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Validation of a disease forecasting model to manage late blight (Septoria) in celery

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Purpose of project:
This project details the outcomes of a 2 year study of late blight of celery which investigated efficacy and economics of the TomCast disease forecasting model for timing fungicide sprays to control late blight without reducing quality or yield.

Report completed: November 2008.

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Media Summary

Model tackles sprays for celery late blight

Research has evaluated modifications to a computer model that can reduce the number of sprays for control of late blight in celery. Late blight is a fungal disease that attacks the leaves and stalks of celery crops as they mature. Celery is usually sprayed weekly to control late blight, which can result in up to 16 sprays being applied per crop.

The model showed that savings on sprays could be made in the early stages of crop production, before the plant canopy closed in. Most savings were made on winter crops. In these crops the model predicted a saving of up to 8 sprays.

The model is called TomCast and it uses weather data to forecast the appearance of late blight in crops. Temperature and leaf wetness data are collected by a weather station positioned in the crop and fed into a computer-based model. The model determines when to spray and when not to spray for late blight. If conditions are favourable for late blight and provided no sprays have been used in the last 7 days, then a spray is recommended. If conditions are not favourable for late blight then the model shows that no sprays are required.

Growth chamber studies showed the fungus produced spores at 8 °C. By modifying the model to start at this lower temperature beyond canopy closure, it was possible to also save sprays during the later phase of crop production. Although there are additional hardware and monitoring costs, the reduced spray program under the model, was as economical as weekly fungicide applications.

At present for winter celery crops the model calculates the need to spray when temperatures exceed 13 °C. Our research recommends a systemic fungicide 10 weeks after planting or at canopy closure and then the use of the model at a lower temperature of 8 °C to calculate the need for further spraying. More research is required to confirm the trial is repeatable in both summer and winter celery crops.

An economic analysis indicated that TomCast, when used as an IPM tool could increase profits by 0.78%.

Evaluations of alternative disease predictive models such as the Septoria and Cercosproa models indicated they either overestimated or underestimated the need to spray.

Laboratory experiments demonstrated that Vapour Pressure Deficit (VPD) calculations are not an alternative for leaf wetness sensors for use in disease predictive models.

Research by scientists at DPI's Knoxfield Centre was supported by funds from the Vegetable Industry, Horticulture Australia Ltd, the Department of Primary Industries Victoria and the Federal Government.

Technical Summary

Celery (*Apium graveolens*) is an intensively managed crop due to exceedingly high aesthetic standards and low damage thresholds. Late blight, caused by the fungus *Septoria apiicola* Speg., is a major foliage disease of celery. The high disease pressure from late blight in commercial celery crops is managed by weekly spraying with contact fungicide sprays, up to 16 times after transplanting. Growers are keen to reduce pesticide applications to minimise production costs, even if by only one spray. The public is also demanding fewer pesticides and less contamination of the environment.

During this 2-year study, two trials were conducted to evaluate modifications to the disease forecasting model TomCast. This model is a decision support tool for timing fungicide sprays for late blight control in celery. The model converts temperature and leaf wetness data, collected by a weather station in the crop, into disease severity values (DSVs) which are accumulated to reach a threshold for spray applications. An economic analysis appraised the cost effectiveness of the model for reducing sprays without compromising yield or quality.

The major findings were:

- The TomCast disease-predictive model for late blight in celery which estimates disease activity commences at 13 °C, requires modification, as our growth chamber studies demonstrated spore release was substantial at 10 °C, measurable at 8 °C, but sparse at 5 °C.
- The TomCast model is very effective as a decision support tool in the early stages of crop growth prior to canopy closure, where it can save 6–8 sprays with spray thresholds of 10 or 15 DSVs for winter grown crops. At 10 weeks, first lesions or canopy closure (whichever comes first), application of a registered systemic fungicide followed by weekly applications of chlorothalonil will produce an economic yield equal to weekly sprays, with yields based either on grower estimates or incidence data. An increase in profitability of 0.78% was achieved with the 10 DSV spray threshold of TomCast.
- This is the first report of the TomCast model being deployed until harvest, by reducing the start temperature to 8 °C at either 10 weeks, or first lesions or canopy closure (which ever comes first). This protocol reduced the number of sprays by 5 to control the disease and produced an economical yield, based on incidence data.
- The Disease Doctor™ computer program designed to deliver the TomCast model was validated and produced similar or better control of Septoria late blight than the Excel equivalent.
- Desk-top simulations of the Septoria predictor and Cercospora model, which have been touted as alternatives to TomCast for Septoria late blight control, overestimated or underestimated the number of sprays required, respectively, and are consequently inferior to TomCast.
- Gibberellic acid may have the potential to enhance late blight control as two applications in glasshouse trials considerably reduced lesion size and the number of pycnidia on lesions.
- Vapour Pressure Deficit (VPD) cannot be use to replace leaf wetness sensors under field conditions due to air movement.
- A fuzzy logic model which estimates leaf wetness based on measurement of temperature, relative humidity and wind speed predicted periods of leaf wetness under field conditions with an accuracy of only 75%.

Recommendations for future work:

1. Conduct a comprehensive field trial with the modified TomCast model on a commercial scale and in a commercial crop and report actual yield data, for all seasons and locations.
2. Test Gibberellic acid in field trials.
3. Refine the fuzzy logic model to replace leaf wetness sensors or alternatively develop a new generation leaf wetness sensors.
4. Refine the TomCast model using a lower start temperature. Based on our work, the active temperature range is 8–17 °C, which has a lower start temperature than the current model (13 °C

Chapter 1

Introduction

1.1 Disease predictive models

The influence of weather on disease is well known (Jones 1986). Disease predictive models are a mathematical description of an attempt to forecast the future development or appearance of a disease in a crop, based on climatic measurements made within the crop (Madden and Ellis 1988, Parry 1990, Galea and Minchinton 2005). Models can be based on climatic variables such as temperature, relative humidity, leaf wetness etc. and on an understanding of how the fungus reproduces and infects under field conditions (Fritt *et al.* 1989).

There are several motivations for use of disease predictive models (Fry and Fohner 1985). They can increase income by reallocating disease management resources to other areas of production. The risk of large unexpected crop losses is reduced. They provide the means to lower pesticide application to crops, which alleviates concerns for human health and pollution of the environment. Disease predictive models may assist in the management of fungicide resistance strategies by assisting the grower to identify the most appropriate timing for the application of systemic (curative) compounds. Consequently they are an ideal tool for integrated pest management (IPM).

Factors that contribute to growers' adoption of predictive models are (Kable, 1991; Maloy 1993, Polley 1983):
1. Significant economic losses are associated with the crop disease.
2. Economically viable control measures must be available.
3. Seasonal variability may make the appearance of the disease difficult to predict.
4. There must be validation of the model under local field conditions.
5. The system must be readily available to end-users.

Growers must be confident that measurable benefits can be expected from using the model that would be unavailable without its use. Attributes that will ensure the success of a model include: (1) reliability, (2) cost effectiveness, (3) simplicity, (4) importance to the industry, (5) usefulness and (6) availability (Campbell and Madden, 1990).

1.2 Current limitations of disease predictive models

There are a number of issues associated with disease predictive models:
1. They predict sporulation or infection based on historical microclimatic data, which means that the response time to apply fungicides may be limited.
2. They can overestimate sporulation or infection events. If the disease is not present in the crop and there are no obvious sources of spores in the field or farming area, the microclimate data can still predict sporulation or infection events.
3. They may require the tolerance of very low levels of symptoms in the field, as it may not be economically viable to completely eradicate the disease from the crop.

The accuracy of models could be improved by:
(i) Incorporating predicted microclimate or meteorological data into the model so it was truly a 'forecast' of expected events.
(ii) Thresholds for spraying obviously need to be set below the actual sporulation and infection parameters of the pathogen so contact, preventative fungicide applications can be employed. Generally models predict either sporulation or infection, however, the accuracy of models would be enhanced if they predicted both sporulation and infection. Spore trapping alongside collection of microclimate data would enhance predictive models.
(iii) The use of systemic fungicides with curative activity to remove infections, which may have taken place due to the lag time between:

(a) collection of microclimate data and output from the predictive model,
(b) the output from the model and the time to organize spraying of the crop.

1.3 Evolution of models for Septoria late blight on celery

The motivation for the development of a predictive model for Septoria late blight arose from concerns about the cost of production and the effects of pesticides on human health and the environment (Mathieu and Kushalappa 1993). Early field observations on the epidemiology of late blight showed that meteorological conditions had a huge impact on disease development. High rates of infection were associated with periods of heavy rainfall and average monthly temperatures below 25ºC (Berger 1970). Models have been developed for late blight based on *in vitro* studies and field observations. A weather station in the crop collects microclimate data which is fed into the models. Some models have been validated in the field and assessed for their economic viability.

A number of disease predictive models, based on either spore production or infection, have been developed and trialed to time fungicide sprays for late blight control in celery (Pitblado 1992, Mudita and Kushalappa 1993, Lacy 1994, Lacy *et al.* 1996, Reitz *et al.* 1999). An existing integrated pest management scouting program in Quebec initiates fungicide sprays for late blight only when the disease first appears in the field. Late blight can appear 30 days after transplanting but usually appears between 40-60 days. This program reduced the number of sprays applied from 10 fewer than 7 per crop in Canada (Mudita and Kushalappa 1993). In Australia late blight appears in summer and winter grown crops at approximately 40 and 70 days after transplanting, respectively (Minchinton et al 2005). Similarly, in Australia, preliminary trials with a predictive model indicated savings in spray applications could be made early in the crop's life (Minchinton et al 2005).

1.3.1 The action threshold model

Mudita and Kushalappa (1993) recognised that the disease appeared later in the crop's life and tried to delay spraying until a disease threshold was reached. They applied the first spray to transplanted seedlings at blight incidence levels of 0, 2, 4, 8 and 16% and then sprayed weekly. Yield losses occurred at all initial blight incidences, so it was not advisable to wait for the disease to appear before applying the contact fungicide, chlorothalonil. A systemic fungicide with curative activity may have been more successful as a first spray in their program. Interestingly there was no significant yield loss between 0 and 2% initial blight incidence.

1.3.2 The disease severity model

Mathieu and Kushalappa (1993) developed an infection model based on disease severity at various temperatures and ranges of leaf wetness. The number of lesions increased with temperatures of 10, 15 and 20 ºC but declined at 25 and 30 ºC and with increased hours of leaf wetness (12, 24, 48, 72 and 96 hr). The responses were divided into four disease severity values using cluster analysis, representing 'very low', 'low', 'moderate' and 'severe infection'. However, further research is needed to define and validate spray thresholds in the field and to evaluate infections below 10 ºC.

1.3.3 The Septoria predictor model

An infection model based on 12hr-leaf wetness was developed by Lacy (1994). Lesions formed on inoculated celery leaves within a period of 15 days only after 24 hrs of continuous or interrupted (12 hr wet - 12hr dry - 12hr wet) dew at 21 ºC. Fungicides were applied at a threshold of greater than or equal to 12 hrs of leaf wetness, if no sprays had been applied in the past 7 days, up to canopy closure and thereafter weekly fungicides sprays are applied. Temperature was not included in the model, as it was not a limiting factor in Michigan, where the model was developed. Temperatures below 10 ºC and above 30 ºC could be limiting factors at other locations. In 3 years of field trials in Michigan the model reduced by 2 the number of sprays of chlorothalonil per crop compared to weekly spraying, without sacrificing efficacy of disease control. Later trials in Michigan using the Septoria predictor generally saved 1-2 sprays (Bounds and Hausbeck 2004, Bounds and Hausbeck 2006a, Bounds and Hausbeck 2006b, Bounds and Hausbeck 2007) and at times 3-5 sprays when spraying commenced 4 weeks after planting (Bounds and Hausbeck 2008). Further north in Ontario only one spray was avoided with the Septoria predictor (Trueman *et al.* 2006, 2007). Fungicides applied with the model

were generally chlorothalonil and a strobilurin. The Septoria predictor is considered to give control of late blight equal to weekly sprays (Trueman *et al.* 2007), although Bounds and Hausbeck (2007) found the results could be inconsistent.

1.3.4 The Cercospora model

An infection model to predict *Cercospora apii*, the cause of early blight in celery, was developed by Berger (1969a, 1969b). The original model used temperature, relative humidity (RH) and a spore trap, but later versions have omitted the spore trap. The current version consists of applying a fungicide spray if all the following criteria are met (Bounds and Hausbeck 2007, Raid *et al.* 2007):

1. No fungicides applied during the previous 7 days;
2. ≥ 12h of ≥ 90% RH were recorded the previous day (0700 yesterday to 0600 today);
3. Mean temperature was at least 15 but not above 27°C during the previous day (0700 yesterday to 0600 today);
4. Temperatures 3 days ago were ≥ 12°C, or if the temperatures fall below 12°C the mean night temperature (2200 to 0700) on each of the 2 succeeding nights was ≥ 15°C with a mean RH ≥ 95%.

The Cercospora model has been trialled in Michigan on several occasions for control of late blight and reduced the number of sprays by 2 to 6. Parameters measured such as incidence of late blight and yield of celery are often higher but not significantly different from levels of control achieved with weekly spray programs (Bound and Hausbeck 2004, 2007). Again, fungicides applied with the model were generally chlorothalonil and a strobilurin. Bounds and Hausbeck (2007) reported the Cercospora model could produce inconsistent control of late bight.

1.3.5 The TomCast model

The TomCast disease-forecasting model is based on sporulation and was modified from the earlier FAST model of Madden *et al.* (1978). FAST was originally developed to predict the sporulation of *Alternaria solani* on tomatoes and is based on periods of leaf wetness and temperature which score disease severity values (DSVs); (Table 1.1). A scale of DSVs is derived from the number of hours of leaf wetness in a temperature range. Daily DSVs are calculated at 11.00am and accumulated until a spray threshold is reached. A period of two hours leaf dryness is required to interrupt a leaf wetness period. If leaf wetness extends 3 hours beyond 11.00 am (i.e. 2.00 pm), then it is included in the 11.00 am calculations. When a nominated threshold is reached, an appropriate fungicide is sprayed to prevent late blight. If conditions are not conducive to sporulation and the threshold is not reached then fungicides are not sprayed.

Table 1.1 The TomCast disease predictive model (Reproduced from Madden *et al.* 1978)

Mean temperature (°C)	Leaf wetness periods (in hours) required to produce daily disease severity values				
13-17	0-6	7-15	16-20	21+	
18-20	0-3	4-8	9-15	16-22	23+
21-25	0-2	3-5	6-12	13-20	21+
26-29	0-3	4-8	9-15	16-22	23+
DSV	0	1	2	3	4

DSV = Disease Severity Values (scored 0-4).
0 = conditions unfavourable for spore formation.
4 = conditions highly favourable for spore formation.

Since its inception TomCast has been evaluated for predictions of several diseases such as *Septoria lycopersici* and *Colletotrichum coccodes* on tomatoes (Pitblado 1992, Gillespie *et al.* 1993); *Cercospora carotae* and *Alternaria dauci* on carrots (Bounds *et al.* 2006, 2007; Rogers and Stevenson 2006); *Septoria apiicola* on celery (Reitz *et al.* 1999, Trueman *et al.* 2005, 2006, 2007, Bounds and Hausbeck 2007, 2008); *Stemphylium vesicarium* on asparagus (Myer *et al.* 2000) and *Stemphylium* spp. on tomatoes (Bolkan and Reinert 1994).

DSV thresholds to commence spraying were initially high when TomCast was first evaluated as a decision support tool to manage spray applications for late blight, but DSV thresholds now suggested are much lower. Reitz *et al.* (1999) reduced by one the number of fungicide sprays for late blight using an initial threshold of DSV30 reducing to DSV20 at canopy closure for celery grown in California. A conservative accumulation of DSV20 is now recommended in the US (Phillips 2005). In Michigan, Bounds and Hausbeck (2006a, 2006b, 2007) working on artificially infected crops used a TomCast spray threshold of DSV10 and reduced by 1–5 the number of sprays until canopy closure, whilst maintaining yields comparable to weekly sprays programs. They found DSV15 produced inconsistent yields and DSV20 had unacceptable levels of disease compared with weekly spray programs. A DSV20 was suggested as a spray threshold for natural infections of late blight. More sprays could be saved (2–6) if spraying did not commence until 4 weeks after transplanting using the TomCast spray threshold of DSV10. Trueman *et al.* (2006, 2007) working with inoculated crops in Ontario found that TomCast spray thresholds of DSV10 reduced by 1–3 the number of sprays, DSV15 and DSV20 reduced by 2–5 the number of sprays up till canopy closure, but the latter exhibited too much disease. In Australia more sprays were saved but only in the early stages of crop production prior to canopy closure. In summer crops the number of sprays were reduced ny 3-5 using TomCast DSV15, 20 and 25; and by 7–8 sprays in winter crops using TomCast DSV10, 12, 15 and 20 with no difference in late blight when compared with the weekly spray schedule (Minchinton *et al.* 2005).

All celery produced for Campbell's Soup Company in the USA now uses the TomCast model to time fungicide sprays for late blight. Growers using the model have reduced the number of sprays by 9–12 per year, but the spray threshold is not stated (Bolkan and Reinert 1994). TomCast was successfully used in the Netherlands to improve the timing of chlorothalonil sprays (Schepers and Meiers 1998).

1.4 Chemical usage with predictive models

Chlorothalonil, or a combination of chlorothalonil and copper, both of which have multi-site activity, were the fungicides generally sprayed with the disease predictive models (Mudita and Kushalappa 1993, Phillips 2005). Benomyl, chlorothalonil and propiconazole (DMI) were used by Reitz *et al.* (1999). More recently an array of strobilurin fungicides or combinations of a strobilurin and chlorothalonil (Grumet and Hausbeck 2003, Bounds and Hausbeck 2007, 2008), or strobilurin and boscalid were alternated (Trueman *et al.* 2007). Combinations of a systemic fungicide and chlorothalonil are considered to give the best control of late blight (McDonald 2004). Overseas, when disease predictive model thresholds have been used to time fungicide sprays for late blight control, there was a tendency for excessive use of strobilurin fungicides, even though they may be alternated with contact fungicides.

1.5 Economics of predictive models to control late blight

In California, savings of $US45/ha using a TomCast spray threshold of DSV30 reducing to DSV20 at canopy closure were reported by Reitz *et al.* (1999). In Michigan, a TomCast spray threshold of DSV10 until canopy closure saved $US213–215/ha and the Septoria predictor saved $US71/ha (Bounds and Hausbeck 2007, 2008). In Ontario, TomCast DSV10 saved $C87–169/ha and the Septoria predictor model saved $C41–76/ha, depending on the spray program (Trueman *et al.* 2007). Grumet (2003) noted the TomCast model saved the most money, followed by the Cercospora model and lastly the Septoria predictor. All authors, except Reitz (1999) based the economics of the models only on the cost of fungicides. Reitz (1999) also included application, shipping and scouting cost, but the latter were considered negligible. None of the researchers included depreciation and operating costs of the weather stations or interpretation of the model predictions.

1.6 Deployment issues associated with weather stations and late blight models

Weather data for input into models to predict late blight is always collected on a microclimate level which necessitates a weather station in each planting or crop of celery. Even though the cost of weather stations has declined over the years, they are still considered too expensive by growers to place one into each planting or crop.

To reduce the cost of weather stations there is the potential to collect data from one station and use it to predict disease thresholds in several crops in an area. Weather stations in crops are also subject to mechanical damage from machinery. Sensors are exposed to weathering and corrosion by pesticides, which can generate unreliable data, especially leaf wetness data. An option to avoid mechanical damage and share weather station data between crops to reduce costs was to locate the weather station in turf outside, but near the crop. The main contributor to leaf wetness is dew and its formation in turf and crops is similar in temperate zones (Gleason *et al.* 1997, Kim *et al.* 2002, 2006, Sentelhas *et al.* 2005). This scenario may not be appropriate for Australian celery crops as they are overhead irrigated, often at different times and a weather station located outside the crop may not record leaf wetness associated with irrigation. Also Minchinton *et al.* (2005) working with the DownCast predictive model on spring onions reported variation in weather data collected in crops planted only a week apart and variation in data collected across a bay, which consequently produced different spray predictions. Additionally there is generally only one leaf wetness sensor on a weather station which is moved upward as the canopy grows, so leaf wetness of the lower canopy, especially in older celery crops, is not taken into account. There is a need to find a new generation, more robust leaf wetness sensor, less susceptible to weathering, or a method of calculating or estimating leaf wetness in the entire canopy.

Another issue is the historical rather than forecast nature of the data collected. The historical nature of predictive models albeit only 24 hours old, may not give growers sufficient warning to organize spray applications for crops to control fungal diseases. Pathogens can often set up processes of infection within 3 hours, for example *Peronospora parasitica* (Channon and Hampson 1968). If there is a risk the pathogen may have already infected the crop then systemic rather than protectant fungicides are necessary. The repeated used of systemic fungicides increases the risk of pathogens developing fungicide resistance.

1.6.1 Data and data access

To overcome problems of weather station costs, deployment and the historical nature of weather data collected on site in the microclimate, several models have been developed to calculate and collect leaf wetness and other weather data parameters in advance. These are: (i) Vapor pressure deficit (VPD); (ii) models to forecast site specific leaf wetness duration, and (iii) the SkyBit™ e-weather forecasts.

VPD identifies when condensation and consequently leaf wetness is likely to occur. It requires the measurement of air temperature inside the canopy and air temperature and RH outside the canopy. It can be calculated using a mathematical model or read from a graph. One of its main applications is to predict condensation in glasshouses (Prenger and Ling 2000).

Three models have been developed to forecast site specific leaf wetness duration for input into disease predictive models; the classification and regression tree/stepwise linear discriminant model (CART/SLD/wind or CART; Gleason *et al.* 1994, Kim *et al.* 2002), the fuzzy logic model (FL; Kim *et al.* 2004); and the corrected fuzzy logic model (CFL; Kim *et al.* 2005). The CART model input variables are dew point depression, wind speed and RH. The input variables for the FL model are air temperature, RH and wind speed. The CFL model requires the same inputs as the FL model but consists of a correction factor for systematic errors in input data based on statistical analysis of historical data. These models can use either on site or remote data and could access data from many already deployed weather stations which do not have leaf wetness sensors attached.

SkyBit™ is a site specific electronic weather information service for the United States, northern Mexico and southern Canada. It provides 3-hourly forecasts for a number of parameters such as temperature, RH, rainfall, wind speed and direction etc. over 0–48 hours and can directly generation spray thresholds (DSVs) for the TomCast disease predictive model. The accuracy of forecast may be satisfactory for processing crops, such as tomatoes, where the whole plant is not harvested only the fruit, and as it is for processing, the quality of the fruit does not have to be perfect. The forecasts,

however, may not be accurate enough for crops of high aesthetic standards where the whole plant is harvested, such as celery.

Simulations to predict spray thresholds were conducted for the Melcast and TomCast models to compare the CART, FL, CFL and SkyBit™. These models were useful when site specific data was not available (Kim *et al.* 2002). The CART model was the most accurate and consistent for estimating leaf wetness duration but the accuracy needed to be improved for site-specific forecasts in practice (Kim *et al.* 2006). Similar information is available from the Australian Bureau of Meteorology (BOM).

If any of these models or data collection methods were to be used to generate leaf wetness duration then the effects of overhead irrigation on duration of leaf wetness need to be taken into account. To minimize effects of overhead irrigation on leaf wetness duration, crops would have to be irrigated at dawn when dew would normally be expected to occur on crops. The advantage of accessing forward leaf wetness duration, even if only estimated, could impact on disease predictive models by predicting when a spray threshold could be reached. This scenario would give a grower time to organize spraying a crop with cheaper protectant fungicides before a sporulation or infection event rather than using more expensive systemic fungicides after the potential infection or sporulation event.

1.7 Celery

Celery (*Apium graveolens* L.) is an intensively managed crop due to exceedingly high aesthetic standards and low damage thresholds. It requires weekly fungicide applications for control of late blight. Up to 16 fungicides sprays can be applied after seedlings are transplanted from the glasshouse at 8 weeks of age. The high cost of chemicals and labour and the frequency of spraying are a major cost for growers. Growers are constantly seeking ways to reduce the cost of production, whilst maintaining control of the disease without reducing yield or quality.

Nationally the cost of fungicide applications is estimated at $1.7M (chapter 4) in an industry which grew 991ha of celery and had a gross value of $42.2 M in 2007 (Table 1.2).

Table 1.2 Production and value of celery industry in Australia (2006-07, ABS)

State	Area (ha)	Area (%)	Production (tonne)	Yield (tonne/ha)	Production (%)	Gross Value ($M)
Victoria	661	66.7	38,828	54	26.0	30.2
Queensland	125	12.6	7,119	57	27.5	6.7
Western Australia	150	15.1	4,545	30	14.5	4.5
South Australia	27	2.7	275	10	4.8	0.2
New South Wales	13	1.3	174	13	0.6	0.2
Tasmania	14	1.4	600	43	20.7	0.6
Total	991		51,041	207		42.2

1.8 The Disease – Septoria Late Blight

The fungus *Septoria apiicola* Speg. causes the disease late blight of celery (*Apium graveolens* L.) and celeriac (*Apium graveolens* var. *rapaceaum* DC.). It is a major foliage disease causing losses of 50–90% in commercial crops (Sherf and MacNab, 1986, Lacy and Cortright 1992). Crop losses from late blight are associated with defoliation, slower growth rates, increased labor costs for trimming diseased leaves and petioles, and post harvest rots. Late blight occurs worldwide and generally forms on older leaves later in the crop's life (Walker, 1952, Sutton and Waterston 1966, Mudita and Kushalappa, 1993, Cerkauskas, 1994).

1.8.1 Symptoms

Symptoms of late blight initially appear as chlorotic spots on leaves and petioles, which later turn necrotic (Fig. 1.1). They can range up to 10 mm in size. Spots on heavily infected leaves may coalesce causing leaf blight and later death. Embedded in the spots are black pimple-like pycnidia

containing long flexuous or rod-shaped, 3–5 septate conidia (spores) (Sutton and Waterston 1966). There are estimated to be about 1500 to 5400 spores per pycnidium, on average 56 pycnidia per spot and 2,000 spots per plant, thus up to half a billion spores could be produced on one plant (Lin 1939). Ten or more spores are necessary for an infection (Sherf and MacNab 1986). No sexual stage has been reported (Sutton and Waterston 1966, Hausbeck, 2002). Early descriptions of *Septoria* on celery suggested there were two distinct species associated with symptoms of large and small spots (Cochran 1932), but a study of world-wide isolates of the large and small spot forms lead to the recognition of only one species (Gabrielson and Grogan 1994).

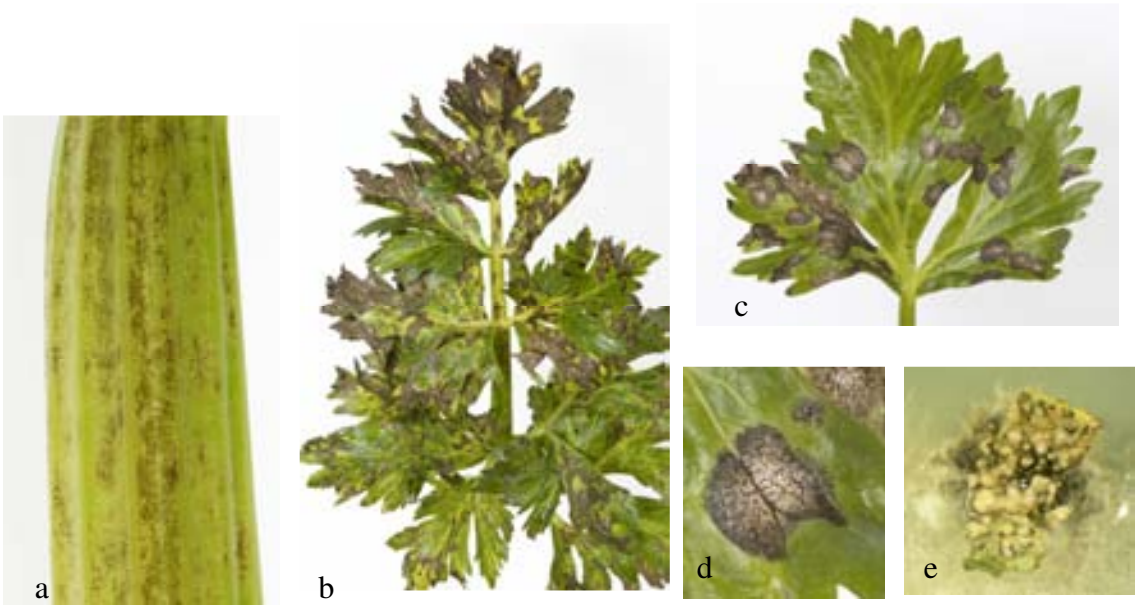

Fig 1.1 Symptoms of late blight. (a), Lesions on petiole; (b), leaf spots and blight on leaf; (c), leaflet with leaf spots; (d), close-up of leaf spot showing dot-like pycnidia; (e), gelatinous tendrils of conidia oozing out of pycnidia in culture.

1.8.2 Dispersal

S. apiicola is dispersed by seed, crop debris and adjacent infected crops. The mycelium of *S. apiicola* has not been found inside seed (endosperms and embryos), but has been detected on the outside of seeds in pericarps and testas (Sheridan 1966, Cerkauskas, 1994, Hausbeck 2002). Pycnidia can be found on seed, but their viability decreases with time. Mycelium and pycnidia can survive on stored seed up to 15 months (Sheridan 1966), but not longer than 2 years (Sutton and Waterston 1966). Viability of contaminated celery seed can drop to 2%, 8 months after harvest (Sutton and Waterston 1966). When contaminated seed germinates, infected seed coats may remain attached to the cotyledons and when these are wet, spores ooze from them onto cotyledons resulting in infection (Cerkauskas 1994).

The fungus can survive in crop debris for 11 months, in buried crop debris for 18 months but not for more than 2 years (Sutton and Waterston 1966). Spores, however, only survived for 7 months in crop debris (Maude and Shuring 1970). Survival is shorter during warmer conditions. In the absence of host plant tissue, spores only survived for 6 weeks (Sutton and Waterston 1966, Sherf and MacNab 1986, Cerkauskas, 1994).

In the field, spores are exuded from pycnidia in long gelatinous tendrils during wet weather. They are dispersed by irrigation water, rain splash, wind driven rain (Fritt *et al.* 1989), by contact with machinery, animals or workmen's tools (Linn 1939) especially as the canopy closes over (Chupp and Sherf 1960). In this way the spores are readily moved from plant to plant and crop to adjacent crop.

1.8.3 Disease development

1.8.3.1 Spore germination

Spores germinate on water agar within 12 hr at 20–22.5ºC. The temperature requirement for germination is 5–25ºC, with no germination at 30ºC after 30 hrs (Sheridan 1968a). If relative humidity (RH) is above 95%, free water is not required for germination (Sheridan 1968a), but on celery leaves spores generally germinate and infect in a thin film of water, eg. dew (Schein 1964).

1.8.3.2 Infection

The fungus directly penetrates the epidermis or enters the plant via the stomata (Donovan *et al.* 1990, Hausbeck 2002). After infection, hyphal growth is intercellular and occasionally intracellular when leaves are necrotic (Donovan *et al*. 1990). During warm conditions, 21–27°C, the time from infection to lesion appearance is 7–8 days. At cooler temperatures (18ºC) lesions take 12 days to appear. Mathieu and Kushalappa (1993) quantified the relationship between leaf wetness and temperature in growth chamber studies. They found at temperatures of 10, 15 and 20ºC and increasing periods of leaf wetness up to 96 hrs, increased numbers of lesions, but at 25ºC and 30ºC fewer lesions were formed.

High levels of precipitation promoted disease development (Walker 1952, Sheridan, 1968a, Berger 1970), and relative humidity below 90% limited infection (Sheridan 1968a). In the field infection did not occur when mean RH was < 90% for 2 days following inoculation (Sheridan,1968b).

The time from infection to spore production is generally 10–12 days (Cerkauskas 1994). Lesions develop on susceptible celery in 10 days whilst in more resistant celery varieties, lesions can take 16–21 days to develop (Hausbeck 2002). Late blight generally forms on older leaves later in the crop's life (Walker 1952, Cerkauskas 1994). It can appear as early as 30 days after transplanting but more commonly at 40–60 days (Mudita and Kushalappa 1993). Late blight is a polycyclic disease. It can complete its lifecycle many times during the crop's life (Fig. 1.2).

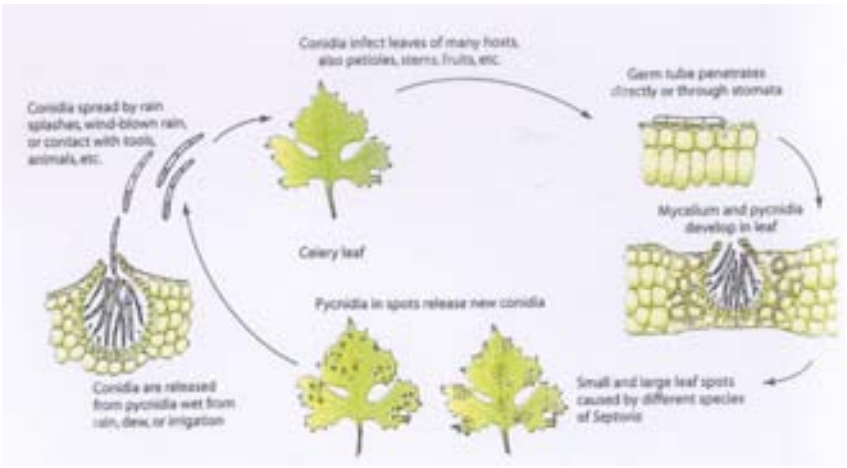

Fig 1.2 Life-cycle of *Septoria apiicola* (modified from Agrios 2005).

1.9 Controls

1.9.1 Chemicals

Early, fungicide control of late blight centered on inorganic compounds, Bordeaux and other copper based fungicides and later moved to the dithiocarbamate and cyclicimide fungicides which have multi-site activity (Avcare). The introduction of systemic fungicides appears to have occurred in three phases. Firstly fungicides from the benzimidazole activity group were introduced, then the DMI triazoles activity group and more recently the strobilurin activity group. All greatly improved control of late blight, however, fungal resistance and occasionally fungicide phytoxicity occurred.

Other chemical options such as, adjuvants, antibiotics and bio-controls have been trialed but with variable results.

Protectant fungicides for late blight control have included were Bordeaux, tribase copper, copper hydroxide, sulphur, chlorothalonil, maneb, ziram, zineb, nabam, propineb, captafol, anilazine, and captan (Chupp and Sherf, 1960, Sutton and Waterston 1966, Lacy, 1973, Aloj and Garibaldi 1982, Sherf and MacNab 1986, Chinchilla and Mora 1986, Lacy and Cortright, 1992). Their application was usually recommended on a 7–14 day preventative spray schedule, but under conditions of very high disease pressure they gave only partial control and some growers applied 3 or more chemical sprays per week to control late blight (Berger 1970, Sherf and MacNab 1986). Today chlorothalonil is probably the most commonly applied protectant fungicide for late blight, but it is classified as a B2 carcinogen, so many celery growers are keen to reduce its usage (Bounds and Hausbeck 2007).

The early systemic fungicides for late blight control included benomyl, carbendazim and thiophanate-methyl (Paulus *et al.* 1970, 1979, 1980, Vulsteke and Meeus 1981, 1986). The emergence of fungal resistance to benomyl and carbendazim (Paulus *et al.* 1979, Gladders and McKeown 1985), led to spraying contact and systemic fungicides either in combination or alternation, such as benomyl + chlorothalonil, or benomyl alternated with chlorothalonil (Paulus *et al.* 1979, 1980, Vulsteke and Meeus 1981, 1986). Fungicide resistance did not always eventuate but Spanish isolates of *Septoria* were still sensitive to benomyl and carbendazim in the early 1990s (Sorribas and Izquierdo 1992).

Later systemic fungicides used for late blight control have largely come from the triazole group. Propiconazole showed curative and eradicative activity along with diclobutrazole, penconazole, myclobutanil, flusilazole, fenarimol, tebuconazole and triadimenol (di Marco 1987, Wicks 1989, 1990, Amer *et al.* 1993a, 1993b). Propiconazole, flutriafol, and combinations of propiconazole and contact fungicides (anilazine or chlorothalonil) have been effective against late blight in the field (Brunelli *et al.* 1989, Wicks 1989, 1990, Amer *et al.* 1993a, 1993b). Penconazole, myclobutanil and flusilazole were unsuitable for late blight control in the field, although they were effective on glasshouse seedlings (Wicks 1989). The addition of adjuvants to low concentrations of carbendazim, flutriafol and propiconazole produced efficacy as good as or better than the fungicide sprayed alone (Amer *et al.* 1992, 1993a). However, addition of adjuvants triadimenol and tebuconazole reduced their efficacy of (Amer *et al.* 1993b).

More recently the strobilurin group of fungicides which includes azoxystrobin, pyroclostrobin, and trifloxystrobin or combinations of them with contact fungicides, has been extensively trialed (Hausbeck *et al.* 2002, Bounds and Hausbeck 2004, 2007, 2008). All have had excellent efficacy, but the frequency of sprays, sometimes up to nine per crop, raises the risk of fungi developing resistance to this fungicide group (FRAC 2005). They have been designated as 'reduced health risk' by the US EPA, but exclusive use has lead to resistance in cucurbit powdery and downy mildews (McGrath, unpublished).

Alternative options for late blight control have been variable. *In vitro* trials demonstrated that the antibiotics kasugamycin and polyoxin-B were highly effective for *S. apiicola* (Sorribas and Izquierdo 1992). The biocontrols *Trichoderma harzianum* partially controlled late blight when applied weekly or 5 days before inoculations with the fungus but gave no control after inoculation with *S. apiicola* in glasshouse trials (Ciccarese *et al.* 1995). Field trials with Messenger (harpin) or Serenade (*B. subtilis)* alternated with chlorothalonil and applied over 10 weeks did not improve control of late blight compared with only chlorothalonil sprays (Bounds and Hausbeck 2004). Phosphonic acid had no efficacy for late blight control in Queensland (Heaton and Dullahide 1990), nor did neem kernal extract (Rovesti *et al.* 1992).

1.9.2 Seed treatments

Seed is considered a major source of *S. apiicola* inoculum and a number of methods have been developed to produce pathogen-free seed. The fungus generally does not survive on seed for more

than two years, so storage of seed for this period of time generally eliminates contamination. A seed soak in 0.2% thiram for 24 hr at 30ºC or a hot-water at 47–49ºC for 30 min. reduced inoculum (Walker 1952, Cerkauskas 1994, Hausbeck 2002). Maude (1970) reported the thiram seed treatment was superior to a hot water treatment of 50ºC for 25 min. (Bant and Storey 1952, Maude 1964). In addition it had no adverse effect on germination compared with the hot water treatment. Wilson (1974) found more losses in germination with thiram 0.25% for 24 hr at 30ºC compared with a hot water treatment of 50ºC for 30 min. An alternative to thiram was a captan dusting reported by Dullahide (1979). A combination of plant growth regulators (PGRs) and a benomyl seed soak at 20ºC for 24 hr completely eliminated *S. apiicola* from seed and broke dormancy (Humpherson-Jones *et al.* 1984, Gott *et al.* 1989). Aerated steam completely eradicated *S. apiicola* from seed, however, an expensive machine is a prerequisite for this treatment (Navaratnam *et al.* 1980).

1.9.3 Genetics

Resistance in celery to *S. apiicola* is recessive and polygenic (Bohme 1960). It has been recognized for some time that wild *Apium* species are sources for resistance in celery (Ochoa and Quiros 1989). Edwards *et al.* (1996) developed a visual key of symptoms to identify resistance to *S. apiicola*, which they found in wild celery lines, lovage and parsley. Some resistance was identified in celery varieties crossed with wild celery, and in the variety Giant Red, but none was found in other celery varieties tested. Breeding for resistance to *S. apiicola* has been undertaken with both conventional and molecular approaches (Moravec *et al.* 1988, Quiros 1993). Donovan *et al.* (1993) found resistant celery had higher essential oil contents, which were inhibitory to *S. apiicola* and suggested they could be used as a tool to identify resistant varieties. Perhaps the most interesting source of resistance was identified from somaclonal variants. Plants regenerated from single cells or cluster of cells showed variation in responses to *S. apiicola* ranging from susceptible to resistant, which suggests that not all plant cells are uniformly susceptible to the pathogen (Wright and Lacy 1985, 1988, Rappaport *et al.* 1991, Donovan *et al.* 1994, Evenor *et al.*1994).

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Chapter 8

General discussion and conclusions

The current research has clearly demonstrated spore release at temperatures below that assigned to the model TomCast, and others in use worldwide. At both 8 and 10 °C, there was a measurable increase in spore numbers over a 24-hr period, contradicting the earlier assertion that spore release was inconsequential below 13 °C (e.g. Phillips 1999). Only 10 spores are required for infection to be initiated (Sherf and McNab 1986), and as spores are spread by rain splash and celery plants are grown under over head irrigation; the disease has the potential to spread even at low temperatures.

It is also well established that spore germination can occur below the 13 °C threshold of the TomCast model (Sheridan 1968). In addition, infection by Septoria late blight was shown to occur (Tvede 2006), albeit at a lower severity level than optimum conditions (Green *et al.* 2002). However, infection at these lower temperatures cannot be discounted when investigating models for a polycyclic disease (Agrios 2005).

This investigation is the first to use the disease predictive model TomCast to harvest by reducing the start temperature in the latter phase of crop production to 8 °C. TomCast is an IPM option for Septoria late blight at either 10 or 15 DSV 13 °C – systemic fungicide at 10 weeks, first lesions or canopy closure (which ever comes first) - 10 DSV 8 °C up to harvest, as it reduced a total of 15 sprays. These modifications led to a comparable harvest, based on grower estimates but not on incidence estimates), when compared to the industry standard, since the loss in yield was offset by the reduction in chemical use and labour (see Chapter 4).

A less risky IPM strategy is to use TomCast at either 10 or 15 DSV 13 °C + systemic fungicide at 10 weeks, first lesions or canopy closure (which ever comes first) then revert to weekly sprays of the protectant fungicide. Whilst this strategy only reduced by 8 the number of sprays in the early phase of crop production, production was similar to the weekly spray program for both the grower and incidences estimates of yield (see chapter 4). The 10 DSV option increased profits the most, by 0.78%.

'Estimated' cost benefits:

Total cost of applying weekly fungicide sprays ……..= $1,689/ha
Cost of treatment 2 which improved profits by 0.78%
(10 DSV 13 °C + systemic fungicide at 10 weeks,
first lesions or canopy closure then weekly sprays
of the protectant fungicide)……. = $1,298/ha
Estimated benefit…….. = $391/ha
Estimated benefit industry wide, assuming 991 ha of production……= $0.5M approximately
On an industry basis the disease predictive model TomCast, used as an IPM tool, could save $391/ha or approximately $0.5M industry wide in fungicide sprays.

In laboratory trials *S apiicola* conidia were fully viable after 4 days in free water, which suggests that water on beds, in furrows, channels or puddles could be a means for inoculum to spread this disease. It is well known that late blight can be spread by workers and machinery moving through a wet celery crop. (Fitt *et al.* 1989).

Gibberellic acid may well be another piece of an IPM strategy against late blight, since 2 applications in glasshouse studies reduced both lesion size as well as total pycnidia numbers on infected leaves. If this could be applied in the field, it may lead to a dramatic reduction in the pathogen pool in celery crops and thus result in less severe outbreaks of Septoria late blight.