Sci. 8:Article 3.

[99] Thom ER et al. 2013. Impact of novel endophytes in perennial ryegrass on herbage production and insect pests from pastures under dairy cow grazing in northern New Zealand. Grass forage Sci. 69:191-204.

[100] Bultman TL et al. 2018. Complex interactions among sheep, insects, grass and fungi in a simple New Zealand grazing system. J. Chem Ecol. 44:957-964.

[101] Wheatley WM. 2009. The effect of perennial ryegrass (*Lolium perenne*) endophyte (*Neotyphodium lolii*) on grazing systems in the central tablelands of NSW. PhD Thesis. University of Sydney, Aust.

[102] Quigley PE. 2000. Effects of Neotyphodium lolii infection and sowing rate of perennial ryegrass on the dynamics of ryegrass/subterranean clover swards. Aust. J. Agric. Res. 51:47-56.

[103] Moate PJ et al. 2012. Effects of wild-type, AR1 and AR37 endophyte infected perennial ryegrass on dairy production in Victoria, Australia. An. Prod. Sci. 52:1117-1130.

infected with the AR37 endophyte strain. This endophyte did not affect the nutritional value of pasture or cow health.

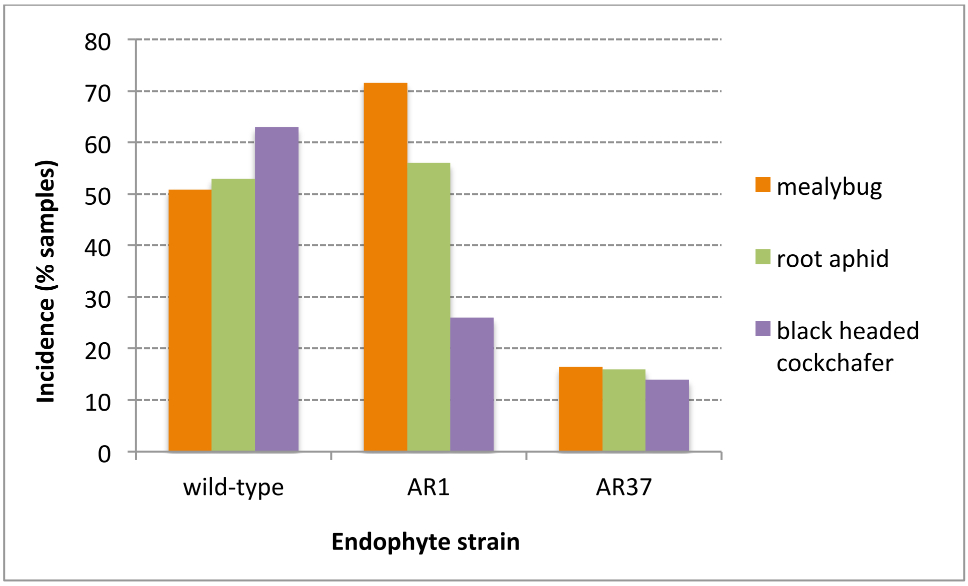

Figure 21. Incidence of mealybugs, root aphids and black headed cockchafer beetle larvae in Australian ryegrass pasture that was infected with a wild type endophyte or strains AR1 or AR37. Derived from Moate et al. 2012.

- Endophytes can also increase drought tolerance[104] and help grass to survive in phosphorous deficient soils[105], primarily by modification of the plants root system. The result can be an increase in yield, even in the absence of insect attack. These effects of endophyte infection on perennial ryegrass are similar in subtropical areas of Australia to those observed in southern states[106].
- The vast majority of research on the insecticidal effects of fungal endophytes in pasture grass has focused on ryegrass and tall fescue, both grasses of temperature climates. Relatively little is known about the effects of endophytes on warm climate species. However, the protective effects of grass endophytes against insects appear to be a general principle[107].
    - Endophyte-infected bluegrass was resistant to spider mites. Moreover, extracts from the infected grass were lethal to mosquito larvae (used as a general bioassay technique), whereas extracts from un-infected grass had no effect[108].
    - *Neotyphodium* fungal endophytes have been found in the leaf sheaths of a number of tropical pasture grasses including buffel grass, paspalums, guinea

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[104] Malinowski DP, Belesky DP. 2000. Adaptations of endophyte-infected cool-season grasses to environmental stresses: Mechanisms of drought and mineral stress tolerance. Crop Sci. 40:923-940.

[105] Malinowski DP, Brauer DK, Belesky DP. 1999. The endophyte Neotyphodium coenophialum affects root morphology of tall fescue grown under phosphorous deficiency. J. Agron. Crop Sci. 183:53-60.

[106] Lowe KF et al. 2008. The effect of endophyte on the performance of irrigated perennial ryegrasses in subtropical Australia. Aust. J. Agric. Res. 59:567-577.

[107] Azevedo JL et al. 2000. Endophytic microorganisms: a review on insect control and recent advances on tropical plants. EJB. 3:1-32.

[108] Ju Y, Sacalis JN, Still CC. 1998. Bioactive flavonoids from endophyte-infected blue grass (*Poa ampla*). J. Agric. Food Chem. 46:3785-3788.

grass (*Panicum maximum),* fountaingrass (*Pennisetum* sp) and birdwood grass (*Cenchrus setigerus*)[109].

- However, in some cases the toxins produced by wild type endophytes have caused severe damage; in Australia in 2002 more than 100,000 livestock (mainly sheep) died from ryegrass toxicosis [110].
- Even where endophytes are nominally non-toxic, high concentrations can still act as feeding deterrents to livestock. For example, steers offered Italian ryegrass with low, medium or high infection rates of the endophyte *Epichloe occultans* consistently preferred the lowest infection rate, even though this endophyte is considered non-toxic to livestock[111].

3.1.4. Mealybugs on Australian pastures

- Mealybugs have now been observed on pasture grass (Figure 23), including in areas with severe dieback. This has been identified as a species closely related to the mealybug that attacked paspalum in 1926; *H. summervillei*. The species has been detected across a wide range of sampling sites, grass species and soils.
- The mealybug is hard to detect not only because it is small (0.2 to 2.3mm long), but also because it can live deep under the soil surface, feeding on the plant roots. Waxy egg masses and crawlers have been found in dieback-affected areas at depths of up to 90cm (C Hauxwell pers. com.).

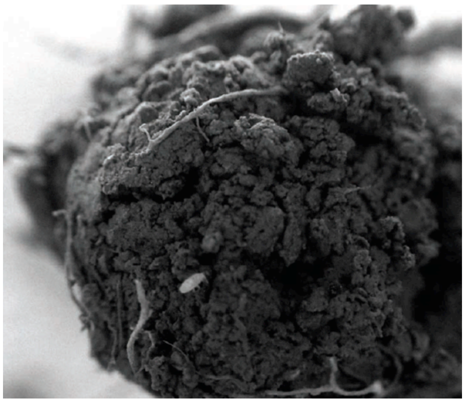

Figure 22. Pasture mealybug on soil. Photo C. Hauxwell, QUT.

- Like other species the mealybug can reproduce asexually, with several hundred eggs in each mass. Crawlers can disperse short distances, settling on either roots or leaves (C Hauxwell pers. com.).

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[109] Latha R, Suryanarayanan TS, Swaminathan MS. 2004. Genetic diversity in Acremonium endophytes isolated from warm-season grasses as revealed by RAPD markers. J. Biochem. Biotech. 13:39-42.

[110] Hume DE, Sewell JC. 2014. Agronomic advantages conferred by endophytic infection of perennial ryegrass (*Lolium perenne*) and tall fescure (*Festuca arundinacea*) in Australia. Crop Pasture Sci. 65:747-757.

[111] Hernandez-Agramonte IM et al. 2017. A fungal endophyte of a palatable grass affects preference of large herbivores. Austral. Ecol. 43:172-179.

Figure 23. Mealybug on buffel grass.

3.1.5. Mealybugs and dieback symptoms

- Makiela[11] found that the roots of buffel grass with dieback were stunted with soft, sunken regions. They also lacked smaller feeder roots when compared to healthy plants. Although no mealybugs were recorded, this damage appears consistent with the necrotic lesions that can be caused by mealybugs injecting saliva, feeding on sap and suppressing the plant defences (Figure 24).

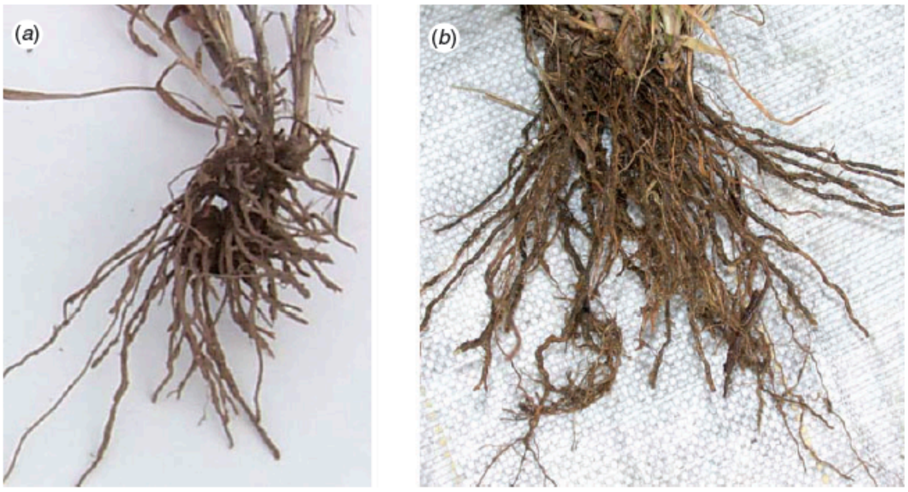

Figure 24. Roots of buffel grass plants with dieback (a) or healthy (b). From Makiela and Harrower, 2008.

- It is further noted that although the leaves of dieback affected and healthy plants appeared the same on a cellular level, there was clear cellular damage to the roots. In plants with dieback the root cortex (outer layer) was often absent, mesophyll cells disrupted and there were tyloses in the xylem vessels. Tyloses are produced as the result of wounding, injury or infection, as they allow the plant to seal off injured parts[10]. Again, these observations appear potentially consistent with damage caused by mealybugs, which feed by inserting their stylets into the root vascular system.

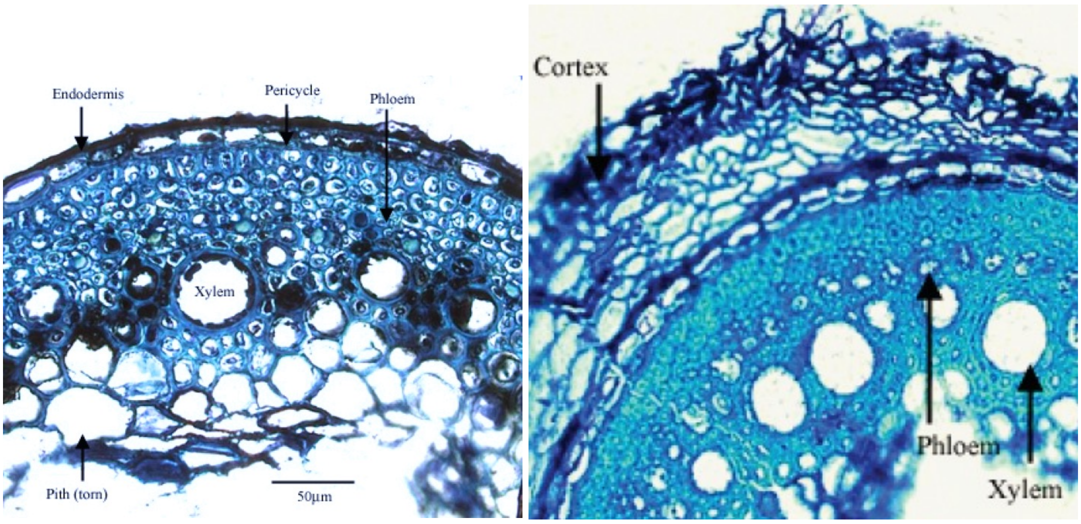

Figure 25. Transverse root sections of buffel grass plants with dieback (left) or healthy (right). Image sizes have been adjusted so as to present at the same scale. From Makiela, 2008.

- One of the first symptoms of dieback is reddening of the plant leaves, starting from the tips of the oldest leaves. Reddening can occur due to either loss of chlorophyll or increases in anthocyanins. Makiela[10] found that anthocyanin content was more than doubled and chlorophyll was reduced by around 87% in red, dieback affected buffel grass leaves compared to healthy controls.
- Feeding by insects can trigger development of red colour in leaves by either reducing chlorophyll or increasing anthocyanins.
    - For example, the sap-sucking bug *Thaumastocoris peregrinus* is a major pest in Eucalyptus plantations. Foliage of infested trees changes from green to yellowish red, in severe cases resulting in forest dieback[112].
    - Similar effects may be observed with other sucking insects, such as psyllids (Figure 26), as chlorophyll is destroyed and underlying anthocyanin compounds become visible.
    - Alternatively, anthocyanin accumulation can occur as a plant defense response. Wounding triggers accumulation of jasmonic acid, which in turn increases anthocyanin production. Interestingly, phosphorous deficiency triggers anthocyanin accumulation using the same chemical pathway, which accounts for the similarity in results from two very different causations[113].

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[112] Oumar Z, Mutanga O. 2011. The potential of remote sensing technology for the detection and mapping of Thaumastocoris peregrinus in plantation forests. Southern Forests. 73:23-31.

[113] Abbas Khan G et al. 2016. Phosphate deficiency induces the jasmonate pathway and enhances resistance to insect herbivory. Plant Physiol. 171:632-644.

Figure 26. *Eucalyptus blakelyi* leaf infested by psyllids. Insect feeding has destroyed the leaf chlorophyll, unmasking the underlying (red) anthocyanin pigments. Photo by Friends of Mount Majura.

- Despite extensive investigations, Makiela[10] was unable to determine a pathogen responsible for dieback. However, her trials demonstrated conclusively that for dieback to spread (under cultivated conditions) from plant to plant, both a live plant and an undisturbed core of soil had to be present.
    - Spread was faster and more reliable if a core of affected soil and a plant were placed into the centre of a larger container with unaffected plants.
    - Spread could still occur (although less reliably) if the soil core remained inside a pot.
    - Spread did not occur if the affected plant died.
    - She noted that there was a delay of around 2 months before symptoms spread from the affected to unaffected plants; this is consistent with mealybug reproduction, growth and finally development of symptoms on parasitized plants.
    - She concluded that dieback was soil-borne, which is consistent with it being caused by soil dwelling mealybugs.
- Recent glasshouse trials at NSW DPI Ourimbah found that buffel grass that was infested with mealybug and suffering severe dieback fully recovered when the plants were cut back severely and sprayed with imidacloprid (a systemic insecticide).

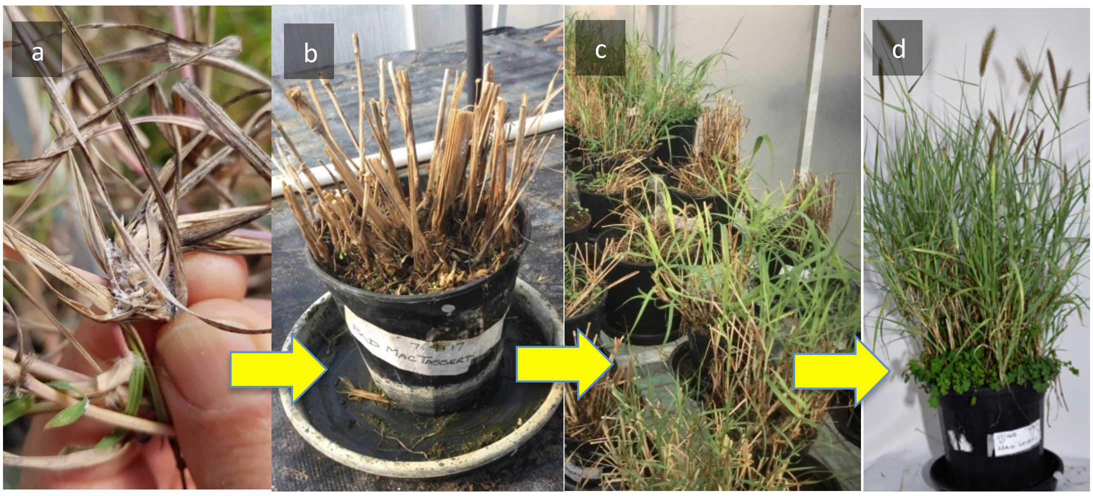

Figure 27. Buffel grass infested with mealybugs (a) was cut back and sprayed with imidacloprid (b). The plants soon started to regrow (c), and were still vigorous and healthy 4 months after treatment (d).

- From January to June 2018 trials conducted by AHR at grower properties in Queensland examined the effectiveness of a range of treatments to control dieback. These included burning, cultivation, re-sowing, fertilizer, fungicides and insecticides. While all of the treatments increased pasture growth to some extent, the greatest improvements were found in treatments that involved either
    - Treatment with insecticide
    - Cultivation + resowing with a legume
    - Cultivation + resowing with insecticide treated grass seed
- This was investigated further in more structured, replicated trials with the pyrethroid insecticide bifenthrin (75g ai/ha). These had a variable but positive effect in terms of both reducing visible mealybug populations and increasing pasture growth (Figure 28). The best results were recorded at the Yerra site (Figure 29). Note that as bifenthrin is primarily a contact insecticide, it would not have controlled mealybugs in the soil.

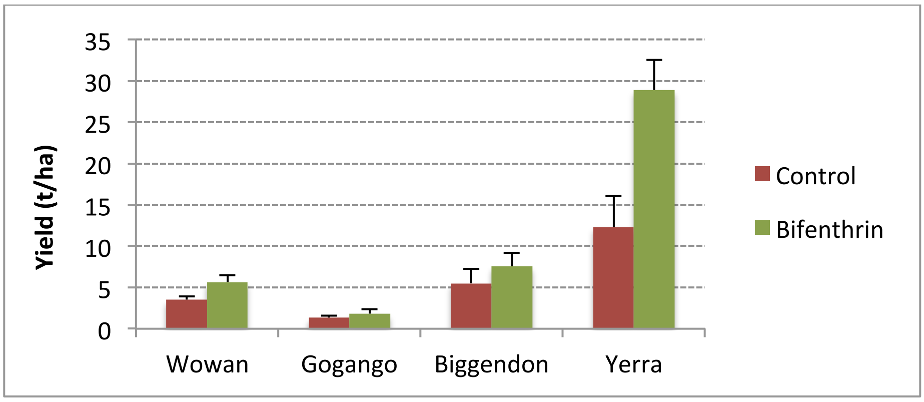

Figure 28. Pasture growth (t/ha) at four sites with die off that were treated with bifenthrin insecticide

Figure 29. Pasture sprayed with bifenthrin insecticide (left) or left untreated (right) at Yerra, Qld. Pictures taken two months after treatment.

3.2. Other insect pests

Key point

The key international pest of buffel grass – spittlebugs – do not occur in Australia. However, it may be noted that burning can control these pests, as it can other immobile insects on plant leaves. Documented insect pests of buffel grass in Australia include a seed caterpillar, whitefly, scale and rusty plum aphid, however none of these is known to cause significant damage.

- The spittlebug *Aeneolamia albofasciata* is a pest of buffel grass in many parts of the world, including Mexico, the USA and South America. Infestation tends to increase with more intense grazing[114], especially if there is good summer rainfall[115].
- Summer burning has been found highly effective at controlling spittlebugs on buffel grass. Burning after accumulation of 50mm rain or early summer killed 100% of spittlebugs and stimulated buffelgrass production for 3 to 4 years after treatment. Burning during peak summer growth was also effective, but reduced buffel grass productivity by 50%[116].
- Spittlebugs do not occur in Australia. Official reports of insects attacking Australian buffel grass include:
    - Buffel grass seed caterpillar *Mampava rhodoneura*, which feeds exclusively on the seed heads[117].
    - Sugarcane whitefly *Neomaskellia bergii*, which has been reported infesting patches of feral buffel grass in central Australia[118].
    - Rusty plum aphid *Hysteroneura setariae*, which was also reported from patches of feral buffel grass in central Australia. This aphid can transmit a number of viruses, so has the potential to be a significant pest to numerous plants[119].
- Scale insects (coccids) are known to attack the crown of buffel grass plants, but were reported by Perrott to cause no commercial damage[120].
- Mites are common pests of warm climate turfgrasses. Mites are extremely small, and can be difficult to detect. Their presence is usually determined indirectly through distortion of the new growth, reduced stolon development and weak, patchy areas within the grassed area. The presence and species of mites on turfgrass have been extensively studied and reviewed by Loch et al[121].

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[114] Botelho W et al. 1985. Effect of animal burdon on the population of the spittlebug *Zulia enteriana* (Berg, 1879)(Homoptera-Cercopidae) in pastures of buffel grass, *Cenchrus ciliaris*. An. Soc. Entomol. Brasil 14:205-214.

[115] Martin RM et al. 1995. Spittlebug (Homoptera: Cercopidae) life cycle on buffelgrass in northwestern Mexico. Ann Entomol. Soc. Am. 88:471-478.

[116] Martin-R M et al. 1999. Spittlebug and buffelgrass responses to summer fires in Mexico. J. Range Manage. 52:621-625.

[117] Cantrell B. 1981. A new insect pest for Queensland. News Bull. Entomol. Soc. Qld. 9:56-57.

[118] Palmer CM. 2009. Buffel grass (*Cenchrus ciliaris*) is a host for the sugarcane whitefly *Neomaskellia bergii* (Signoret)(Hemiptera:Aleyrodidae) in central Australia. Austral. Entomol. 36:89-95.

[119] Palmer CM. 2009. Presence of the rusty plum aphid *Hysteroneura setariae* (Thomas)(Hemiptera:Aphididae) on buffel grass (*Cenchrus ciliaris*) in Central Australia. Austral. Entomol. 36:105-110.

[120] Perrott R. 2001. Diseases of buffel grass. In Buffel Grass Symposium. Ed. Cook B. DPI Publications.

[121] Loch DS et al. 2017. Distribution, field recognition and implications of phytophagous mite species on *Cynodon* spp. (Bermudagrass) and *Pennisetum clandestinum* (Kikuyugrass) in Australia. Int. Turfgrass Soc. Res. 13:502-511.

- Redlegged earth mites are a major pest of pasture legumes, and are also found on ryegrass and young cereal crops. They live on or near the soil surface, but feed on plant leaves causing silvery patches. While they have a widespread distribution, they are not thought to occur north of approximately Newcastle, NSW on the east coast or Geraldton on the west coast[122].
- The symptoms of mite infestation on turfgrass are very different to the dieback symptoms observed central Qld pasture areas. There are no reports of mites infesting buffel grass

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[122] Umina P. 2007. Redlegged earth mite. http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/redlegged-earth-mite

3.3. Pest monitoring and control

3.3.1. Volatile organic compounds (VOCs)

Key points

Plants produce volatile compounds in response to attack by insects, infection by disease, stress or physical damage. Fungal infection generally causes the greatest response and insect feeding the least, with chewing insects stimulating greater release of volatiles than piercing insects such as mealybugs. Despite this, mealybug feeding has been shown to stimulate herbivore induced plant volatiles. Moreover, grasses are likely to produce more volatiles than other types of plants. Volatiles released by plant roots can be measured using laboratory techniques. If key specific compounds are identified, it may be possible to detect these in the field using an 'electronic nose' type of sensor array.

- Biologically produced volatile organic compounds (VOCs) include thousands of trace organic compounds that are gas at normal temperature and pressure. Most are produced by plants and provide their distinctive aromas – such as the smell of pine needles, camphor wood, or tomatoes. Others are produced by insects. Most of these are pheromones used for finding mates, but others include compounds for marking territory or improving mating success.
- A subset known as 'herbivore induced plant volatiles' (HIPVs) or 'green leaf volatiles' (GLVs) or are produced by plants when they suffer tissue damage. More than 2,000 compounds, including aldehydes, esters and alcohols, have been identified from over 900 plant families[123].
    - These compounds are often produced in response to insect attack but can also be triggered by environmental stresses such as drought, fungal infection or mechanical damage.
    - HIPVs can function as warning signals to neighbouring plants, act as anti-feedants / toxins or attract predatory insects to the plants' defense (Figure 30)[124].

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[123] War AR et al. 2011. Herbivore induced plant volatiles: Their role in plant defense for pest management. Plant Signaling Behavior. 6:1973-1978.

[124] Ameye M et al. 2018. Green leaf volatile production by plants: a meta-analysis. New Phytol. 220:666-683.

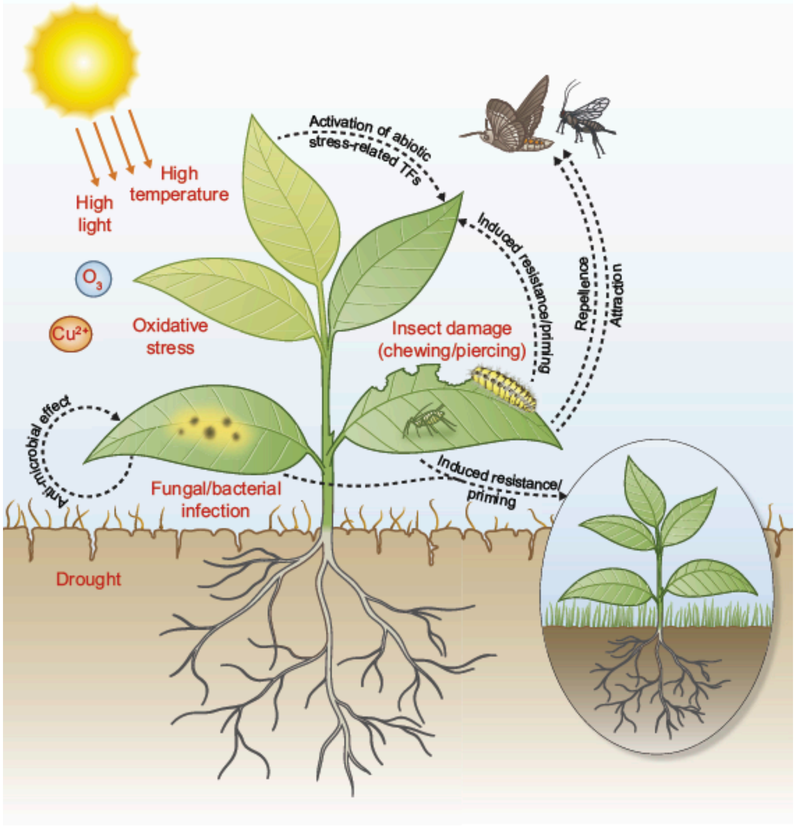

Figure 30. Functions of green leaf volatiles (GLVs) including types of stress that drive GLV production (red) and functions of GLVs (black). From Ameye et al, 2018.

- While the majority of studies have focused on HIPVs produced by leaves and shoots, it is clear that plant roots also produce significant amounts and different types of volatile compounds. As with aerial compounds, these have a range of signaling and practical functions[125]. There are a number of studies on HIPVs produced in response to feeding on plant roots. For example:
    - Carrot roots damaged by wireworms release volatiles that attract predatory nematodes. Conversely, undamaged roots release volatiles that repelled these entomopathogens[126].
    - The Russian wheat aphid *Diuraphis noxia*, which feeds on roots as well as shoots, induces emission of the volatile 1,8-cineole[127]
    - Maize roots infested by western corn rootworm larvae produce the sesquiterpene (*E*)-β-caryophyllene, which attracts entomopathogenic nematodes[128].
- Feeding by mealybugs has also been shown induce production of HIPVs:

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[125] Delory BM et al. 2016. Root-emitted volatile organic compounds: can they mediate below ground plant-plant interactions. Plant Soil. 402:1-26.

[126] Laznik Z, Trdan S. 2016. Can entomopathogenic nematodes (Steinernematidae and Heterohabditidae) function as an indirect plant defense? IOBC/WPRS Bull. 113:105-109.

[127] Tripathi AK et al. 2001.. Toxicity, feeding deterrence and effect on activity of 1,8 cineole from *Artemisia annua* on progeny production of *Tribolium castaneum*. J. Econ. Entomol. 94:979-983.

[128] Rasmann S et al. 2005. Recruitment of entompopathogenic nematodes by insect-damage maize roots. Nature. 434:732-737.

  - The odour of cassava plants infested with the mealybug *Phenacoccus manihoti* is highly attractive to the predatory ladybird Exochomus flaviventris. Moreover, the ladybirds can distinguish between plants that have already been targeted by other females and those where the mealybugs have not yet been attacked[129].
  - Cotton plants infested by the mealybug *Phenacoccus solenopsis* have increased production of several volatile compounds including 3-Henex-1-ol acetate, cyclohexane and β-caryophyllene[130]. Mealybug feeding also suppressed some compounds involved in plant defenses. As a result, more mealybugs were attracted to the host plant, and mealybugs developed faster on plants that were already infested.
- A 2018 meta analysis found that the amount of volatiles produced by plants depends on the type of stress, as well as whether the plant is a monocotyledon.
  - Fungal infection produced the most volatiles, with production increasing over time.
  - Insect damage produced a fast response, but resulted in less volatiles overall than either disease or physical damage.
  - Chewing insects produced a greater response than piercing insects.
  - This is consistent with Walling[131], who noted that plant responses to phloem feeding insects such as mealybugs are likely to be less than those to chewing insects because physical damage to the plant is limited. This is especially the case if the insect is stationary and its feeding stylet remains in one position.
  - While Walling[131] proposed that sucking insects may induce similar defense pathways as those activated by fungal and bacterial pathogens, this is not supported by the evidence accumulated by Ameye et al[124].
  - Monocots (e.g. grasses) had less response to fungal infection, but greater responses to insects, compared to dicot plants (e.g. legumes).

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[129] Le Ru B, Makaya Makosso JP. 2001. Prey habitat location by the cassava mealybug predator *Exochomus flaviventris*: olfactory responses to odor of plant, mealybug, plant-mealybug complex and plant-mealybug-natural enemy complex. J. Insect Behav. 14:557-571.

[130] Zhang P et al. 2011. Suppression of jasmonic acid-dependant defense in cotton plant by the mealybug Phenacoccus solenopsis. PLoS One. 6:e22378.

[131] Walling LL. 2000. The myriad plant responses to herbivores. J. Plant Growth Regul. 19:195-216.

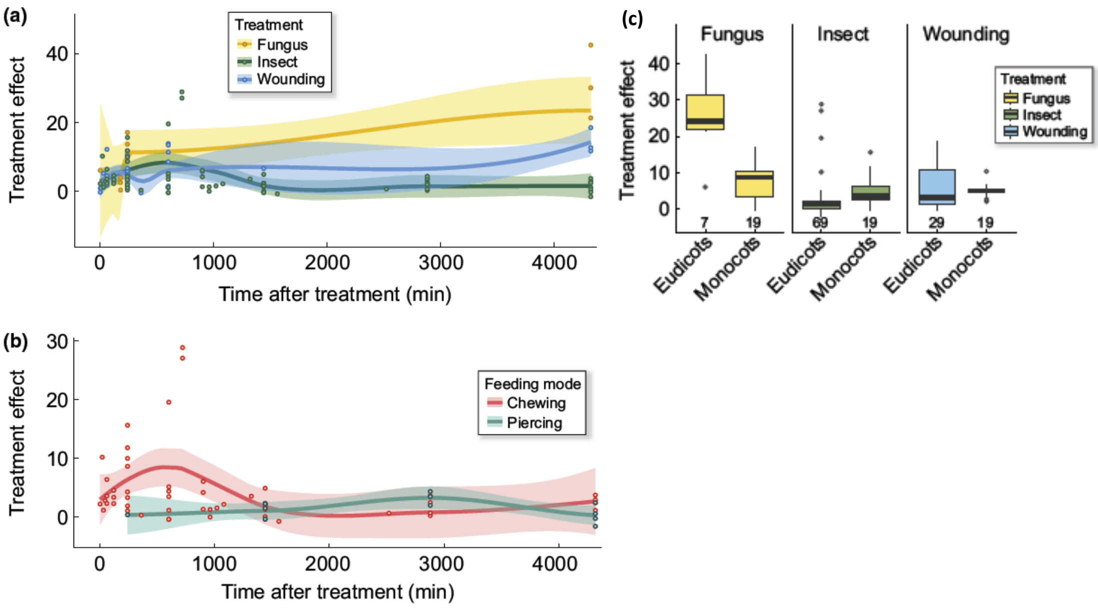

Figure 31. Release of HIPVs in response to (a) fungal infection, insect attack of physical wounding; (b) chewing vs piercing insects; (c) monocots vs other plants to different types of injury. From meta-analysis by Ameye et al, 2018.

- It is possible to detect the HIPVs produced by infested plants even before symptoms are apparent. This would be particularly useful for detection of soil borne diseases or pests, where diagnosis can be particularly difficult.
    - Initial separation and identification of HIPVs released by plant roots can be conducted by sorbing the gases released from the soil surface with a trap or fibres, then analysing using Gas Chromatography or Gas Chromatography Mass Spectrometry (GC-MS).
    - Fast, online detection of volatiles released by plants in a laboratory situation can be achieved using Proton Transfer Reaction Mass Spectrometry (PTR-MS)[132].
    - Electronic noses can also be used to detect plant volatiles. These are portable and provide an instant response. A number of commercial devices are available, broadly grouped as conductivity sensors, gravimetric sensors and optical sensors. Each sensor is able to detect a range of volatile compounds. E-noses have been successfully used to detect fungal infections (e.g. wood rot), as well as insect damage and physical injury to plants. Cui et al[133] recently reviewed the types of sensors available, their advantages and disadvantages.

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[132] Crespo E et al. 2012. On-line detection of root-induced volatiles in *Brassica nigra* plants infested with *Delia radicum* root fly larvae. Phytochem. 84:68-77.

[133] Cui S et al. 2018. Plant pest detection using an artificial nose system: A review. Sensors. 18:378.

3.3.2. Entomopathogenic nematodes

Key point

Entomopathogenic nematodes prey on soil dwelling insects and have been successfully used as biological controls in some situations. However, good laboratory results often fail to translate into field control due to high/low soil moisture and other environmental factors. Introduction of EPNs as a management strategy for mealybugs appears more suited to intensive situations, particularly for irrigated crops, than pasture application.

- Entomopathogenic nematodes (EPNs) are a group of nematodes that live parasitically inside insects. They can infect many types of soil dwelling insects, including larval forms of beetles, flies and Lepidopterans. Once they have penetrated their insect host, the nematodes release an associated mutualistic bacterium. This breaks down the insect tissues, providing food to both nematode and bacterium, which multiply rapidly inside. The host is killed, and juvenile nematodes burst from the disintegrating cadaver in search of new hosts.

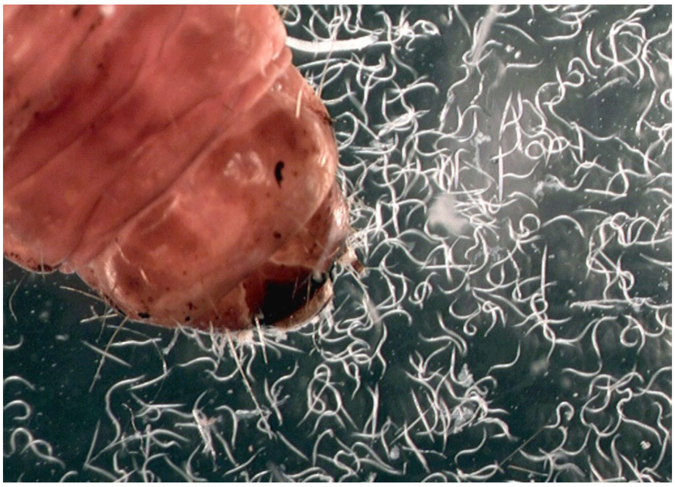

Figure 32. Juvenile *Herorhabditis bacteriophora* nematodes leaving a wax moth carcass. Photo by B. Adhikari.

- Members of Steinernematidae and Heterohabditidae have been widely investigated for use in biological control. Laboratory trials have demonstrated that strains of these EPNs are able to kill mealybugs, including soil dwelling species;
    - *Heterorhabditis* spp. nematodes are effective against the coffee root mealybug *Dysmicoccus texensis*. They have been reported as causing 70%[134] and up to 100% [135] mortality.
    - Two strains of *Heterorhabditis* spp. nematodes also proved effective against the sugarcane mealybug *Saccharococcus sacchari*[136].
- EPNs vary widely in their tolerance of environmental conditions, hunting methods and preferred soil depths. As a result, positive results in the laboratory often fail to translate into good results in the field.

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[134] Mani M, Smith MS, Najitha U. 2016. Root mealybugs and their management in horticultural crops in India. Pest Mgmnt. Hort. Ecosys. 22:103-113.

[135] Alves VS et al. 2009. Pathogenicity of entomopathogenic nematodes against the coffee root mealybug *Dysmicoccus texensis*. Arquivos do Instituto Biologico. 76:67-73.

[136] El-Roby ASMH. 2018. Efficiency of entomopathogenic nematodes (Rhabdita) against *Saccharococcus sacchari* under laboratory conditions. Pak. J. Nematology.

- Desiccation and the effects of UV have greatly limited effect use of EPNs on aerial pests. For example, although laboratory bioassays found that EPNs were highly effective against the citrus mealybug *Planococcus citri*, application above ground is limited by available water. After application, nematodes have only 2-4 hours to find hosts, and are 15 times less potent at 80% compared to 100% RH[137].
- Even though soil is the natural habitat of EPNs, many attempts to control insects in the soil have also failed. These can be due to factors such as soil moisture (too much or not enough), soil texture (sandy / loam or clay), temperature and pH[138].
- The vine mealybug *Planococcus ficus* lives both on the trunk and roots. Applications of EPNs to vineyards initially yielded good results. However, nematodes did not always leave the dead cadavers and persistence in the soil was extremely variable[139].

3.3.3. Parasitoids and Predators

Key point

Numerous parasitoid wasps are known to attack mealybugs. Species-specific parasitoids have been deliberately introduced into some countries to attack an exotic mealybug pest. In other cases parasitoids are generalists attacking multiple mealybug species. Parasitism rates are highly variable, ranging from 10 to 80% of the mealybug population. The availability and suitability of food sources for the adult wasps is likely affect control by this mechanism.

- There are numerous parasitoid wasps that will attack mealybugs, laying their eggs inside their prey. Several species are commercially available. For example, in the USA and Canada there are at least 13 companies that supply *Leptomastix dactylopii* for control of citrus mealybug.
- In 2009 the parasitoid wasp *Anagyrus lopezi* was deliberately introduced into several countries in SE Asia for control of the invasive cassava mealybug *Phenococcus manihoti*. Rates of parasitism vary widely, ranging from 10 to 57% of the population[57]. Despite this, it is estimated that control by this wasp has increased cassava yield in Thailand by 5.3–10t/ha[140].
- Like *A. lopezi*, the parisitoid *Allotropa burrelli* will be deliberately introduced to control a specific mealybug pest. In this case the target is *Pseudococcus comstocki* in southern France. The wasp will not parasitize even closely related mealybug species, making it a suitable agent for biological control[141].

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[137] Van Niekerk S, Malan AP. 2012. Potential of South African entomopathogenic nematodes (Heterohabditidae and Steinernematidae) for control of the citrus mealybug *Planococcus citri*. J. Invert. Path. 111:166-174.

[138] Kung S, Gaugler R, Kaya HK. 1991. Effects of soil temperature, moisture and relative humidity on entomopathogenic nematode persistence. J. Intervebr. Pathol. 57:242-249.

[139] Le Vieux PD, Malan AP. 2015. Prospects for using entomopathogenic nematodes to control the vine mealybug Planococcus ficus, in South African vineyards. S. Afr. J. Enol. Vitic. 36:59-70.

[140] Thancharoen A et al 2018. Effective biological control of an invasive mealybug pest enhances root yield in cassava. J. Pest Sci. 91:1199-1211.

[141] Quaglietti B et al. 2017. Pre-release host range determination of the parasitoid Allotropa burrelli for the biocontrol of pseudococcus comstocki in Europe. J. Appl. Entomol. 8:665-668.

- Other species of parasitoid will attack a range of mealybug species. A study of the mealybug *Delottococcus aberiae* found it was attacked by at least three parasitoids. *Anagyrus* nr *pseudococci* and *Leptomastix algirica* lay eggs in nymphs and adult mealybugs, whereas *Leptomastix algirica* will only parasitize adults. The researchers noted that although the mealybugs try to escape by flipping, swivelling and withdrawing their stylet and walking away, the wasps were always successful[142].
- Releases of bred *Ericydnus sipylus* have been trialed in France to control *Heliococcus bohemicus* (vine mealybug). The first three releases did not appear to have any impact on the mealybug population. However, subsequent releases resulted in 50 to 60% parasitism, while the following summer 75 to 85% of mealybugs were found to be parasitised. Despite stopping releases, rates of parasitism continued at around 80% for approx. 12 months[143].

3.3.4. Entomopathogenic fungi

Key point

Entomopathogenic fungi are commercially available and have been shown to be effective against insect pests including mealybugs and other soil dwelling insects. However, the majority of reports relate only to laboratory trials where the fungus is inoculated direclty onto the insect. High mortality is likely to be harder to achieve under open field conditions, and may be strongly affected by soil type and moisture. However, some limited field studies do suggest that entomopathogenic fungi may be able to suppress populations of some soil dwelling insects.

- Entomopathogenic fungi (EF) usually attach to insects as spores. Under the right conditions of temperature and humidity, the spores germinate, bore through the insect cuticle, and proliferate inside the body cavity. After a time the insect is killed, after which fungal spores and hyphae often appear on the outside of its body.

Examples of EF include *Beauvaria*, *Isaria*, *Metarhizium*, *Lecanicillium* and *Cordiceps* (

- Figure 33). A number of these have been shown to be effective against mealybugs.
    - *Beauveria bassiana* is commercially available in a number of different formulations for use against insect pests. It has been shown to be effective

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[142] Tena A. 2018. Defensive bahviors of the new mealybug citrus pest Delotococcus aberiae against three generalist parisitoids. J. Econ. Entomol. 111:89-95.

[143] Sentenac G et al. 2011. Biological control of *Heliococcus bohemicus* with the natural enemy *Ericydnus sipylus*. Conf. Proc. Integrated Protection and Production in Viticulture. Staufen im Breisgau, Germany 1-4 Nov 2009.

against cassava mealybug[144] as well as grapevine mealybugs, surviving for at least 21 days in a glasshouse and up to five weeks in a vineyard[145].

  - The green muscardine fungus *Metarhizium anisopliae* is also commercially available. When inoculated onto the mealybug *Paracoccus marginatus* it rapidly penetrated the cuticle and grew through the insect body. The insect died within 7 days of infection[146].
  - Citrus mealybug *Planococcus citri* has likewise been shown to be susceptible to species of *Lecanicillium*, especially at the nymph stage.
  - *Lecanicillium lecanii* has also been shown to be able to kill the root mealybug *Formicoccus polyspheres*[134].

Figure 33. Weevil infected with *Cordiceps* fungi (left) and mealybug killed by green muscardine fungus (right)

- As with entomopathogenic nematodes, one of the barriers to commercial use of biological control agents is their limited ability to survive on crop surfaces. However, application to soil could provide the more stable temperatures and higher humidity needed for germination and infection. Some EF are naturally soil dwelling, so may be adapted to the soil dwelling mealybug environment.
  - The soil fungus *Isaria fumosorosa* has been proposed for control of subterranean termites, with isolates causing 50 – 95% mortality when inoculated onto the insects[147].
  - *Metarrhizium* fungi are also naturally isolated from the soil. While *M. brunneum* showed good effectiveness against wireworm, this was strongly dependent on soil type; the fungus failed to perform well in sandy media[148].
  - *Metarhizium anisopliae* caused around 90% mortlaity of chestnut weevil larvae, while *Beauveria bassiana* strains resulted in 80% and 77% mortality[149].

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[144] Amnuaykanjanasin A. et al 2013. Infection and colonization of tissues of the aphid *Myzus persicae* and cassava mealybug *Phenacoccus manihoti* by the fungus *Beauveria bassiana*. Biocontrol. 58:379-391.

[145] Rondot Y, Reineke A. 2018. Endophytic *Beauveria bassiana* in grapevine *Vitus vinifera* reduces infestation with piercing sucking insects. Biological control. 116:82-89.

[146] Amutha M, Gulsar Banu J. 2015. Pathogenisis of entomopathogenic fungus *Metarhizium anisopliae* on mealybug *Paracoccus marginatus*.

[147] Jessica JJ et al. 2019. Evaluation of the virulence of entomopathogenic fungus *Isaria fumosorosea* isolates against subterranean termites *Coptotermes* spp. J. Forestry Res. 30:213-218.

[148] Ensafi P et al. 2018. Soil type mediates the effectiveness of biological control against *Limonius californicus*. J. Econ. Entomol. 5:2053-2058.

[149] Torrini G et al. 2018. Entomopathogenic fungi and nematodes against larvae of the chestnut weevil *Curculio elephas*: a laboratory evaluation. Int. J. Pest Mgmnt. 64:287-293.

  - Soil drenches with the EF *Cephalosporium lecanii* more than halved the population of root mealybugs on banana plants when evaluated five months after planting[150].

- While there are a very large number of references regarding the use of EF against insect pests, the vast majority of these studies are laboratory based. Some trials have also been reported for greenhouses, but trials under open field conditions are rare. While the many positive results therefore appear promising, it seems likely that in many of these represent best case scenarios, rather than commercial conditions.

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[150] Smitha MS, Mathew MP. 2010. Management of root mealybugs Geococcus spp. in banana cv. Nendran. Pest Mgmnt. Hort Ecosys. 16:108-119.

4. Diseases

4.1. Pasture diseases

Key points

Many different fungal species are known to attack grasses. These can cause symptoms resembling either dieback or decline. In many cases dieback is due to a range of different fungal pathogens which are able to attack and cause symptoms due to poor plant health.

A number of different viruses can infect Australian pasture grasses. The only known vector that has been found on buffel grass is the rusty plum aphid. No references were found to this aphid occurring on buffel grass in areas with dieback, and no viruses have been isolated from buffel grass.

4.1.1. Fungal pathogens

- The symptoms of dieback of buffel grass appear to be consistent with a soil-borne disease. These include; how patches of dieback appear and spread, the distinct boundaries of these patches, the rapid development of symptoms and the lack of any other obvious causal agent eg root nematodes, phytoplasmas or changes in soil chemistry[12].

- There is no doubt that fungal pathogens can cause dieback in other pasture species. Much of the observed dieback of subterranean clover has been attributed to soil borne diseases. Examples of grasses severely affected by diseases include:
    - Infection by *Nigrospora sphaerica causes* turfgrass blight, which affects species such as bermudagrass, bentgrass and zoysiagrass. The symptoms of leaf dieback are not caused by the fungus itself, but by a phytotoxin it produces[151].
    - Signal-grass (*Brachiaria brizantha*), a widely used pasture grass in Brazil, has been shown to suffer dieback due to infection by *Bipolaris cynodontis*[152].
    - Isolates of *Rhizoctonia solani* (N.B. recently isolated from Queensland pasture affected by dieback) have been shown to cause severe stunting in wheat, particularly when crops were direct drilled rather than cultivated. Re-inoculating the isolates into annual ryegrass and barleygrass, caused severe root rot symptoms[153].
    - The fungus *Cylindrocladium scoparium*, although primarily a disease of legumes, has been found to reduce emergence and stunt growth of several pasture grasses, including perennial ryegrass[154].

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[151] Ja Choi G et al. 2000. Phytotoxin production of *Nigrospora sphaerica* pathogenic on turfgrasses. Plant Pathol. 16:137-141.

[152] Macedo DM, Barreto RW. 2007. First report of leaf blight of *Brachiaria brizantha* in Brazil caused by *Bipolaris cynodontis*. Plant Path. 56:1041.

[153] Rovira AD. 1986. Influence of crop rotation and tillage on *Rhizoctonia* bare patch of wheat. Phytopthol. 76:669-673.

[154] Waipara NW et al. 1996. Pathogenicity of *Cylindrocladium scoparium* to pasture clover and grass species. Aust. P. Pathol. 25:205-211.

- Soil-borne disease is a major cause of loss of pasture productivity in general. Causal pathogens range from broad generalists such as *Pythium irregulare* and *Fusarium oxysporum*, to highly virulent specialist pathogens such as *Phytophthora clandestina*[155].
- In most pasture systems, plant dieback occurs as a result of a disease complex. This makes it hard to quantify the specific effect of one pathogen or another[156]. It may also make it difficult to find a 'magic bullet' solution. Rather, the solution lies in improving plant health and therefore resistance to disease.

4.1.2. Viruses

- Virus diseases affecting Australian pasture grasses were comprehensively reviewed by Jones in 2013[157]. At the time of publication 21 viruses had been found infecting 36 pasture grasses and 59 wild grass species including subtropical – tropical grasses grown in Queensland e.g. Qld blue couch, African lovegrass, paspalum and *Pennisetum* spp.. No viruses have been found infecting buffel grass, despite extensive sampling.
- Similarly, at least 8 plant viruses are known to infect introduced pasture grasses in New Zealand. Luteoviruses, which cause reddening or stunting, are the most common, and are vectored by a number of different aphid species. Other viruses tend to cause mottling of leaves[158].
- Viruses tend to be vectored by mites and aphids.
    - The rusty plum aphid, has been found on uncultivated buffel grass patches near Alice Springs and in southern Western Australia[159, 119].
    - This aphid can vector a number of viruses including barley yellow dwarf virus (BYDV), cereal yellow dwarf virus (CYDV) and sugarcane mosaic.
    - No reports of aphid species on buffel grass in the Queensland rangelands were found for this report. However, this aphid is widely distributed worldwide and could likely survive in this environment.
- Although initial symptoms of dieback (reddening from the tips, typical of BYDV infection of paspalum) can resemble certain viral infections, the lack of evidence of local vectors suggests that buffel grass dieback is not due to a virus.

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[155] Dignam BEA et al. 2016. Challenges and opportunities in harnessing soil disease suppressiveness for sustainable pasture production. Soil Biol. Biochem. 95:100-111.

[156] Skipp R, Christensen, M. 1989. Disease complexes in New Zealand pastures. In "Pasture and Forage Crop Pathology", Madison, Wisconsin USA, pp. 429-451.

[157] Jones RAC. 2013. Virus diseases of pasture grasses in Australia: incidences, losses, epidemiology and management. Crop Pasture sci. 64:216-233.

[158] Guy PL. 2014. Viruses of New Zealand pasture grasses and legumes: a review. Crop Past. Sci. 65:841-853.

[159] Hawkes JR, 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. Aust. J. Agric. Res. 56:257-270.

4.2. Diseases affecting buffel grass

Key points

Buffel grass can be affected by several diseases, the most important of which is *Magnaporthe grisea (also M. oryzae)*, which causes 'blast' or 'blight' disease in a wide range of grass species. Although the symptoms of 'buffel blight' are different to dieback, the two issues can occur together.

Despite many attempts, researchers have failed to induce dieback symptoms by inoculating plants with pathogens isolated from apparently diseased plants and soil. Moreover no fungal hyphae were present in the roots of apparently diseased plants. This suggests that buffel grass dieback, despite disease-like symptoms, is not caused by a disease.

- The most serious disease affecting buffel grass is 'buffel grass blight' caused by the fungus *Magnaporthe grisea,* also sometimes referred to as *M. oryzae* (when it occurs on rice). Symptoms include appearance of dark discoloured spots, which turn into necrotic lesions with a dark brown or reddish outline and chlorotic halo. Plants wilt and die.
- The pathogen can be separated into at least two distinct isolates. These cannot interbreed, and appear to have a high level of genetic diversity[160].

Figure 34. *Magnaporthe grisea* infection on millet. Photo by P. Bachi, Uni Kentucky, Bugwood.org.

- The fungus also affects many important cereal crops including rice, wheat, rye, barley and millet. It is the most important worldwide disease of rice ('rice blast'), each year causing losses that would feed over 60 million people, and economic loss of over $70 billion[161].
- In Texas, an epidemic of this pathogen swept through large monoculture areas of buffel grass, with major losses as a result[162].

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[160] Madhaven S et al. 2013. Molecular characterisation of *Mangnoporthe grisea* isolated from buffel grass (*Cenchrus ciliaris*) in Tamil Nadu, India. Ann. Pl. Prot. Sci. 22:122-126.

[161] Fang X et al. 2017. Races of *Magnaporthe oryzae* in Australia and genes with resistance to these races revealed through host resistance screening in monogenic lines of *Oryzae sativa*. Eur. J. Plant Pathol. 148:647-656.

[162] Rodriguez O et al. 1999. First report and epidemics of buffel grass blight caused by *Pyricularia grisea* in south Texas. Plant Dis. 83:398.

- Buffel grass blight also occurs in Mexico, where it reduces biomass yields by 20-26%, especially if plants were stressed by other factors[163].
- The *M. oryzae* fungus is known to occur in northern Australia, including northern Queensland, the NT and northern WA[161].
- Buffel grass blight has been found in central Queensland[164]. Although the symptoms differ from dieback, the authors describe blight as commonly found in and near circular patches of dead and dying plants and associated with 'ill-thrift' of buffel grass. It is suggested that there may be a link between the appearance of blight and the occurrence of dieback.
- However, this pathogen has not been isolated from dieback patches and is not considered to be a primary cause of buffel grass dieback[12].
- A team at CQU isolated *Fusarium oxysporum* fungus from the roots of diseased buffel grass. However it was unclear whether this was a primary or secondary infection, and pathogenicity tests failed to demonstrate causality[12].
- Makiela[10] also failed to induce symptoms of dieback in buffel grass using isolates from areas with dieback;
    - In total, 85 different isolates were prepared from apparently diseased plants and soil.
    - Each isolate was inoculated into 15 healthy plants using five different techniques.
    - Despite a high rate of spore germination, none of the seedlings expressed any symptoms of disease or dieback.
    - In another trial, seeds from dieback-affected plants were grown in soil collected from dieback-affected areas; none of the seedlings that emerged had dieback symptoms, indicating that dieback was not transmitted through seed.
    - No hyphae were observed in microscopic examinations of the roots, appearing to confirm that no fungal pathogen was present.
- Greenhouse trials conducted recently at NSW DPI Ourimbah tested pathogenicity of 10 different isolates on pots of buffel grass. *Rhizoctonia*, *Fusarium* and *Bipolaris* all caused dieback symptoms, particularly if plants were stressed by flooding. However, symptoms did not occur consistently across the experiments. Moreover, some of the control plants also developed dieback symptoms (L. Tesoriero, pers. com.).

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[163] Diaz Franco A, Rodriguez AM, Cedillo RG. 2007. Buffelgrass leaf blight: its presence in Tamaulipas, Mexico. Ag. Tecnica Mex. 33:285-295.

[164] Perrott RF, Chakraborty S. 1999. *Pyricularia grisea* causes blight of buffel grass (*Cenchrus ciliaris*) in Queensland, Australia. Trop. Grassland. 33:201-206.

5. Plant dieback– case studies from other species

5.1. Rural tree dieback

Key Points

Rural tree dieback can be caused by factors including drought, waterlogging, rising temperatures, accumulation of soil nitrogen, changes in fire management and increased attacks on trees by insects, animals and pathogens. In many cases, interactions between two or more of these factors are what cause tree death. So, for example, reduced burning increases soil nitrogen, leading to more nutritious leaves and increased feeding by insects/animals. Parasitic psyllids attract bell miners, which protect them (and other insects) from insectivorous bird species. Solutions to dieback largely focus on re-instating low intensity burning, increasing biodiversity and managing stock grazing.

5.1.1. Background

- Rural tree dieback or decline first occurred in Australia during the late 1800's, following wide scale clearing by the early European settlers[165]. The issue re-appeared in the mid 20th century, but dramatically increased during the 1980's and onwards.
- Jurskis[166] defines dieback as the sudden death of trees associated with root rots, drought or waterlogging. An example is 'drought scorch' where the leaves of the tree stay attached but turn brown due to sudden death of the tree from water stress.

Figure 35. Dieback in the ACT (left) and Monaro, NSW (right)

- Decline may also be referred to as dieback, but is a process occurring over a much longer period of time. Decline is characterised by a thinning of the trees' crown, starting from the branch ends and progressing towards the trunk, leaving dead branches protruding beyond the remaining foliage[167].

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[165] Norton, A. 1886. On the decadence of Australian forests. Proc. Royal soc. Qld. 3:15-22.

[166] Jurskis V. 2005. Eucalypt decline in Australia, and a general concept of tree decline and dieback. Forest Ecol. Mgmnt. 215:1-20.

[167] Close DC, Davidson NJ. 2004. Review of rural tree decline in a changing Australian climate. Tasforests 15:1-18.

5.1.2. Causes – defoliation

- The causes of rural tree dieback have been a source of much debate. However, defoliation by leaf chewing insects and other foliage eaters is frequently cited as a key trigger.
    - The foliage of trees with dieback tends to suffer more damage from chewing insects than the foliage of neighbouring, healthy trees. This is because these trees put out more new foliage, which is attractive to insects[168].
    - For example, trees severely attacked by sawfly larvae often shed their remaining foliage and put out a major flush of new growth. This is highly attractive to sawflies, leading to continual re-infestation of the same tree[169].
    - Trees suffering dieback have been found to often have higher leaf nitrogen, as well as sometimes phosphorus and potassium. This is associated with young and epicormic shoots that develop after defoliation, and makes them more nutritious for insects[170].
    - Brushtail possums provided with eucalypt seedlings irrigated with tapwater or a balanced nutrient solution fed almost entirely on the fertilised trees. The foliage of these trees was moister and contained more nitrogen, sugars and fibre, but less tannin, than trees grown in water alone. The possums were clearly able to distinguish which leaves were nutritionally better, even though they appeared similar and were intermingled[171].
    - Similar results have been reported for koalas, which will preferentially graze on foliage that has higher nitrogen content, and therefore lower fibre content[172].
    - Bell miners (*Manorina melanophrys*) are considered as likely contributors to eucalypt dieback due to their habit of ‘farming’ parasitic psyllids for the protective sugary coating they produce[173]. The birds themselves are honeyeaters that aggressively defend their territory from other bird species. By excluding insectivores, and encouraging psyllids, the presence of bell miners results in an increase in insect populations within the tree canopy[174].

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[168] Landsberg J. 1988. Dieback of rural eucalypts: Tree phenology and damage caused by leaf-feeding insects. Aust. J. Ecol. 13:251-267.

[169] Carne PB. 1965. Distribution of the eucalypt defoliating sawfly *Perga affinis*. Aust. J. Zool. 13:593-612.

[170] Landsberg J, Wyllie FR. 1983. Water stress, leaf nutrients and defoliation: a model of dieback of rural eucalypts. Aust. J. Ecol. 8:27-41.

[171] Landsberg J. 1987. Feeding preferences of common brushtail possums, *Trichosurus vulpecula*, on seedlings of a woodland eucalypt. Aust. Wildl. Res. 14:361-369.

[172] Degabriele R. 1983. Nitrogen and the koala (*Phascolarctos cinereus*): some indirect evidence. Aust. J. Ecol. 8:75-76.

[173] Haythorpe KM, McDonald PG. 2010. Non-lethal foraging by bell miners on a herbivorous insect: potential implications for forest health. Austral. Ecol. 35:444-450.

[174] Lambert KTA, Reid N, McDonald PG. 2017. Does the removal of Lantana camara influence eucalypt canopy health, soil nutrients and site occupancy of a despotic species. For. Ecol. Manage. 394:104-110.

5.1.3. Causes – soil

- In contrast, numerous publications by Jurskis[175] argue that the root cause of dieback is soil eutrophication – particularly the accumulation of nitrogen.
    - Nitrogen can accumulate in the absence of the frequent, low-intensity forest burns that aborigines conducted for thousands of years before European settlement.
    - Many studies of soils under dead or dying eucalypt stands have found unnaturally elevated levels of nitrogen, due to either pasture improvement or lack of burning[176].
    - Increases in nitrogen change soil pH and chemistry and affect vegetation structure, inhibiting root growth of eucalypts and resulting in dieback[177].

5.1.4. Causes – climate and weather

- Climate change, rising temperatures and increasing frequency and severity of droughts are also likely to have an important role.
    - More than half of all *Eucalypt* species have a mean annual temperature range of <3°C, suggesting that even a degree or two increase in mean temperature will cause major dieback events[178].
    - The high-altitude areas of the NSW tablelands and central Tasmania have both experienced significant increases in mean temperatures and declining rainfall as well as severe rural tree dieback[179].
    - An extensive study by Fensham and Holman[180] used historical evidence, modelling and modern surveys to link observations of dieback to drought.
        - Such drought related dieback events were worse where soils were based on alkaline, igneous rocks compared to alluvial areas.
        - There were also differences in drought tolerance between tree species, and between trees and understory plants.
        - However, the authors remained unable to explain patchiness in dieback events, which was likely to be the result of complex interactions between soil type, drought and tree density.
- Heavy rain events can also cause dieback. This is particularly the case in the Jarrah forests of Western Australia.
    - It was initially believed that dieback of jarrah was caused by the introduced soil pathogen *Phytophthora cinnamomi*[181]. Research focused on controlling

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[175] Jurskis V. 2015. Firestick ecology: Fairdinkum science in plain English. Connor Court Publishing, Ballarat 370pp.

[176] Jurskis V. 2016. 'Dieback' (chronic decline) of *Eucalyptus viminalis* on the Monaro is not new, unique or difficult to explain. Aust Forestry. 79:261-264.

[177] Horton BM et al. 2013. Temperate eucalypt forest decline is linked to altered ectomycorrhizal communities mediated by soil chemistry. Forest Ecol. Manag. 302:329-337.

[178] Hughes L, Westoby M, Cawsey M. 1996. Climatic range sizes of *Eucalyptus* species in relation to future climate change. Global Ecol. Biog. Lett. 5:23-29.

[179] Close DC, Davidson NJ. 2004. Review of rural tree decline in a changing Australian climate. Tasforests 15:1-18.

[180] Fensham RJ, Holman JE. 1999. Temporal and spatial patterns in drought-related tree dieback in the Australian savanna. J. Appl. Ecol. 36:1035-1050.

[181] Podger FD. 1972. *Phytophthora cinnamomi*, a cause of lethal disease in indigenous plant communities in

this disease, and preventing its spread into unaffected areas of forest. Individual trees were even injected with phosphite, which induces plant defences against root rot fungi[182].

  - Logging and bauxite mining have increased the incidence of waterlogging in jarrah forests. This triggers blockage of the xylem vessels by tyloses (cell outgrowths), resulting in hydraulic failure and dieback[183].
  - New research indicates that although *P. cinnamomi* is associated with areas of dieback, this is due to this organism prospering in wet areas. The fungus is not the primary cause of dieback itself[184].

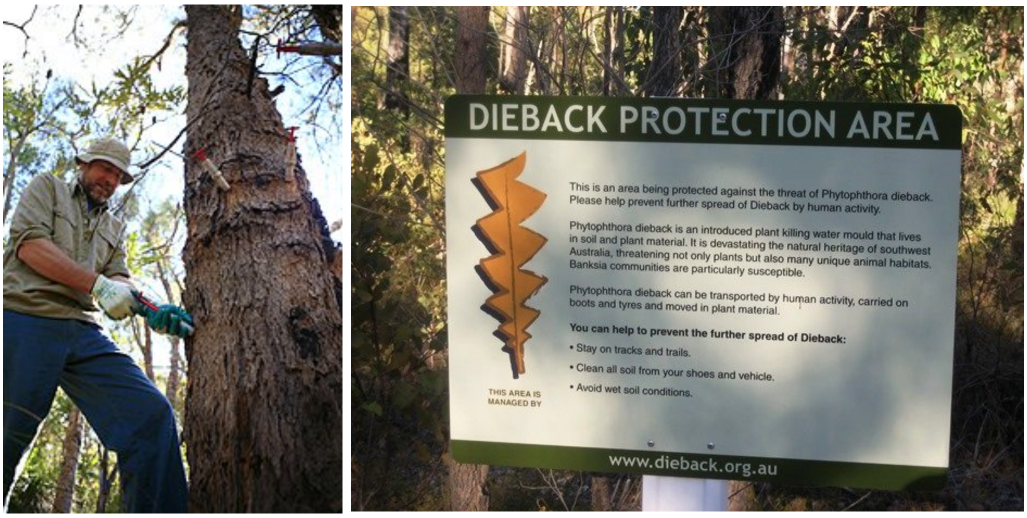

Figure 36. Attempts to control dieback in WA jarrah forests with injections of phosphite (potassium phosphonate) and biosecurity measures against *Phytophthora cinnamomi* (Photo: WA Parks and Wildlife). It is now thought that *Phytophthora* infection is a symptom, not a cause, of dieback.

Western Australia. Phytopath. 62:972-981.

[182] Pilbeam RA et al. 2011. Phosphite stimulated histological responses of Eucalyptus marginata to infection by Phytophthora cinnamomi. Trees. 25:1121-1131.

[183] Davison EM, Tay FCS. 1985. The effect of waterlogging on seedlings of *Eucalyptus marginata*. New Phytol. 101:743-753.

[184] Davison EM. 2018. Relative importance of site, weather and *Phytophthora cinnamomi* in the decline and death of *Eucalyptus marginata* – jarrah dieback investigations in the 1970's to 1990's. Aust. Plant Path. 47:245-257.

5.1.5. Conclusions

- It appears likely that most rural tree dieback is due to combinations of stresses, rather than single, isolated causes.
    - Although increasing droughts and rising temperatures have been blamed for dieback of subalpine Tasmanian cider gums (*Eucalyptus gunnii*), there is a stronger relationship between dieback and increased stock grazing than with climate alone[185]. The authors suggest it is the combination of these stresses that makes trees vulnerable to drought.
    - Drought commonly increases susceptibility to disease in many tree species, as stressed trees are less able to partition pathogens, preventing spread[186].

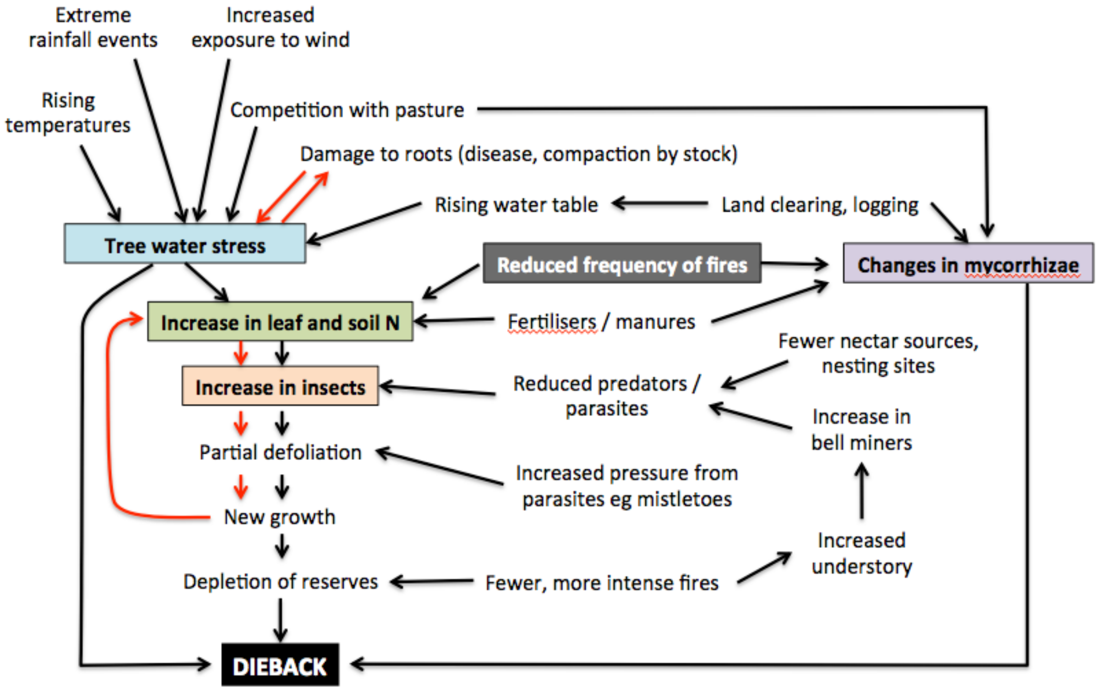

Figure 37. Model of eucalypt dieback, based partially on that proposed by Landsberg and Wylie (1983)

- Proposed methods to reduce dieback of rural trees include:
    - Re-instate traditional burning practices
    - Retain remnant patches of vegetation rather than isolated trees, and connect using wildlife corridors
    - Fence to exclude livestock OR allow stock in but use rotational grazing
    - Avoid applying fertiliser close to trees
    - Plant fast growing, flowering species near perimeters of remnant vegetation
    - Maximise environmental biodiversity

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[185] Calder JA, Kirkpatrick JB. 2008. Climate change and other factors influencing the decline of the Tasmanian cider gum (*Eucalyptus gunnii*). Aust. J. Botany. 56:684-692.

[186] Desprez-Loustau ML et al. 2006. Interactive effects of drought and pathogens in forest trees. Ann. Forest Sci. 63:697-612.

5.2. Clover dieback and decline

Key Points

Decline of subterranean clover is a major issue, causing productivity losses of 30% or more. Decline is caused by a number of different soilborne pathogens. Some are favoured by high moisture and loamy soil, others by dry conditions and sandy soil. Multiple species of fungi are often present in diseased roots. These species are also present in healthy, symptomless pastures, suggesting that decline is not due to soil pathogens alone. Symptoms are reduced by treatments that improve soil and plant health including fertilisers, cultivation and increased soil biota.

5.2.1. Background

- Subterranean clover (*Trifolium subterraneum*) is an extremely important component of many pasture systems around the world. It is not only a source of nutritious feed for livestock, but adds nitrogen to the soil and is a useful rotation with cereal crops[187].
- A diverse range of soil-borne pathogens attacks subterranean clover. These can cause damping off of seedlings and devastation of large areas of mature pasture. Pasture decline reduces livestock carrying capacity, allows weed growth, and impacts the economic viability of affected properties[188].
- In New Zealand, root diseases of clover reduce productivity by around 30%, costing growers from $750 to $1,506 ha^{-1}.year^{-1} [189].
- Similarly, a comprehensive survey of 202 clover pastures throughout southern Australia, taken from widely differing soil types and climates, showed that many were suffering severe decline. Most samples had very severe taproot rot (60–80% disease) and/or extremely severe lateral root disease (80–100% disease), with resulting poor *Rhizobium* nodulation.[190].

Figure 38. Subterranean clover pasture. Photo by Heritageseeds.

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[187] Nichols PGH, Jones RAC, Barbetti MJ. 2014. Genetic improvement of subterranean clover (*Trifolium subterraneum*) 2. Breeding for disease and pest resistance. Crop Pasture Sci. 65:1207-1229.

[188] Barbetti MJ, Sivasithamparam K, Wong D. 1986. Root rot of subterranean clover. Rev. Plant Pathol. 65:287-295.

[189] Wakelin SA et al. 2016. Cost of root disease on white clover growth in New Zealand dairy pastures. Aust. P. Pathol. 45:289-296.

[190] Foster K et al. 2017. Soilborne root disease pathogen complexes drive widespread decline of subterranean clover pastures across diverse climatic zones. Crop Pasture Sci. 68:33-44.

5.2.2. Pathogens

- A complex of soilborne pathogens[190] has been isolated from diseased clover roots including;
    - *Rhizoctonia* spp. especially *R. solani*
    - *Pythium* spp., especially *P. irregulare*.
    - *Fusarium* spp.
    - *Aphanomyces trifolii*
    - *Phytophthora clandestina*

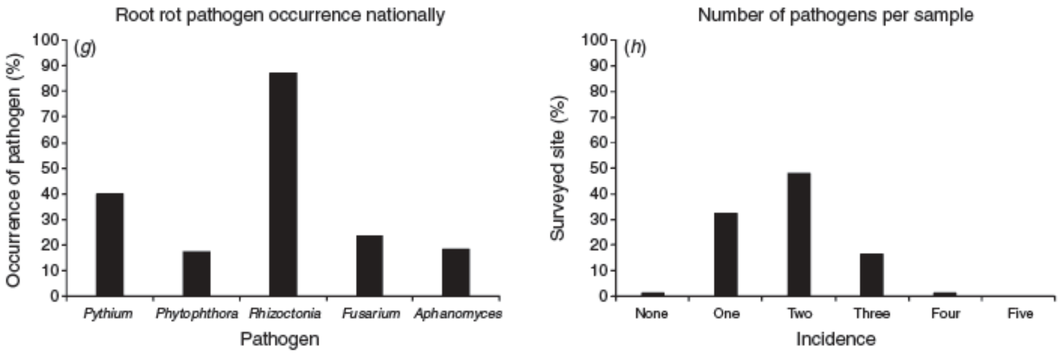

Figure 39. Pathogens isolated from diseased roots of subterranean clover (left) and number of pathogens isolated from each sample (right). From Foster et al, 2017.

- Factors that increased the severity of disease caused by *Rhizoctonia solani* included:
    - Cool temperatures (14–18°C day, 9–13°C night)
    - Dry conditions
    - Sandy soil (compared to loam)
    - Poor nutrition

5.2.3. Environment and nutrition

- Studies in Western Australia have demonstrated that adding a mix of nutrients to impoverished, sandy soils can reduce root disease of subterranean clover by 45%. Even simply adding K, N, Zn or Mo singly reduced symptoms, suggesting that improving plant nutrition helped the plant tolerate the presence of soilborne pathogens[191].
- Cultivation has also been demonstrated to reduce the symptoms and severity of root rot diseases, especially when combined with metham sodium fumigation. Following this treatment clover germinated and grew successfully, even in soils containing high residual populations of the virulent pathogen *Pythium irregulare*[192].

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[191] O'Rourke TA et al. 2012. Amelioration of root disease of subterranean clover (*Trifolium subterraneum*) by mineral nutrients. Crop Pasture Sci. 63:672-682.

[192] You MP et al. 2016. Cultivation offers effective management of subterranean clover damping-off and root disease. Grass Forage Sci. 72:785-793.

- Root knot nematodes have been associated with severe root rotting in complexes with soilborne diseases[193]. However, a study in WA found the opposite relationship, with a negative relationship between root disease and gall formation[194].

5.2.4. Conclusions

- A comprehensive study in WA of environmental effects on infection by *Pythium irregulare* demonstrated that temperature, soil type, moisture, plant nutrition and variety all significantly affect disease severity, with complex interrelationships between these variables. While trends were noted (e.g. less disease in sandy soils) the authors conclude that the relationships between pathogen and environment are extremely complex, with disease severity determined by as many as five different variables[195].

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[193] Powell NT. 1971. Interactions between nematodes and fungi in disease complexes. Ann Rev. Phytopathol. 9:253-274.

[194] Pung SH, Barbetti MJ, Sivasithamparam K. 1988. Associaiton of *Meloidogyne arenaria* with root rot of subterranean clover in Western Australia. NZ J. Exp. Agric. 16:91-96.

[195] You MP et al. 2017. Modeling effects of temperature, soil, moisture, nutrition and variety as determinants of severity of pythium damping off and root disease in subterranean clover. Frontiers Microbiol. 8:2223.

5.3. Mitchell grass dieback

Key Points

Mitchell grasses are a dominant pasture species in western Queensland. Despite their ability to survive prolonged dry periods, large areas failed recover following the millenium drought. An MLA report identified that dieback was reduced by short periods of heavy grazing during the dry and spelling during the wet, as this allowed the grass to tiller and set seed. Other useful management tools included rotational grazing, low intensity burns and intensively grazing sheep to eliminate weed species.

Mitchell grasses (*Astrebla* spp.) are the dominant pasture species on the cracking clay soils of central western Queensland. These are areas with average annual rainfall of 200-600mm, but which regularly suffer prolonged drought. The Mitchell grass survives due to its deep (~1.2m) root system and ability to enter a state of stasis during dry periods.

Figure 40. Mitchell grass growing well after rain, near Aramac, February 2015 Photo by J. Harris ABC Local.

Despite this ability, large areas of dormant Mitchell grass failed to recover from the 'millennium drought' from 2000 to 2006. An MLA report on Mitchell grass death following this extreme and prolonged drought[196] found that soil moisture fell below a critical limit for survival. When combined with a lack of seeds to regenerate the landscape, large areas failed to recover even once it rained. However, dieback was not uniform, and the report notes a number of useful management strategies including;

- Short periods (3-6 weeks) of high pressure grazing during the dry season and spelling during the wet season.
    - This strategy greatly increased survival compared to continual grazing, even at very low stocking rates, because it allowed the grass to develop new tillers and set seed.
- Avoiding soil compaction through rotational grazing.

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[196] Phelps D, Orr D, Houston I. 2007. Mitchell grass death in Queensland: extent, economic impact and potential for recovery. Final Report MLA project NBP.348

  - Occasional low intensity burns, followed by spelling over the following summer to allow grass to recover and set seed.
  - Heavy grazing (by sheep) during the early wet season to reduce growth of competing annual grass species.
  - Avoiding overgrazing following short bursts of winter rain (which result in phase 1 growth).

It was also noted that the key to increasing the ability of Mitchell grass to survive drought is likely to be in the soil. Soil structure, microbial activity and moisture infiltration are critical for maintaining healthy pastures.

6. Summary of potential causes of dieback

	Evidence for	Evidence against
Climate	• Dieback events tend to follow wet periods and are less severe during dry weather • Temperature and rainfall patterns are changing; higher temperatures, more extreme rain events increase plant stress	• Dieback occurs in regions with different climates • Dieback occurs in expanding patches, not uniformly across a region
Nutrition	• Low foliar phosphorus in dieback affected plants • Reddening of the leaf tips during early dieback resembles phosphorous deficiency • Deficiencies in phosphorous, sulphur, zinc and calcium can induce leaf reddening in buffel grass • Positive response to fertilisers (DAP, MAP) in field and glasshouse trials • Dieback occurs across different grass species in the same area • Poor nutrition reduces root growth and makes plants more vulnerable to drought, disease etc.	• Dieback is sudden, whereas soil nutrients have decreased gradually over ~50 years • Spread pattern is not consistent with nutrient deficiency • Dieback often worse in areas where pasture is growing strongly • High nitrogen can make dieback worse • Soil phosphorous increased under trees, but dieback can be worse in these areas

Mealybugs	• Found widely in dieback affected areas, including in soil • Insect injury can cause leaf reddening • Feeding causes physical damage to roots, consistent with observations of reduced root mass and root lesions; root diseases may be secondary infections of damaged areas • Spread of dieback patches consistent with movement of mealybug crawlers • Insecticides increase pasture growth and vigour • Dieback occurs across different pasture species, consistent with an insect pest • Mealybugs are known to have caused pasture dieback in NZ and previously caused dieback of paspalum in Qld • Dieback worse in areas protected from grazing e.g. roadsides, under fence-lines • Dieback worse after rain and where grass is thick; high RH favours insects • Dieback increased by N fertilisation and presence of N-fixing plants; increases nutritional value of grass • Temporary improvement after burning, consistent with elimination of foliar mealybugs but repopulation from those in the soil • Mealybug saliva reduces plant resistance to disease and environmental stresses	• Mealybugs not observed with dieback in original studies • Patches of dieback occur long distances from each other
Virus	• Leaf symptoms consistent with virus or mycoplasma • Pattern of spread consistent with an insect or disease vector	• No virus found in electron microscope examinations • Viruses not detected and not known to affect buffel grass • Symptoms occur across different species
Fungi	• Reduced root mass and lesions consistent with a soil borne disease • Extensive studies by Makiela support soil borne disease hypothesis • Torpedo root symptom typical of *Rhizoctonia* infection • Pathogens commonly isolated from dieback affected plants • Spread of patches consistent with a disease • Favoured by wetter conditions	• No consistent fungal species isolated • No clear results from numerous attempts to prove Kochs postulates for pathogenicity • No fungal hyphae visible in roots of dieback affected plants • Many different pasture species affected

7. Conclusions and Recommendations

Pasture dieback in Queensland presents a range of symptoms and observations, some of which appear contradictory. It often seems to occur where plants are growing best, where stock can't graze, and following periods of high rainfall. However, trials have found that dieback can be reversed through burning, fertilizing or re-sowing, suggesting that plants are lacking some vital input.

Dieback occurs in distinct, spreading patches, which slowly spread outwards. As no fungal lesions were visible on the upper parts of the plant, this immediately suggested that the grass was dying from a soil-borne disease. This was supported by observations of the roots, which were clearly stunted and damaged. However, diseases known to affect buffel grass do not produce the same symptoms as dieback. Moreover, attempts to isolate a pathogen and induce dieback in buffel grass plants have so far been unsuccessful. Also, although roots of plants with dieback have clear symptoms of damage, no fungal hyphae appear to be present within the root cells.

The initial symptoms of dieback are reddening of the older leaves, starting from the tips. Leaf reddening can occur either due to degradation of chlorophyll or accumulation of red and purple anthocyanins. In this case, the symptoms appear to resemble phosphorous deficiency, which stimulates anthocyanin production. This observation was confirmed by Makiela, who found that anthocyanin content had doubled in affected leaves.

Australian soils are low in phosphorous, which is a key limiting factor in buffel grass growth. Moreover, foliar phosphorous has been shown to be lower in dieback affected plants than in neighbouring healthy grass. However, the patchiness and spread of dieback is inconsistent with a nutritional disorder, which would be expected to cause a gradual loss of vigour over a widespread area.

If plants are already borderline deficient in phosphorous, it seems possible root injury could trigger the symptoms observed, as damage to the roots reduces transport of nutrients to the leaves. Moreover, both phosphorous deficiency and insect damage can trigger the jasmonic acid signalling pathway, which also increases anthocyanin accumulation.

New evidence suggests that mealybugs may be a key factor in dieback. While significant populations of these insects have been observed on the plant leaves, much greater numbers may be present beneath the soil. This hypothesis is supported by a number of independant pieces of evidence:

- Mealybugs have been reported to cause significant destruction in other pasture species, including ryegrass and paspalum
- Ryegrass pastures infected with endophytic fungi have improved resistance to mealybugs and are more productive
- Patches of dieback are roughly circular and expand slowly (5cm/week), which reflects the potential movement of mealybug crawlers

- Dieback has been observed on a range of other pasture species as well as buffel grass, which is consistent with the polyphagous adaptability of mealybugs
- Roots on plants with dieback are stunted, soft and dark with few small feeder roots present, suggestive of having been eaten or otherwise damaged
- The roots of affected plants have tyloses present in the xylem vessels while other cells are missing or disrupted, confirming that the roots vascular system has been penetrated and damaged
- Dieback often occurs first in areas where grass is growing long and thick, conditions likely to favour increases in insect populations
- Patches of dieback often appear following major rainfall events, as pasture dries out, conditions which are also likely to favour insect populations
- Dieback has frequently been observed in areas protected from or not grazed by cattle (such as along fence lines, under trees and inside fenced areas), which may favour survival by mealybugs on grass leaves

The evidence suggests that mealybugs are a key factor in pasture dieback. This mealybug has been identified as *Heliococcus* nr *summervillei*, as it is closely related to the mealybug that caused dieback of paspalum in the 1920's. However, mealybugs are not new in the Australian environment and have surely co-existed with pastures in the past. This raises the question of why now? And why is the damage so catastrophic?

The causes of plant dieback are often complex. While they may be catalysed by a specific disease, pest or climate event, mass dieback is often the result of numerous stresses. Changes in soil nutrients, fire regimes, animal grazing, climate and biodiversity can all increase cumulative damage on plants, until a single factor tips them past the point of no return. Thus, a soil-borne disease universally present can suddenly destroy large areas of clover, or a common insect or marsupial pest can kill the trees with which they previously co-existed.

This appears likely to be also the case with buffel grass, and indeed other pasture grasses in central eastern Queensland. Lack of nutrients (particularly phosphorous), poor soil health and loss of biodiversity seem likely to have contributed to the issue.

Possible, partial solutions include:

- Burning, to release phosphorous into the soil and control mealybugs on grass leaves. (NB managing frequency and intensity are likely to be critical to success and may only provide a temporary solution)
- Fertilisation, particularly with phosphorous, to improve plant health
- Introduction of endophytic fungi – an area of increasing interest worldwide, used to control insect pests in pastures
- Managing grazing intensity so as to allow pastures to grow plus set seed, reduce competition from woody weeds, and control mealybugs on grass leaves.
- Improving biodiversity and soil health through re-planting with a range of pasture species

- Re-vegetation, as has occurred in the northern tablelands of NSW, effectively slowing rural tree dieback and resulting in more productive, healthier pastures[197].

In summary, there is unlikely to be a single, easy solution for dieback of pasture grasses in central eastern Queensland. However, there are a number of management strategies which may be integrated to find a solution for this devastating problem.

ADD MANAGEMENT STRATEGIES HERE

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[197] Williams GT. 2017. Cost-effective landscape revegtation and restoration of a grazing poperty on the northern tablelands of NSW: 65 years of change and adaptation at 'Eastlake'. Rangland J. 39:461-476.