THE USE OF POTATO AND MAIZE DISEASE PREDICTION MODELS USING AUTOMATIC WEATHER STATIONS TO TIME FUNGICIDE APPLICATIONS IN KWAZULU-NATAL

by

Neil Craig van Rij

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Faculty of Science and Agriculture

University of Natal

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ABSTRACT

Maize grey leaf spot (GLS), caused by *Cercospora zeae-maydis,* and potato late blight (LB), caused by *Phytophthora infestans,* are foliar diseases of maize and potato, two of the most widely grown crops in KwaZulu-Natal (KZN), after sugarcane and timber. Commercial maize in KZN accounts for just on 4.3% of the national maize crop. This is worth R563 million using an average of the yellow and white maize price for the 2001/02 season (at R1 332.87 ton^{-1}). In 2003 KZN produced about 5% of the national potato crop (summer crop: 7 531 300 10kg pockets from 2243 hectares). This equates to a gross value of R89.4 million based on an average price of R1 188 ton^{-1} in 2001. Successful commercial production of maize and potatoes depends upon control of these diseases by translaminar fungicides with highly specific modes of action.

This study extends an existing model available for timing of fungicide sprays for GLS and tests and compares two LB models for two calendar-based spray programmes. The study also evaluated the use of an early blight model which is caused by *Alternaria solani*, and over the single season of evaluation showed potential for use in KZN. For the GLS model it was found that a number of refinements are needed, *e.g.*, the amount of infected maize stubble at planting and not the total amount of maize residue at planting.

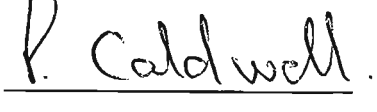
Based on two years' data, it was found that for the LB models there are no significant differences in levels of control between using a predicted fungicide programme and a calendar-based programme. The importance of knowing initial infection sites, and hence initial inoculum, was demonstrated. This led to the creation of a KZN LB incidence map, now being used to more accurately time the start of a preventative spray programme and to time the inclusion of systemic fungicides in the preventative spray programme.

This study has contributed to the further development and expansion of the Automatic Weather Station Network (AWSN) at Cedara, which now comprises 15 automatic weather stations in KZN. The AWSN is currently used to aid farmers and advisers in decision-making regarding fungicide spray timing for GLS and LB.

DECLARATION

I, Neil van Rij, declare that the research reported in this thesis, except where otherwise indicated, is my own original research. This thesis has not been submitted for any degree or examination at any other university.

Neil Craig van Rij



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CHAPTER 2

DESCRIPTION AND SENSITIVITY ANALYSIS OF A MODEL (SPRAYAID) FOR TIMING OF FUNGICIDE APPLICATIONS FOR *CERCOSPORA ZEAE-MAYDIS*

CHAPTER 3

EVALUATION OF THE MAIZE GREY LEAF SPOT MODEL (SPRAYAID) IN THE TIMING OF FUNGICIDE SPRAYS AND FORECASTING OF MAIZE GREY LEAF SPOT EPIDEMICS

GENERAL INTRODUCTION

The purpose of this research was to investigate modelling grey leaf spot (GLS) of maize caused by *Cercospora zeae-maydis* Tehon and Daniels and late blight (LB) of potatoes caused by *Phytophthora infestans* (Mont.) de Bary. These two pathogens are yield limiting in both commercial and small-scale agriculture. At the time of writing GLS is not as important as it once was due to the selection of tolerant/resistant cultivars available. Modelling was used to calculate correct timing of control measures, *i.e.* when is the optimum time to apply a fungicide spray ? Using recorded weather data it is possible to predict the growth and development of a pathogen. This is illustrated in the potato LB model from Plant-*Plus* (Dacom, Emmen, Netherlands www.dacom.nl). The Plant-*Plus* models use recorded weather data to predict:

- spore development
- spore germination
- number of spores generated from the crop
- infection chances based on recorded weather, the previous calculated spore development, germination and creation.

Further inputs to the model are cultivar tolerance to LB, size of land planted purpose of use and fungicides applied.

The maize GLS model is a mathematical model based on the use of an equation to predict percentage disease severity. Inputs to the model are cultivar susceptibility, time of fungicide sprays, amount of initial infected residue and time of emergence.

In order to conduct the study more thoroughly it was necessary to bring in other factors not necessarily used directly in the modelling. These are a comparison of rating scales, the Horsfall-Heuberger Index (HHI) and percentage disease severity scale. The creation of a LB incidence map for KwaZulu-Natal (KZN) was to increase the accuracy of timing the initial fungicide spray. The presence of inoculum is assumed in the LB model. However, in KZN this is not always correct and it was shown that, in the first season of using the model, two systemic fungicide sprays were wasted due to the absence of inoculum. If it is known that there is no LB present in an area, it is possible

to ignore the model warnings for a systemic fungicide and continue to use the preventative, contact fungicide until the presence of LB is confirmed in the area. This work will serve to increase the accuracy of predictions from the existing model.

For these models to predict disease progress accurately, weather data of the microclimate is needed and the Automatic Weather Station Network (AWSN) has been developed to provide these data. The AWSN currently comprises 15 automatic weather stations (AWS) in KwaZulu-Natal. Data from these stations are recorded every 15 minutes and a daily summary is created. The AWSN uses three types of AWS, *i.e.*, Campbell Scientific (CS Africa, PO Box 2450, Somerset West, 7129, South Africa, www.csafrica.co.za), Adcon Telemetry (Agrotop, P.O. Box 861, Durbanville, 7551, South Africa, www.agrotop.co.za) and Davis Vantage Pro (CW Price, P. O. Box 150, Halfway House, Midrand,1685, South Africa, www.cwprice.co.za).

CHAPTER 1

DISEASE EPIDEMICS: ENVIRONMENTAL FACTORS INFLUENCING PLANT DISEASE, DISEASE CONTROL AND SIMULATION OF EPIDEMICS

1.1 Introduction

Maize (*Zea mays* L.), grey leaf spot (GLS) caused by *Cercospora zeae-maydis* Tehon and Daniels (Tehon and Daniels, 1925) and potato (*Solanum tuberosum.* L.) late blight (LB) caused by *Phytophthora infestans* (Mont.) de Bary are yield-limiting diseases in KwaZulu-Natal (KZN). Commercial maize in KZN accounts for just on 4.3% of the national maize crop. This is worth R563 million using an average of the yellow and white maize price for the 2001/02 season (at R1 332.87 ton^{-1}) (Anonymous, 2003). In 2003 KZN produced about 5% of the national potato crop (summer crop: 7 531 300 10kg pockets from 2243 hectares)[1]. This equates to a gross value of R89.4 million based on an average price of R1 188 ton^{-1} in 2001 (Anonymous, 2003)

Grey leaf spot was first recorded in 1988 in KZN, Republic of South Africa (RSA), and reported to cause economic losses in the Midlands area of KZN in the 1990/91 maize growing season (Ward, 1996; Ward *et al.*, 1999; Caldwell, 2000).

Cercospora zeae-maydis has since become pandemic throughout KZN and has spread into neighbouring provinces. It has adapted to the drier conditions found outside KZN, whereas, previously GLS had been reported only in KZN. Nowell (1997) predicted that GLS would be confined to the Eastern seaboard of Southern Africa. Yet GLS has been

[1] Mr J.P.Mostert, Potatoes South Africa, Private bag X135, Pretoria, 0001, South Africa.

recorded in Douglas (Northern Cape) (Kloppers, personal communication)[2]. This shows the pathogen population to be dynamic and able to adapt.

Present commercial control measures consist of one or two fungicide sprays combined with resistant/tolerant maize cultivars. Control measures for small-scale farmers are limited to resistant cultivars. A number of resistant/tolerant cultivars have become commercially available within the last three years.

Modelling of the disease is important, as it is still sometimes necessary to spray more than once a season. The question most often asked by commercial maize producers is that of initial timing of fungicide sprays and if subsequent fungicide sprays are required. The model can be used for small-scale farmers as an educational tool to show the negative effect of using cultivars with low genetic resistance.??

Late blight of potatoes is extremely serious if left uncontrolled on cultivars with low levels of genetic resistance. It is mostly controlled by the use of fungicides and genetic resistance. There is a constant need for fungicide control throughout the season if a susceptible cultivar is being grown (Fernández-Northcote *et al.*, 2000).

Resistance build-up is of major concern to agrochemical manufacturers, as the cost of synthesising, testing, registering and marketing is expensive currently in the region of 140 million euro[3]. Due to the costs of developing new fungicides it is in the best interests of all fungicide users to protect and lengthen the effective life of fungicides. Protection of fungicides involves limiting their use to periods favourable to disease development and applying the product in a preventative manner and not curatively, which would then increase the chances of resistance build-up.

Generally, fungicides are applied on a calendar basis. This means that irrespective of

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[2] Dr F.J. Kloppers, Pannar Seed Company, P.O. Box 19, Greytown 3250, South Africa.

[3] Mr N. Hackland, BASF, P.O. Box 2801, Halfway House, 1685, South Africa.

prevailing climatic conditions, fungicides are applied at set intervals. Fungicides are sometimes applied when conditions for pathogen development are not suitable, leading to less efficient use as the pathogen is not able to infect under conditions adverse to the pathogen. With the advent of highly localised systemic fungicides, incorrect use (sub-lethal doses, extended periods, curative approach) of systemic products can lead to resistance build-up by the pathogen.

1.1.1 Importance of disease modelling, potential and use of predictive models

Any control method where an action such as fungicides application needs a trigger. This trigger is usually the level of visible disease. Disease levels are not always easily visible. There is a perception threshold, *i.e.,* when disease is actually noticed. Trained specialists are able to see the disease at much lower levels than a layman. Most perception thresholds for epidemics are between x (disease) = 0.0001 and x = 0.05, with x = 0.05 being the level for the layman. This has serious consequences for disease control. There are three phases in an epidemic: the exponential phase (x is from 0.000 to 0.05), the logistic phase (x from 0.05 to 0.5) and the terminal phase (x from 0.5 to where x is practically 1) (Zadoks and Schein, 1979).

The best time for a foliar pathogen to be controlled is when x is below the perception threshold. It is during the exponential phase when the largest multiplication occurs. This is because to increase from a level of x = 0.0005 to x = 0.05 requires a hundred-fold increase, whereas between 0.05 to 0.5 is only a ten-fold increase and from 0.5 to 1 is a two-fold increase.

Due to the difficulty of observing disease at levels below 0.05, fungicides are only applied in the logistic phase and not during the exponential phase, when they are the most effective (Zadoks and Schein, 1979).

This is why modelling and prediction of disease development is so important. Through the use of recorded weather information and knowledge of the infection/growth requirement of the pathogen, development of the pathogen can be predicted. This

allows the crop protection specialist to be able to time fungicide applications before disease is visible. In so doing the pathogen is stopped during the greatest time of increase, the exponential phase, and control of the pathogen is simpler, more cost-effective and there is less chance of fungicide resistance build-up.

The potential advantages of timing fungicide control measures through modelling include:

- determining the optimum time for infection
- application of fungicides when conditions are suitable for infection, not on a calendar base
- fungicide use is reduced
- extended length of the effective life of a fungicide is lengthened due to optimum timing of fungicide applications
- curative use is avoided by optimising the time of application
- unnecessary applications are avoided
- reducing environmental pollution by cutting out unnecessary fungicide sprays.

The value in monetary terms is not always easy to quantify as there are many factors that impact on final yield. However, assuming that a region produces potatoes on an area of 5000 hectares. Through timing of fungicide applications by disease prediction systems that one ton extra ha^{-1} is obtained. Furthermore that the average price of potatoes was R1188 ton^{-1} (Anonymous, 2003). This then equates to an increase in gross profit by R5 9 million.

Disease modelling is used not only for scheduling fungicide spray applications. Simulation allows researchers to ask questions and analyse disease epidemics and so increase the level of understanding of the complexities of the pathogen and how it causes disease in time and space. Farmers generally wait for proof of disease before applying fungicides, while progressive farmers pre-empt the pathogen by using models to time their fungicide applications.

Predictive models have been used on a wide variety of crops, this is by no means a complete list so *e.g.*,

- Potato - more than 15 models available for LB (Anonymous, 1997);
- Apple scab - the best known of these is the Mills' System (Mills, 1944; Mills and La Plante, 1951);
- Sugar beet - Cercospora leaf spot (Windels *et al.*, 1998);
- Peanuts - Jensen and Boyle (1966); most other models are based on this work;
- Tomato - TOMCAST, FAST (Madden *et al.*, 1978);
- Grapes - downy mildew (Madden and Ellis, 2000).

1.2 Interactions between environmental variables and fungal pathogens

Climatic variables have a significant effect on the development of plant disease and, in conjunction with the host and pathogen, determine whether or not plant disease occurs. Generally, more disease occurs in areas that are humid or wet and are more temperate in nature, whereas dry areas are usually less prone to disease (Agrios, 1997). Factors which play an important part in the development of plant diseases are: air temperature, leaf wetness, RH, soil nutrients and, to a lesser extent, soil pH and light (Colhoun, 1973; Shaner, 1981; Agrios, 1997).

1.2.1 Air temperature

Air temperature is one of the most important factors influencing disease incidence and severity. Pathogens have a range of temperatures over which they are able to infect and survive. The pathogen *Cercospora zeae-maydis* has an established optimum of 20-30°C (Beckman and Payne, 1982; Ward and Nowell, 1998). Below a minimum air temperature of 19°C it is unusual to find that the pathogen is able to germinate or infect (Caldwell, 2000). These parameters were established under controlled conditions.

Air temperature affects survival, germination, infection, sporulation and release of spores. Many pathogens have different requirements for each stage (Colhoun, 1973). Air temperature affects the speed at which cycles are completed, *e.g.*, if all factors are favourable for disease development but air temperature is unfavourable, infection will not take place. Melching *et al.* (1989) found that at 9-28.5°C, with 16 hrs in a dew chamber, *Phakopsora pachyrhizi* Syd. did not germinate or infect soyabean leaves, but at air temperatures closer to the optimum for *P. pachyrhizi*, spore germination and infection resulted.

Temperature may cause disease without the presence of a pathogen (Colhoun, 1973, Agrios, 1997). This disease is then non-infectious and is caused by an extreme temperature. It manifests as wilting of leaves, leaf tip die-back and burning of new sensitive growth. Diseases not pathogenic in nature are beyond the scope of this review. Unfavourable air temperatures may affect both pathogen and host at the same time. Sometimes the pathogen has a positive response and the host a negative response. In sorghum, ergot is caused by *Claviceps africana* Freder., Mantle and de Milliano. Crop susceptibility to infection is increased by mean night air temperatures <12°C, 3-4 weeks prior to flowering. These low air temperatures also significantly affect pollen viability, which leads to more ergot infections as *C africana* only infects unfertilized ova (Wang *et al.*, 2000).

1.2.2 Atmospheric humidity

After temperature, moisture is the next most significant influence on germination and penetration of pathogens into plants. Rain splash and running water play a very important role in pathogen dispersal (Fitt *et al.*, 1989; Madden, 1997). Moisture also affects the extent and severity of disease by increasing the succulence of the host. This increased succulence increases host susceptibility to certain pathogens (Agrios, 1997).

High atmospheric humidity occurs in a number of ways, *e.g.*, as dew through condensation, as precipitation on the leaf surface from rain or irrigation, as high humidity and as soil water around the plant roots.

1.2.2.1 Relative humidity (RH)

Relative humidity is a general term referring to RH, vapour pressure deficit and vapour pressure. High RH is a pre-requisite for many infection processes. However, RH is a poor measurement and better parameters exist to express this environmental factor. Unfortunately, in the plant sciences, RH is often used incorrectly and without consideration of the underlying assumptions inherent in its use (Savage, 1998).

Relative humidity is calculated by
$\%RH = e/e^0 \times 100$
where e = vapour pressure of air at a specified temperature and
e^0 = vapour pressure of pure water at the same temperature (Ting, 1982).

Relative humidity is inversely related to vapour pressure, temperature and water in the atmosphere. If, at any stage, the temperature varies even slightly RH will change. This is the main reason why RH should not be averaged and instantaneous readings should rather be taken.

Vapour pressure deficit, on the other hand, is inversely related to atmospheric pressure and water in the air. It is not dependable on a third variable and more accurately describes the amount of water available in the air than RH does under a changing temperature regime.

For *C. zeae-maydis* the use of RH is common and values of 90-95% are considered necessary for conidial germination (Beckman and Payne, 1982; Rupe *et al.*, 1982). However, Caldwell (2000) observed that high RH (>95%) causes leaf wetness and it is leaf wetness and not high RH that determines conidial germination.

Humidity affects not only spore germination but viability as well. Low humidity has the effect of reducing a pathogen's ability to germinate. Estrada *et al.* (2000) found that low RH (39%) two weeks before a 24 hr period of high RH caused conidia of Isolate I-2 (*Colletotrichum gloeosporioides* [Stonem.] Spauld. and Schrenk) to have a greatly

reduced capacity to germinate. Appressorial formation was almost completely inhibited after storage of conidia at low humidity (39% RH).

Humidity plays a role in spore release early in the season. The hypothesis is that, in early spring, periods of high humidity enable the formation of conidia within infested crop residue (Ward *et. al.*, 1999). It is thought that fluctuating humidity plays a role in the variation that has been observed in germination rates and latent periods of *C. zeae-maydis* (Nutter and Stromberg, 1999).

1.2.2.2 Canopy wetness

Leaf wetness is usually caused by the leaf surface becoming wet through the deposition of dew, precipitation (rain or irrigation) or condensation, on the leaf. Water on the leaves is necessary for some pathogens, e.g., *Phytophthora infestans* requires at least 3-8 hrs of leaf wetness, depending on temperature, for infection to occur (Colhoun, 1973). Many pathogens need a film of water over the leaf tissue to germinate and infect their host (Pedro and Gillespie, 1982).

Wet conditions are necessary for fungal spore production, while dry conditions promote spore release (Shaner, 1981; Fitt *et al.*, 1989). Dissemination of spores is brought about by free water, either through splash dispersal or by being carried in water droplets/irrigation (Colhoun, 1973).

1.2.3 Wind

Wind generally has a two-fold function in disease development, that of spore dispersal, either intercontinental or within field, *e.g.*, *P. pachyrhizi* has been brought to Africa from India on monsoon winds and spread south to the South Africa through inter-tropical convergence zone winds (Pretorius *et al.*, 2001). The second function of wind is the drying of leaf surfaces, which often prevents infection and disease development.

In addition wind acts to liberate spores from their host substrate and can be roughly

divided into two groups: active release of spores independent of wind such as *P. infestans*, and those that are removed from the substrate by wind, *e.g.,* rust urediospores and conidia of *Botrytis* (Aylor, 1990).

Wind in interaction with rain is important because it is able to liberate spores from infected tissue and aid in their deposition onto a wet substrate, which is then able to be infected immediately (Agrios, 1997).

The action of wind on leaves and plant parts may be a cause of direct injury to the plant and exposes the plant/crop to secondary infection by pathogens such as bacteria and mechanically transmitted viruses, which are unable to penetrate on their own (Agrios, 1997).

1.2.4 Solar radiation

The effect of solar radiation on pathogens is considered to be far less than that of temperature and moisture. However, it does play a role in spore germination, penetration and infection of the host (Colhoun, 1973). Rust spores only germinate in the dark.

Solar radiation intensity influences penetration of hosts by fungal pathogens. Day length may also determine plant reaction to infection. Some plants would appear to be more resistant to infection with longer daylight periods (Colhoun, 1973). Solar radiation plays an important role in sporulation of fungal pathogens. In culture, use is often made of a "black" light to encourage sporulation.

1.3 Climatic factors affecting *Cercospora zeae-maydis* and *Phytophthora infestans*

1.3.1. *Cercospora zeae-maydis*

The life cycle in pictorial form is presented in Figure 1.1. Initial inoculum is from infected crop debris (Beckman and Payne, 1982; Latterell and Rossi, 1983; Ward *et al.*, 1999). Little is known of the exact requirements for the production of primary inoculum from the previous season's infected debris. Conidia are produced in spring following periods of high humidity (Ward *et al.*, 1999). According to Caldwell (2000), 11-13 hours of uninterrupted leaf wetness, or 12-13 hrs of RH above 90%, are required before asexual conidia are produced on maize stover in the spring. Air temperature requirements for initial inoculum production are unknown.

Spores are released from debris early in the spring, as soon as environmental conditions are favourable (Payne and Waldron, 1983; Payne and Duncan, 1987; Ward *et al.*, 1999). The pathogen does not survive beyond a season in infected debris (Latterell and Rossi, 1983; Stromberg, 1986). Exact mechanisms of spore dispersal are unknown, but it has been postulated that wind is the main agent. These initial spores infect the newly planted maize crops or volunteers from the previous season (Ward *et al.*, 1999).

Numerous workers have contributed to the level of current understanding of requirements for spore germination. High RH (>90%) and moderate air temperatures (20-30°C) are required for conidial germination (Rupe *et al.*, 1982; Latterell and Rossi, 1983; Beckman *et al.*, 1981). It was found that GLS conidia did not develop under conditions of low humidity (RH<70 %), even when adequate quantities of infected debris were spread in the plot (Rupe *et al.*, 1982). A minimum of 6 hrs of leaf wetness is required before conidial germination occurs (Rupe *et al.*, 1892; Thorson, 1989).

Rupe *et al.* (1982) found that 18-25°C was the optimum temperature for germination. However, Beckman and Payne (1982) observed that spores germinated after 24 hrs at 22-30°C. Caldwell (2000) showed, by using cultivars of different susceptibility to GLS, that the discrepancies in the literature may be due to cultivar responses. Under the same temperature and RH regimes the more resistant cultivars had slower rates of conidial germination and fewer conidia germinated successfully.

Desiccation periods during spore germination were tested and found to be less significant with the susceptible group of hybrids, as compared to tolerant/resistant hybrids (defined as cultivars either able to yield in the presence of disease or cultivars showing no visible symptoms of disease) (Caldwell, 2000).

Desiccation periods of less than 24 hrs did not reduce conidial germination on either of the cultivar groups tested. Where desiccation periods were 2-5 days in duration, germination was reduced on the resistant group. The susceptible group had higher spore germination than the resistant group after two days' desiccation (Caldwell, 2000). This again shows a cultivar response where germination is being retarded and under unfavourable conditions germination is reduced on the resistant hybrids.

Periods of highly unfavourable climatic conditions reduce disease progress but do not prevent/limit infection (Caldwell, 2000). This is due to the pathogen simply becoming dormant and resuming activity once favourable conditions return (Thorson and Martinson, 1993; Jenco, 1995).

Unlike many other maize pathogens, *C. zeae-maydis* does not require free moisture on leaves to penetrate host tissue (Latterell and Rossi, 1983). Free water reduces stomatal tropism and host tissue penetration and therefore disease development (Beckman and Payne, 1982; Thorson, 1989; Thorson and Martinson, 1993). However this is contradicted by the leaf wetness studies of Caldwell (2000).

Air temperatures favouring infection are between 22-28°C (Beckman and Payne, 1983). Thorson (1989) found that high RH favours germ tube growth, appressorium formation and germling survival. However, if environmental factors become unfavourable, the germ tube may cease to grow and resume growth when favourable conditions resume (Latterell and Rossi,1983; Caldwell, 2000).

Once the infection cycle has been completed there is a 14-22 day latent period before disease symptoms appear and sporulation of lesions occurs (Ringer and Grybauskas, 1995). Variability may be due to the effect of RH on all the processes leading to host

infection (Nutter and Stromberg, 1999). In addition, the effect of different levels of maize resistance affects the length of the latent period, e.g., a moderately resistant cultivar has a 22 day latent period, whereas a susceptible cultivar had a shorter 14 day latent period (Ringer and Grybauskus, 1995). This effect was observed by Caldwell (2000) in spore germination studies on a susceptible and a resistant maize cultivar.

Spore production from the host is dependent on temperature, the dryness of the air (vapour pressure deficit (E_{def})) and low leaf wetness (Caldwell, 2000). No other workers have used E_{def} and Caldwell (2000) found that its use is justified, in that percent RH did not show a positive correlation with spore release, whereas E_{def} did have a positive effect. Other workers using RH and temperature have found more conidia trapped on days with 12-13 hrs of RH>90% and 11-13 hrs of leaf wetness, with a temperature range of 20-30°C (Rupe *et al.*, 1982; Payne and Waldron, 1983). Most conidial release takes place during the day around periods when E_{def} was high and leaves were dry (Caldwell, 2000).

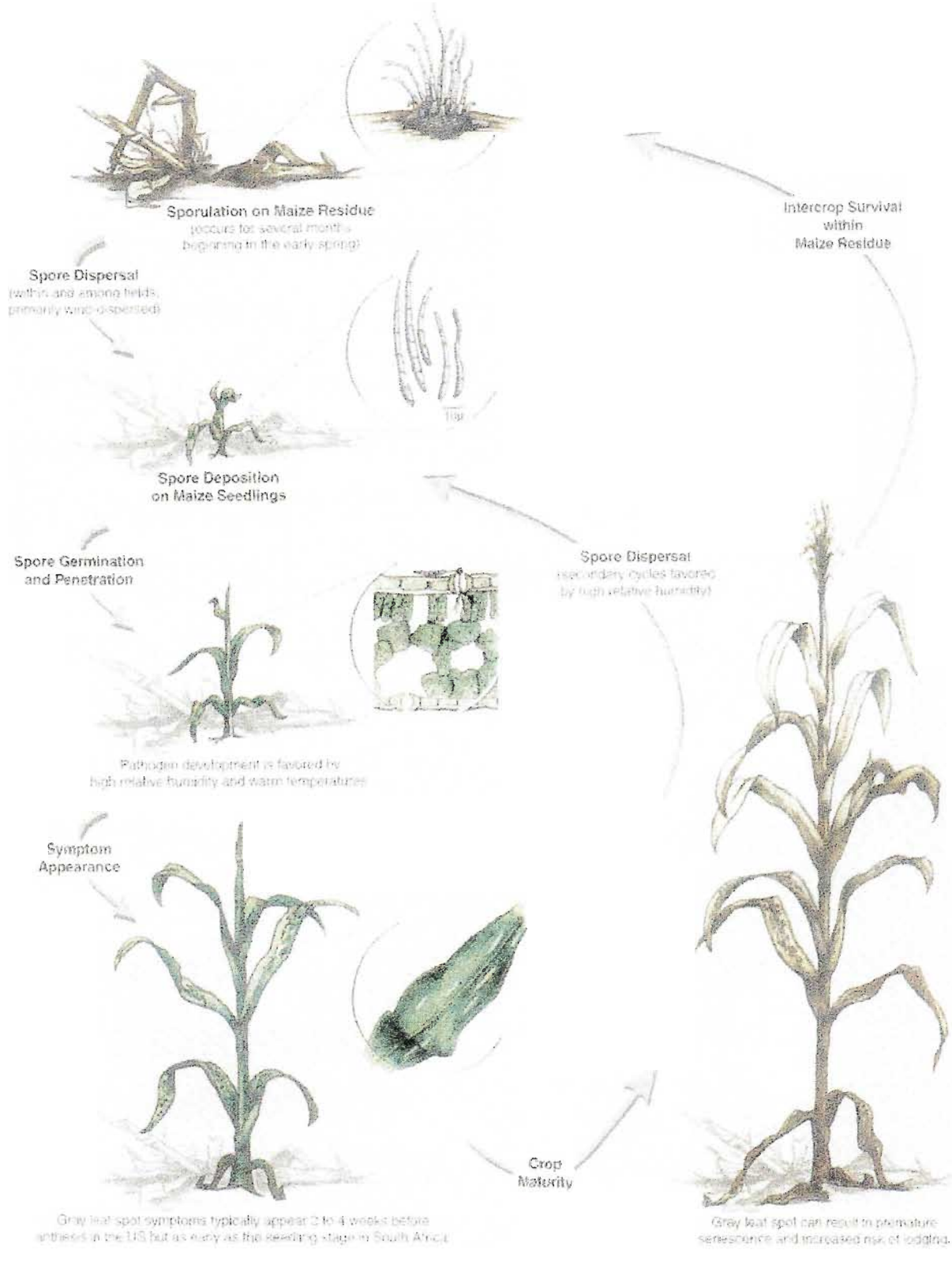

Figure 1.1 The life cycle of Cercospora zeae-maydis from Ward *et al.*, 1999.

1.3.2 *Phytophthora infestans*

This must surely be one of the most well-known diseases to farmers and anyone who has ever tried to grow a potato or tomato. *Phytophthora infestans* is essentially an asexual pathogen, with a very short life cycle (less than four days from infection to sporulation under optimal conditions) (Agrios, 1997). The sporangium is the asexual form while the oospore is the sexual spore. The oospore is the overwintering spore which are able to tolerate unfavourable conditions. Oospore formation is dependant on two mating types being present, the A1 and the A2 (Drenth *et al.*, 1995). Currently South Africa has only the A1 type.

Sporangia are able to germinate directly by germ tube or indirectly through zoospores. Direct germination with a germ tube occurs at temperatures of 18-24°C, while indirect germination occurs at temperatures of 8-18°C (Fry *et al.*, 2001; Anonymous 2000). Zoospores are usually uninucleate biflagellate, which are released from the sporangia, after which they are able to move around for a period (several minutes),encyst and form a germ tube which penetrates the host.

Under optimal conditions (18-22°C) the latent period is three days after infection (Agrios, 1997; Fry *et al.*, 2001). Within a day or two of the lesions appearing, sporulation can occur and this requires temperature of 10-25°C as well as wet conditions *i.e.*, prolonged leaf wetness and/or 100% relative humidity. Sporangiophores bear sporangia within 8-12 hrs (Anonymous, 2000). The sporangia are released through the influence of relative humidity and are distributed via wind or rain splash (Aylor, 1990). The sporangia can survive in the atmosphere for several hours in dry conditions as long as they are not exposed to sunlight whereupon they survive for less than an hour (Minogue and Fry, 1981).

Once on a susceptible host sporangia are able to start the infection cycle over again. According to Fry *et al.*, (2001) the sporangia are able to germinate and penetrate a new host within two hours. However, this would seem to be rare.

Tuber infection can occur whenever tubers and the pathogen come into contact. In South Africa this is rare, trials carried out at Cedara in the 70's showed no tuber infections (Young, 1977). Worldwide tuber infections are variable generally undetectable to 2-3% but tuber infections can be as high as 60-80% (Anonymous, 2000). Figure 1.2 presents the life cycle of the pathogen (Agrios, 1997).

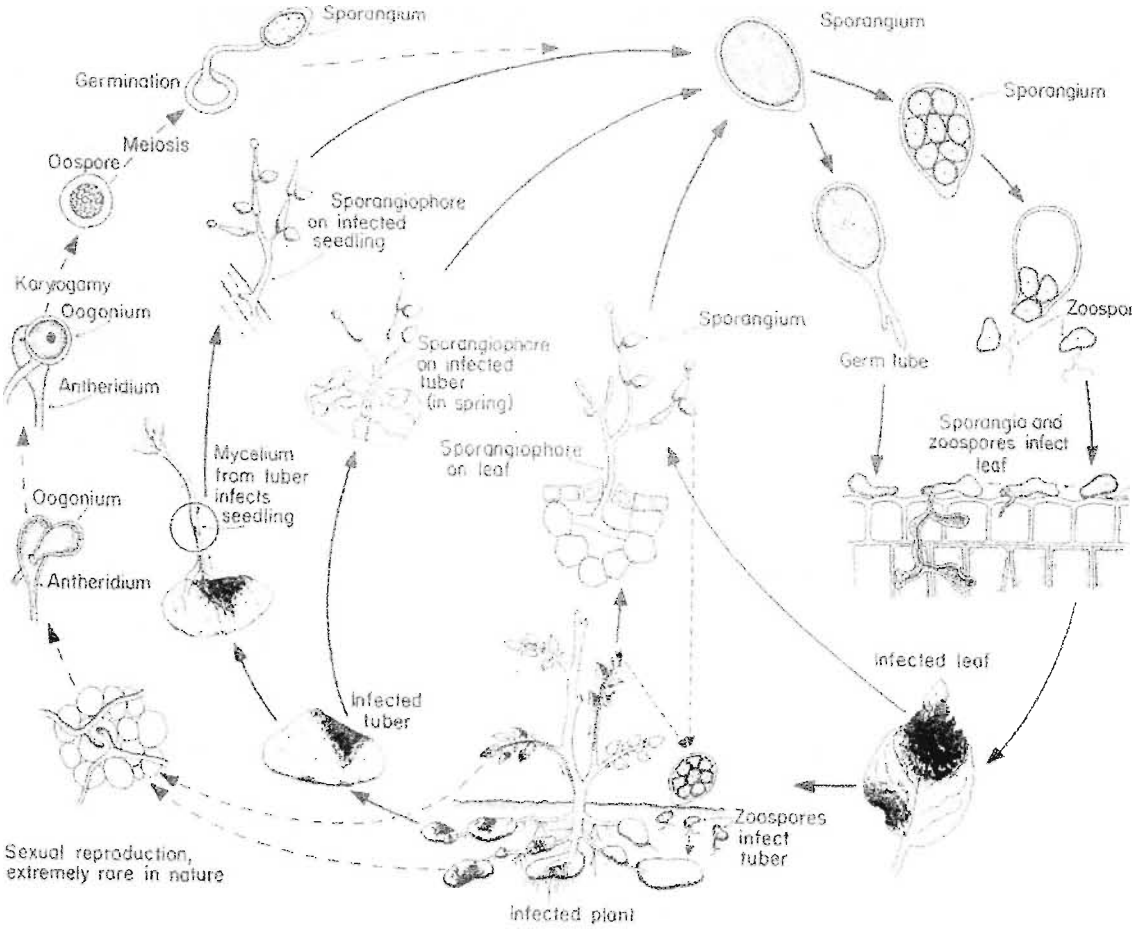

Figure 1.2 Disease cycle of *Phytophthora infestans* causal organism of late blight of potatoes and tomatoes after Agrios, 1997.

1.4 Measurements, problems and solutions for weather parameters

1.4.1 Air temperature

Temperature is one of the most universally measured parameters. Many methods are available to measure air temperature. Non-automated methods make use of thermometers. These need to be read as often as the user requires readings. In the case of minimum/maximum thermometers, readings must be made at least once a day so that the device can be reset.

For semi-automated, readings thermographs/thermohygrographs are commonly used to measure air temperature, while thermohygrographs measure air temperature and RH. These devices use a coiled bimetallic strip that responds to air temperature differences and is transferred to a graph via a pen arm (Sutton *et al.*, 1984). The most common problem with these recorders is that they need frequent calibration and a change of graph paper weekly. For unattended stations this is too frequent and impractical.

Automated temperature recordings can be done through thermistors, thermocouples, infrared thermometers and Vaisala RH sensors (Sutton *et al.*, 1984; Agrios, 1997; Savage *et al.*, 1997; Savage, 1998). These do not need to be calibrated as frequently as thermographs/thermohygrographs, making them more practical for unattended recording stations.

All air temperature recordings must be taken in the shade. This is to remove the influence of solar radiation on the sensor/recorder (Sutton *et al.*, 1984; Savage, 2001a). The sensor should also be protected from outgoing longwave radiation (Savage, 1998; Savage, 2001a). Common errors in air temperature measurement include use of an incorrect sensor for the specific purpose, direct solar radiation on the sensor, obstruction of air movement across the sensor/thermometer and incorrect alignment of the shield for the sensor (Savage, 2001a). When using automated sensors it is necessary to shield and keep the sensor wires as short as possible to avoid heat

transfer along cabling (Savage, 2001a).

Wherever air temperatures are reported, the height of the sensor, the type of shield, the underlying surface, how it was measured and any other variables that may affect air temperature readings must be explicitly stated. This is because of the way air temperature changes in space and time (Savage, 2001a).

1.4.2 Free water

1.4.2.1 Rainfall

Rainfall is commonly measured with a rain gauge, *i.e.*, a conical flask which measures total rain for the period in which the gauge is emptied, in other words all precipitation received in the previous 24 hrs. Recorders, such as a standard funnel, are used to record the total amount of rain in a set period, but not the duration or intensity of rain. Rain duration and intensity may be recorded using a siphon rain gauge. These are manual recorders and require a person to monitor and change graph paper daily.

Manual recorders have a problem with the time period between measurements being read. If high intensity rain occurs, the collection receptacle overflows and the measurement can be affected. An error does sometimes occur with the siphon rain gauges. During a heavy rain event, while the siphon tank is emptying and rain continues to fall, the rain collected during this period is not recorded (Savage, 2001a).

Automatic tipping bucket rain gauges have mostly overcome these problems by counting the number of tips as they occur. The problem of a tank having to empty while rain continues to fall is addressed by using a dual bucket. This works that as one bucket is emptying the other is ready to receive the next amount. The one disadvantage of the bucket is that it requires a certain amount of water in the bucket, usually 0.1-0.2 mm, before it tips. If there are long periods with no rain, evaporation of the water in the "untipped" bucket may occur, leading to slight measurement errors (Savage, 2001a).

Common problems with rain gauges are obstructions preventing rain falling into the funnel and wind causing rain to blow across the funnel. These can be rectified by having a windbreak around the gauge and ensuring that rain gauges are sited away from obstructions, at a distance of the height of the obstruction. For example, if there is a 1.2 m wall then the gauge should be sited at least 1.2 metres from the wall to minimise error (Savage, 2001a).

1.4.2.2 Irrigation

Irrigation is not usually as well distributed as rainfall. Assumptions concerning rainfall distribution are the same as for irrigation. It is assumed that the depth of water falling into a rain gauge is the same as for a large area around the gauge.

However, for irrigation, these assumptions are not valid, as there are more factors affecting overhead irrigation distribution than there are for rain. Irrigation application methods may be different, *e.g.* impact sprinklers compared to centre pivots. Equipment can fail, with the end result that parts of the land receive more irrigation than others.

For irrigation to be measured accurately, multiple rain gauges should be used, to determine errors inherent in the irrigation system. Once these errors are known, if impact sprinklers are used, it is possible to adjust individual stand times to compensate for the errors.

1.4.2.3 Dew

Dew is a important form of precipitation, especially in the dry areas of southern Africa, where it is the only source of water for long periods of time. Dew is an important measurement, as it has a direct impact on the development of plant foliar diseases, through the influence that it has on infection and sporulation processes (Wallin, 1963; Huber and Gillespie, 1992). Dew causes leaf wetness even in the absence of rain or irrigation and therefore has a vital role to play in the development of disease. In high rainfall areas dew is not as significant and is rarely measured as a form of precipitation.

Dew is usually measured with a string type instrument or an electrical resistance sensor. A number of workers have found that the string type recorders are reasonably accurate (<1 hr error). However, size and shape of leaves being simulated are an important factor and influence accuracy. Sutton *et al.* (1984) found that in onions the de Wit recorder (a string type recorder introduced more than 50 years ago) substantially under- or over-estimated the dew period, depending on the growth stage of the crop.

Electrical resistance sensors, described by Gillespie and Kidd (1978), are currently widely used. There are many shapes and forms, but all grids have the same concept of interlacing electrodes using alternating current to avoid electrolysis. The use of off-white latex paint is recommended to enhance the performance of the sensors. Lau *et al.* (2000) conducted experiments using painted and unpainted sensors at a variety of angles and compass orientations. Neither deployment angle nor compass orientation created significant differences in recording accuracy, provided the sensors were painted with an appropriate paint.

Sensors must be calibrated in the crop under investigation and in the area of most interest to the researcher, as leaf wetness duration differs considerably through the canopy (Lau *et al.*, 2000).

1.4.3 Humidity

Relative humidity is a "measure" of water vapour in the atmosphere. However, the real measure of water vapour in the atmosphere is the saturated water vapour pressure (e). Both these measurements are temperature dependent, *i.e.*, as temperature increases there is an increase in the water holding capacity of the air (Savage, 1998; Savage, 2001b).

Humidity (a general term referring to RH, vapour pressure deficit, vapour pressure, *etc.)* is commonly measured with a hygrometer.

There are basically four types of hygrometers:

1. dew point hygrometer (measurement of the dew point temperature);
2. the psychrometer (measurement of a wet and dry bulb);
3. electronic capacitance type sensors and conductivity sensors, for example sulfonated polystyrene (Sutton *et al.*, 1984) and
4. a hygrograph, where a water vapour sensor (such as human hair) is used to measure RH (Savage, 2001b).

Common problems with the above types of hygrometers are inattention to details such as ensuring the wet bulb is constantly wet, that there is adequate ventilation of the hygrometer shelter, presence of dirt in the wet bulb water, non-removal of electronic sensors' protective caps, *etc.* (Savage, 2001b; M.J. Savage, personal communication).[4]

When using the term "relative humidity," or any other terms referring to humidity measurements, it is essential that the term be defined beforehand and that the most suitable humidity determination method is used for application. Confusion often exists in the literature as to whether RH ought to be used or the calculated vapour pressure deficit. Relative humidity is a well-known measurement and is used most often by plant pathologists in spite of its inherent problems.

Caldwell (2000), however, showed that the use of vapour pressure deficit (E_{def}) is more significant in spore release studies than RH. This is important as it is possible that information is being lost because it may be that in certain instances incorrect parameters are being used.

[4] Prof. M.J. Savage, School of Applied Environmental Sciences, University of Natal, Private Bag X1, Scottsville, 3209.

1.5. Description and analysis of a model for timing of fungicide applications for *Cercospora beticola*

1.5.1 Introduction

Cercospora beticola Sacc. is the causal organism of Cercospora leaf spot (CLS) on sugar beet (*Beta vulgaris* L.). In the USA, where this particular model was developed, there are approximately 286 000 ha of sugar beet planted. This model was developed on behalf of the sugar beet industry because, in 1973, higher yielding CLS susceptible varieties (Beta 1345, Beta 1443, Hilleshog Mono 309) were grown on a commercial scale for the first time. Prior to this, only one moderately resistant cultivar, American 2 Hybrid B, was grown in this region. This was the main reason for CLS not being considered economically important in the region.

With the introduction of the susceptible varieties in 1973, disease severity increased in the southern Red River Valley of Minnesota and North Dakota, as well as in southern Minnesota, to economically important levels of CLS (>3% disease severity). In 1981, an aggressive calendar-based fungicide spray programme was introduced. The schedule was preventative, with the first fungicide being applied before disease was observed and then on a 10-14 day or 21 day interval, depending on the fungicide used. The benzimidazoles (benomyl and thiabendazole) fungicides were the most widely used, but by the end of 1981 there were reports of CLS resistant to the benzimidazoles. This is not surprising as the benzimidazole class of fungicides is particularly susceptible, to development of pathogen resistance (Brent and Holloman, 1998). Within a few years resistance became widespread and most producers switched to triphenyltin hydroxide (Windels *et al.*, 1998).

1.5.2 Climatic factors affecting *C. beticola*

The climatic factors affecting *C. beticola* (sporulation, germination and infection) are, in brief:

- daytime temperatures 25-35°C
- night temperatures greater than 16°C
- extended periods of high humidity (90-95%) or free moisture on leaves for at least 8.5 hrs (Rupel, 1986).

Symptoms develop between 5 and 21 days after infection (Windels *et al.*, 1998).

1.5.3 The Cercospora leaf spot model

The model was originally developed by Shane and Teng (University of Minnesota). The idea was to give producers a prediction as to when fungicide application should start (Shane and Teng, 1983; Ward, 2000). The model had two parts, a disease severity and a Cercospora Advisory. The intent was that, using the disease severity ratings for individual fields, and based on the Cercospora Advisory, if conditions for infection were favourable, then the recommendation was for fungicide application to start.

It was found that, in practice, the disease severity assessments were too time-consuming and that the producers and advisers were using the Cercospora Advisory for timing of fungicide applications rather than the two components in tandem. Therefore only the Cercospora Advisory is described in detail.

The model is based on a whole number scale, which ranges between 0 and 14, and describes the potential for infection over the previous 48 hrs. The scale is made up of two consecutive days' Daily Infection Values (DIV), on a scale of 0-7. The DIV is worked out by:

- number of hours in the day (midnight to midnight) when RH > 90%
- the average temperature during these hours of RH > 90%
- determine the DIV that corresponds to hrs of RH≥90% and average air temperature during those hours (Table 1.1).

The interpretation of the Cercospora Advisory is based on the fact that infection conditions for *C. beticola* can last for more than one day and so the Cercospora Advisory consists of the DIVs for the two preceding 24 hr periods. Sums less than 6

indicate low infection chances, between 7-14 a high chance and 6 marginal infection chances (Ward, 2000).

In practice, the use of DIVs to time the first application is not always advised as DIVs are recorded early in the season. So the first fungicide application tends to be according to a number of other factors such as disease incidence, cultivar susceptibility and history of the particular field (see Table 1.2) (Windels *et al.*, 1998).

Once the initial application has been made, then the DIV is used to time subsequent fungicide applications. The DIV threshold value of RH≥90% was reduced to RH≥87% in 1988. This was to more closely match the field observations of disease incidence and reflect infection chances.

The Cercospora Advisory, as used commercially, is mostly based on weekly DIV values. Depending on the production area and the local co-operative, the DIV values are interpreted differently. The Minn-Dak co-operative, where very favourable conditions for disease occur, notes DIVs for seven days. These DIVs are interpreted as 0-4, low disease potential, 5-6, medium disease potential, and 7 indicates high disease potential.

Table 1.1 Daily Infection Values (DIVs) for Cercospora leaf spot on sugar beet calculated from the number of hours per day (24 hrs) with relative humidity (RH) ≥90% and the average temperature during those hours

Hours day^{-1} ≥90% RH										Daily Infection Values																													
24	1	2	4	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
23	1	2	3	4	5	6	6	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
22	1	1	3	4	5	6	6	6	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
21	0	1	2	4	4	5	5	5	5	5	5	5	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
20	0	1	2	3	4	5	5	5	5	5	5	5	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
19	0	0	1	3	4	5	5	5	5	5	5	5	5	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
18	0	0	1	2	3	4	4	4	4	4	4	4	5	5	5	5	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
17	0	0	1	2	3	4	4	4	4	4	4	4	5	5	5	5	5	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
16	0	0	0	1	3	4	4	4	4	4	4	4	4	4	4	4	5	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
15	0	0	0	1	3	4	4	4	4	4	4	4	4	4	4	4	5	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
14	0	0	0	1	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
13	0	0	0	0	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
12	0	0	0	0	2	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
11	0	0	0	0	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
10	0	0	0	0	2	2	2	2	2	2	2	2	3	3	3	3	3	3	4	4	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	3
9	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	4	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	3
8	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3
7	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3
6	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2	2	2	2	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3
5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
°C	16				18				21					24				27				29			32				35											

from Shane and Teng, 1984.

Table 1.2 Factors identified by agriculturalists employed by three sugar co-operatives as the basis for recommending fungicide applications to control Cercospora leaf spot

	Agriculturalists identifying each factor [a] (%)		
Criteria	**Am. Crystal**	**Minn-Dak**	**So. Minn.**
First application			
Cercospora leaf spot found [b]	61	86	38
Weather	45	43	63
Row closure	36	29	75
Daily Infection Value	33	43	25
Cultivar susceptibility	27	57	50
Field location/history [c]	27	29	63
Calendar date	12	0	38
Second (and subsequent application)			
Label recommendation [d]	61	71	63
Daily Infection Value	56	29	25
Disease incidence	50	29	38
Weather	33	86	75
Cultivar susceptibility	11	57	0
Canopy density	11	14	13
Time remaining to harvest [e]	7	0	13
Other sources of recommendations	8	0	0

[a] Responses from 18 of 23 Agriculturalists at American Crystal Sugar Company, 7 of 7 at Minn-Dak Farmers Cooperative, and 8 of 8 at the Southern Minnesota Beet Sugar Cooperative in a survey conducted during November 1996. For each cooperative, values are more than 100% because Agriculturalists identified multiple factors.

[b] In field and/or geographic area.

[c] Includes planting date, proximity to sheltered areas, crop rotation.

[d] Direct recommendation by a chemical company representative.

from Windels *et al.*, 1998.

1.5.4 Benefits of the model

With the introduction of the model the average number of fungicide applications has been reduced by 1.7, before the model was introduced the average fungicide applications were 3.8 (1982 - 1984) and after the model's implementation this dropped to an average of 2.1 (1986 - 1988) fungicide applications (Ward, 2000).

However, weather conditions from 1991 to 1997 were favourable for Cercospora leaf spot and the number of fungicide applications increased. The use of the model resulted in better disease control and allowed for increased yields, which offset the cost of fungicide applications. The model has allowed producers to extend spray intervals and sometimes drop an application. So, even with the limitations in the model and the modifications, the use of the model has saved the sugar beet industry millions of dollars. One missed fungicide application over 50% of the total production area and the lengthening of fungicide spray interval, means a savings of $3.2 million to the industry.

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CHAPTER 2

DESCRIPTION AND SENSITIVITY ANALYSIS OF A MODEL (SPRAYAID) FOR TIMING OF FUNGICIDE APPLICATIONS FOR *CERCOSPORA ZEAE-MAYDIS*

Abstract

An existing model (SprayAid) was subjected to a sensitivity analysis exercise to determine if the assumptions behind the inputs to the model were still valid. It was found that the estimated residue coefficient should be derived from the residue coefficient curve as described by the equation $y=2251.7x^{-0.547}$.

2.1 Introduction

An existing model (Berry *et al.*, 1995), was evaluated to determine if one of the original inputs to the model was still valid. This exercise was undertaken due to the increasing difference between the amount of predicted disease and actual observed disease. The hypothesis was that there had been "drift" in the model or in the inputs to the model.

In addition, the model has been rewritten in a newer programming language with a graphical user interface. The addictions and modifications to the appearance of the programme has been changed and altered to allow various scenarios to be simulated without the need for re-programming.

2.1.1 Description of existing model

A model to simulate maize GLS disease progress was developed and presented by Berry *et al.* (1995). The model is called SprayAid. The objective was to use SprayAid in the CERES-Maize crop growth model (Jones and Kiniry, 1986) as a sub-routine.

The objective was to predict the loss of photosynthetically active leaf area. This information would be passed to CERES-Maize, thus taking into account the effect of GLS on maize yield. Disease progress is calculated in percentage leaf area blighted. Fungicide spray applications are included in SprayAid (Berry *et al.*, 1995). Weather data for use by SprayAid is supplied by the automatic weather station network (AWSN), which is discussed in Chapter 5.

After plants have emerged, the pathogen is modelled through three phases, *viz*, germination, infection and development of blighting symptoms. Defined temperature requirements (mean daily temperatures $\geq$20°C and $\leq$28°C) and duration of RH > 90% in hours (HUMHRS) are used.

For germination, 13 continuous HUMHRS are needed. HUMHRS need to be between the mean daily temperature specifications. Once germination has been triggered, HUMHRS are then accumulated. After 72 HUMHRS are accumulated, infection is triggered. Development of leaf blighting is triggered when HUMHRS have accumulated to 200 hours.

Once leaf blighting has commenced, the percentage of blighted leaf area is calculated by a modified logistic function of cumulative RH and temperature conditions favourable for the development of GLS. At high levels of disease blighting, deviation from a standard logistic function was observed. A better fit to the data was achieved by raising the logistic function to a power of 1.243 (Berry *et al.*, 1995). Leaf blighting was calculated using the following equation:

$$\% \text{ Blighting} = [100/(1.0+b * \exp(-r*\text{CLIMFAC})]^{1.243}$$

Where

b is the residue coefficient,

r is the cultivar resistance coefficient, and is assumed to be constant for a particular maize variety, and

CLIMFAC units are the sum of HUMHRS multiplied by a daily temperature factor (TEMPFAC).

The residue coefficient (b) is a measure of the amount of infected residue on the land at planting. Data from long-term tillage trials at Cedara were used and disease progress curves from the different treatments were compared to the amount of total residue on the land at planting. A curve was fitted to these data (Figure 2.1) (Berry, personal communication)[5].

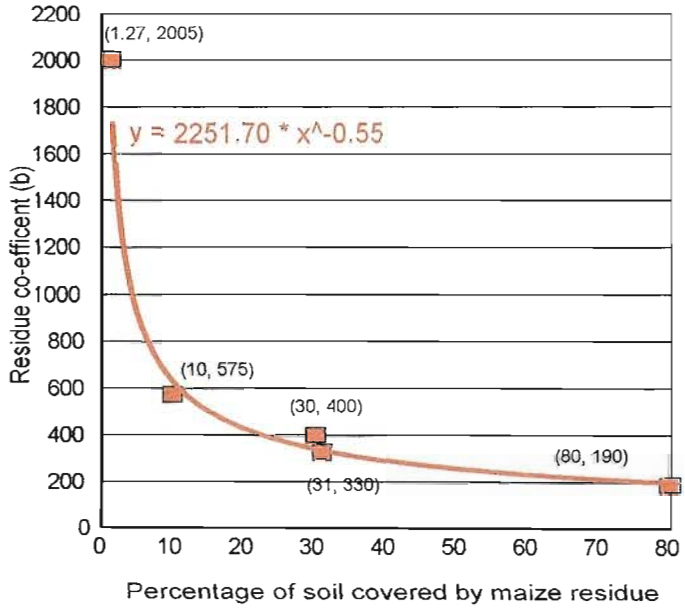

Figure 2.1 Residue coefficient (b) for use in the leaf blighting (logistic) function versus percentage of soil surface covered at planting.

TEMPFAC is determined by the following algorithm:

if MEANTEMP <= 15 then TEMPFAC = 0

if (MEANTEMP > 15) and (MEANTEMP < 22) then TEMPFAC = (MEANTEMP - 15)/7

if (MEANTEMP >= 22) and (MEANTEMP <=30) then TEMPFAC = 1

if (MEANTEMP > 30) then TEMPFAC = (37 - MEANTEMP)/7

(Figure 2.2)

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5 W.A.J. Berry, Golder Associates Africa Pty (Ltd)., P.O. Box 1475, Kloof, 3640, KwaZulu-Natal, South Africa.

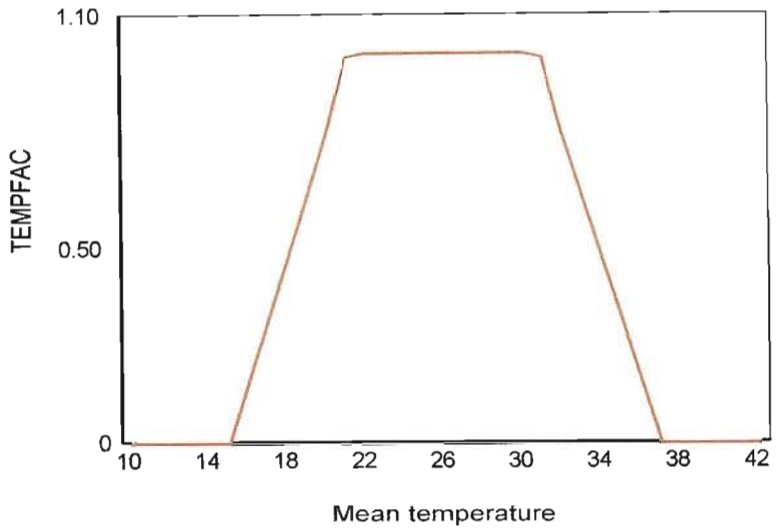

Figure 2.2 Calculation of TEMPFAC (daily temperature factor) for use in determining 'r'(units of infection for SprayAid).

The value of HUMHRS is limited to 12 hrs, in accordance with Beckman and Payne (1982), who observed that prolonged leafwetness reduced the development of GLS. Incorporation of fungicide sprays in the model is achieved by the model halting the calculation of the logistic function for a programmable number of days at run time. This is to allow the effect of different fungicides to be included in the model.

SprayAid was not used in any further work with CERES-Maize, due to the disbanding of the modelling team at Cedara. SprayAid was originally written in Turbo Pascal and was developed in the 1992/93 and 1993/94 maize growing season at Cedara. It was developed at a time when the GLS epidemic was at its peak severity and high levels of inoculum were present, because very little genetically resistant maize was available at the time.

2.2 Materials and methods

2.2.1 Analysis of the existing model and additions to the model

The original model code was re-written in Borland Delphi Enterprise Version 5 (Inprise Corporation, Scott's Valley, California, USA). It was written to enable changes to parameters "on the fly", *i.e.*, parameters were not written in hard code. The main program code for SprayAid32 is included as Appendix 2.1.

Additions to the model, during the course of this study, include the period of control of a fungicide. Fungicide Half Life and Fungicide Effective Period (FEP) are defined as the period of time it takes for the fungicide to become half as efficient as it was at application. The term FEP is preferred over Fungicide Half Life and is therefore used from here on. Once a fungicide spray is applied, the model is halted until the FEP is past. After the FEP, the model is reset to 0 HUMHRS and the cycle is restarted. SprayAid32 includes the ability to change the air temperature requirements at runtime. Number of HUMHRS before the infection process is started can be adjusted. The default value is 200 hours, but with this addition to the model it is possible to simulate different scenarios.

The sensitivity of the model to the quantity of initial residue at planting was tested. This was done because the original model was designed so that any residue on the ground at planting was assumed to be infectious.

Sensitivity to the amount of residue (residue coefficient) was tested, using 1.25, 5, 10, 15, 20, 25, 30, 35, 40 and 80 % as the levels of maize residue covering the soil surface. Due to the nature of the residue coefficient curve (Figure 2.1), there was no significant change in the residue coefficient between 40 and 80 % to warrant further sub-divisions between these two levels.

Using CurveExpert 1.3 (Daniel Hyams dhyams@altavista.net Starkville, Massachusetts, USA) the residue curve was re-fitted to see if the common log fit, previously used, was the best fit possible. The resultant curve was used to derive the residue coefficient using the equation generated and then run through SprayAid and the results graphed to determine differences. In addition, the original equation ($y=2251.7x^{-0.547}$) was used to determine the residue coefficient and the values run through SprayAid and graphed.

2.3 Results

Using the existing graph of the fitted residue coefficient curve, it was visually determined that the points on the curve were as presented in Table 2.1.

Table 2.1 Co-ordinates for the residue curve coefficient, as determined visually for x and y values

x Abscissa	y Ordinate
4	2000
10.5	575
30	400
31	330
80	205

These values were used in CurveExpert to determine the best fitting curve for the data. CurveExpert determined that the heat capacity model best fitted the data. The heat capacity model is:

Heat capacity model: $\mathbf{y=a + bx + c/x^2}$

where

a = 390.78865

b = -2.2700097

c = 25840.4.

Using this equation, residue coefficients were determined (Table 2.2).

Table 2.2 Residue coefficients, as derived from the heat capacity model, using different residue percentages

Residue percentage	Residue coefficient
1.25	16926
5	1413
10	626
15	472
20	410
25	375
30	351
35	332
40	316
80	213

Using the original curve fitted to the residue coefficient, which is a common log curve, with the equation $y=2251.7x^{-0.547}$, the derived residue coefficients were calculated (Table 2.3).

Table 2.3 Residue coefficients, as derived from a common log curve model, using different residue percentages

Residue percentage	Residue coefficient
1.25	1993
5	934
10	639
15	512
20	437
25	387
30	350
35	322
40	299
80	205

These data were run through SprayAid for the susceptible maize cultivar SC206, with estimated residue percentages from the 2000/01 (10%) and 20001/02 (5%) maize trials. The results were compared to actual observed disease progress.

It was found that, for the common log fit coefficients, the trial estimated residue percentage at planting and 1.25% were closest in 2000/01 (Figure 2.3). For the 2001/02 trial the estimated residue percentage of 10% was between the common log fit residue coefficient for 5 and 10% (Figure 2.5).

Using the coefficients from the heat capacity curve the same exercise was done. For the 2000/01 trial the predicted disease progression using the heat capacity model residue coefficient shows 5% residue being closest to the observed disease progression (Figure 2.4). For the 2001/02 trial the closest fit for the heat capacity residue coefficient was 10% (Figure 2.6).

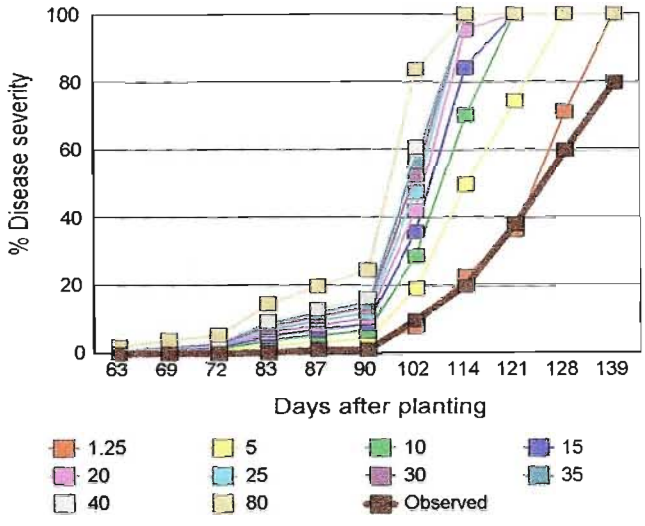

Figure 2.3 Predicted disease severity using common log curve derived residue coefficients and observed disease for cultivar SC206 for the 2000/01 season.

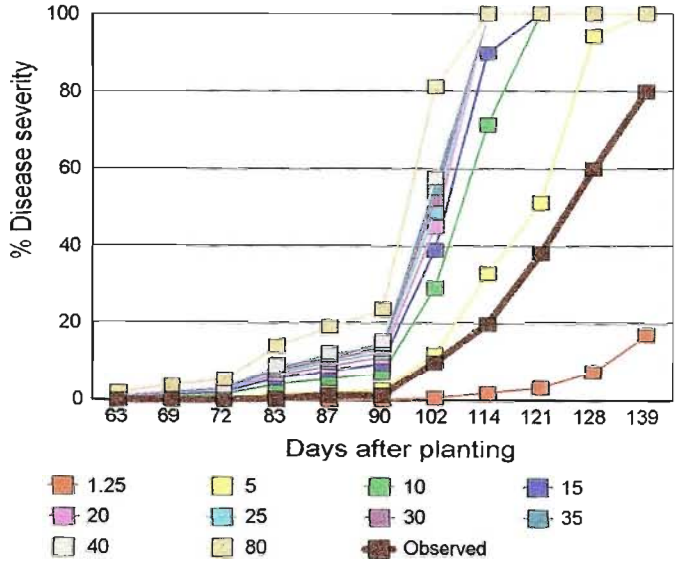

Figure 2.4 Predicted disease severity using heat capacity model derived residue coefficients and observed disease for cultivar SC206 for the 2000/01 season.

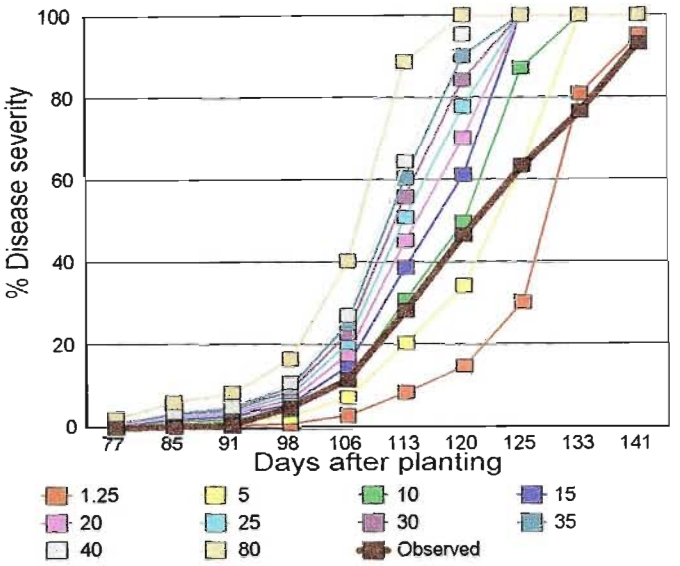

Figure 2.5 Predicted disease severity using common log curve derived residue coefficients and observed disease for cultivar SC206 for the 2001/02 season.

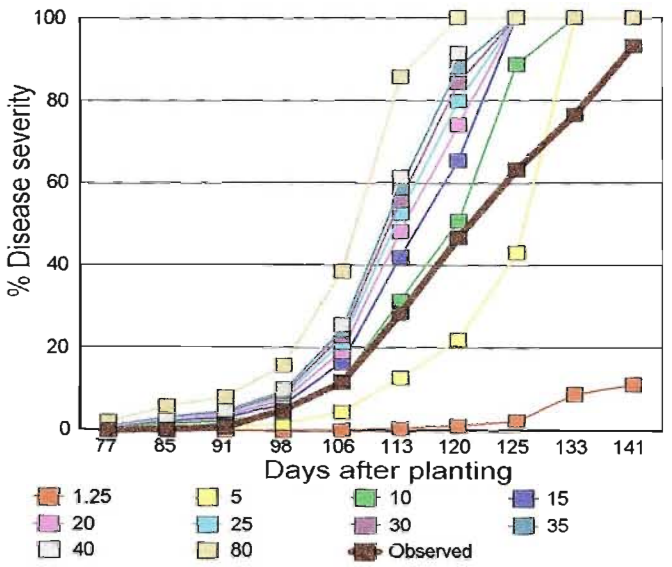

Figure 2.6 Predicted disease severity using heat capacity model derived residue coefficients and observed disease for cultivar SC206 for the 2001/02 season.

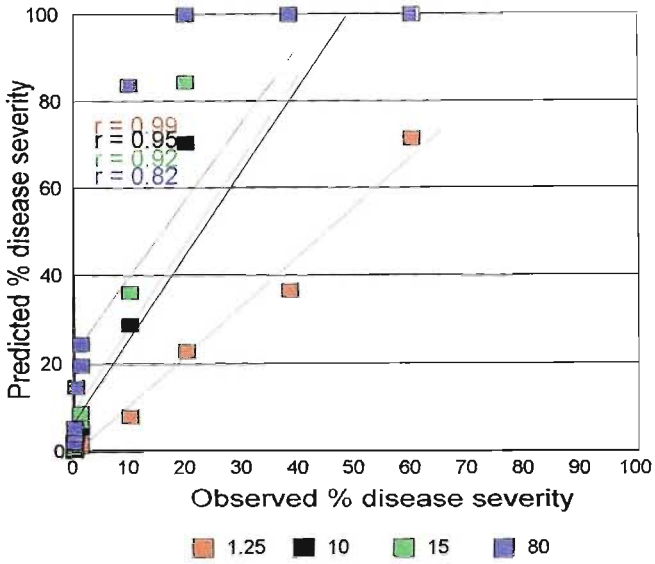

Figure 2.7 Observed percentage disease severity plotted against predicted percentage disease severity for the 2000/01 season at Cedara with the common log fit derived residue coefficients.

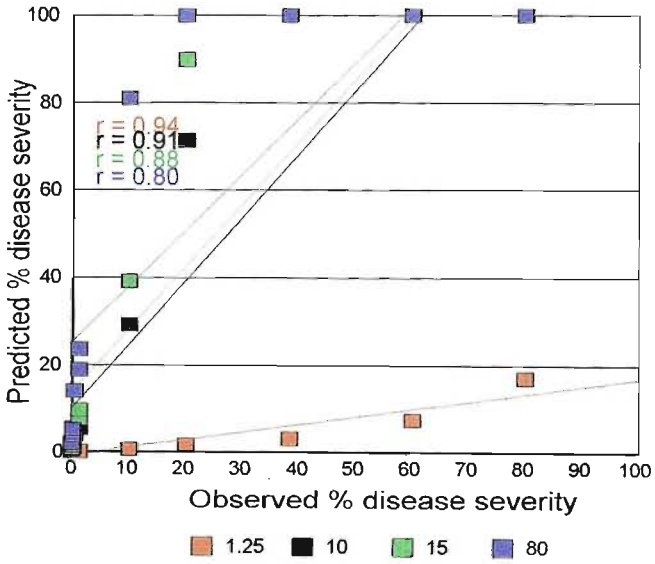

Figure 2.8 Observed percentage disease severity plotted against predicted percentage disease severity for the 2000/01 season at Cedara with the heat capacity model derived residue coefficients.

2.4 Discussion and conclusions

The curve generated by the heat capacity model exhibits a very high coefficient for the low residue counts, declining considerably after 10% and then levelling off. The effect of this is clearly seen in Figure 2.4, where the lines after 10% residue are very close together and hard to distinguish. In contrast, for the common log curve (Figure 2.3 and 2.5) and the derived values, as given in Table 2.3, the difference does not seem to be so marked.

By plotting observed percentage disease severity against predicted disease severity, a direct comparison is obtained. The closest linear fit to 1 is the best curve to use. In Figure 2.7, with the common log fit residue coefficient, 1.25% residue is the best fit r=0.99) as opposed to the best fit for the heat capacity model being 1.25% (r=0.94). This ties in with Figure 2.3 where visually the common log fit derived coefficient at 1.25% matches observed disease whereas, for Figure 1.4 the best visual fit for observed disease is with a residue coefficient of 5%.

In conclusion, when using SprayAid32, the estimated residue coefficient should be derived from the residue coefficient curve, as described by the common log fit, with the equation $y=2251.7x^{-0.547}$.

2.5 Literature cited

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CHAPTER 3

EVALUATION OF THE MAIZE GREY LEAF SPOT MODEL (SPRAYAID) IN THE TIMING OF FUNGICIDE SPRAYS AND FORECASTING OF MAIZE GREY LEAF SPOT EPIDEMICS

Abstract

A maize grey leaf spot (GLS) model, SprayAid, was tested to determine if it was able to accurately schedule application of fungicide sprays to control the pathogen. It was found that in certain seasons SprayAid predicted onset and disease progress accurately, whereas in other seasons it predicted disease progress too quickly. The most likely reason is the difference in current control options, compared to when the model was originally developed. SprayAid was developed in the 1992/93 and 1993/94 seasons, when GLS was epidemic and very low levels of disease tolerance existed in commercial hybrids. This meant that most, if not all, residue left at the end of the season was infected. This led to a very high level of initial inoculum. It is envisaged that by changing the residue coefficient input of total stubble at planting to the amount of total infected residue at planting, this problem may be solved.

3.1 Introduction

Optimum timing of fungicide sprays requires precise information concerning disease progress. It often happens that a farmer will not use a fungicide until there is visible disease. According to the perception threshold, most farmers will not see disease symptoms until a 5% level has been reached (Zadoks and Schein, 1979). This is after the exponential phase, where the use of fungicide control options are the most effective.

There are ways around this problem of timing application. The first is to apply fungicides according to a calendar. However, this may cause mistiming of the application as the weather conditions may not be suitable. The second option is timing

of applications through prediction of infection periods. By measuring weather and climatic data it is possible to predict infection periods, germination, disease symptoms, or whatever is the most appropriate measure of disease for the particular pathogen. This prediction then enables the application of fungicides at the most optimum time.

In the Republic of South Africa (RSA) grey leaf spot (GLS) is a relatively new disease of maize (*Zea mays* L.) It is caused by the fungus *Cercospora zeae-maydis* Tehon and Daniels, (Tehon and Daniels, 1925). It was first recorded in 1988 in the province of KwaZulu-Natal (KZN), RSA and economic losses were reported in RSA in the Midlands area of KZN in the 1990/91 maize growing season (Ward *et al.*, 1996; Ward *et al.*, 1999; Caldwell, 2000). Commercial maize in KZN accounts for just on 4.3% of the national maize crop. This is worth R563 million using an average of the yellow and white maize price for the 2001/02 season (at R1 332.87 ton^{-1}) (Anonymous, 2003).

Present commercial control measures consist of one or two fungicide sprays, combined with resistant/tolerant maize cultivars. Previously, commercial control measures were fungicides sprayed up to three times (Ward *et al.*, 1996). Control measures for small-scale farmers are limited to resistant cultivars (Ward *et al.*, 1999). A number of highly resistant/tolerant cultivars have become commercially available within the last three years (Anonymous, 2002). The use of these more resistant cultivars has enabled commercial producers to reduce fungicide sprays to one or two in a season.

Due to the continued need for fungicide control and the way the progression of the GLS epidemic is different every season, *i.e.*, disease progress does not always follow the same pattern, modelling disease progression is important. The questions most often asked by commercial maize producers are when to apply the first fungicide spray and whether subsequent fungicide sprays are required. By modelling GLS progression at the field level these questions can be answered.

Generally, fungicides are applied on a calendar basis as farmers do not have the equipment to measure climatic data, do not have access to proven models to time fungicide sprays according to weather, do not trust the available models and would

rather over-spray than under-spray if the latter means running the risk of crop failure. This means that, irrespective of prevailing climatic conditions, fungicides are applied at set intervals. This often leads to over-use of fungicides and fungicide abuse, as fungicides are applied when conditions for pathogen development are not suitable, leading to unnecessary application of fungicides. With the advent of highly specific systemic fungicides, over-use of systemic products easily lead to resistance build-up by the pathogen.

Resistance build-up is of major concern to agrochemical manufacturers, as a new fungicide costs millions to synthesise, test, register and market. Due to the costs of developing new fungicides it is in all stakeholders best interests to protect and lengthen the effective life of fungicides.

Strategies to reduce resistance build-up to fungicides include limiting their use during periods favourable to disease development and applying the product in a preventative manner and not curatively.

The advantages of timing fungicide control measures through modelling include:

- determining the optimum time for infection
- application of fungicides when conditions are suitable for infection, not on a calendar base
- fungicide use may be reduced
- extended length of the effective life of a fungicide is lengthened due to optimum timing of fungicide applications
- curative use is avoided by optimising the time of application
- unnecessary applications are avoided
- reducing environmental pollution by cutting out unnecessary fungicide sprays.

The aim of this trial was to evaluate the use of disease progress models in the timing of fungicide control measures.

3.2 Materials and methods

3.2.1 Trial site

The Cedara Research Station (29°32'S, 30°16'E), of the KZN Department of Agriculture and Environmental Affairs (KZNDAE), is situated approximately 20 kilometres north of Pietermaritzburg, KZN, RSA. Cedara is 1076 m high above mean sea level, in Bioclimatic Zone 3 (Phillips, 1969), which is classed as Mistbelt. This area is highly conducive to the development of fungal diseases, due to frequent misty conditions, causing prolonged duration of leaf wetness, which aids fungal germination and development.

Generally the climate is hot and wet, with high humidity during the summer growing season and cold and dry conditions during winter. Soil at the 2000/01 trial site soil is a deep red Hutton form (MacVicar, 1991), with a depth of 1 metre. Clay content was approximately 35%. The previous maize crop on the land was used for silage. The 2001/02 trial was planted on a different range, due to re-contouring of the first season's trial site. The previous crop for the 2001/02 trial was dry beans. Table 3.1 presents the soil analyses for the 2000/01 and 2001/02 trials. Table 3.2 shows climatic data for the 2000/1 and 2001/02 seasons.

Table 3.1 Soil analysis of Cedara trial site for the maize trial for the 2000/01 and 2001/02 trials

Year	Sample density (g/ml)	P	K	Ca	Mg	Acidity (Al+H)	Total cations	Acid sat. (%)	pH (KCl)	NIRS clay (%)
		--------(mg/L)----------								
2000/01	1.04	22	201	1042	139	0.38	7.24	5	4.47	35
2001/02	1.04	11	135	1037	268	0.17	7.90	2	4.84	45

Table 3.2 Long-term averages for Cedara (average of 30.5 years) and averages from the maize trial growing seasons for 2000/01 and 2001/02

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Max Temp	22.3	23.4	24.8	25.2	25.3	22.4	20.6	18.6
2000/01	22.4	21.7	25.2	24.9	24.6	19.3	16.1	13.8
2001/02	23.7	25.5	25.9	28.0	25.3	19.5	17.7	13.7
Min Temp	10.8	12.6	14.1	15.3	15.2	14.0	10.7	6.7
2000/01	11.4	12.1	14.0	13.8	14.4	10.2	7.8	1.2
2001/02	11.5	13.3	13.2	14.9	13.9	13.6	7.1	-0.8
Rain	89.3	108.3	127.8	139.6	115.9	110.5	51.6	27.7
2000/01	65.9	166.4	131.8	117.6	111.1	45.6	103.6	7.4
2001/02	116.2	125.5	157.5	159.4	58.2	58.8	60.6	6.4
Rain days	10.9	13.0	14.3	13.6	11.2	11.0	6.2	3.0
2000/01	11	12.6	13.8	13.6	11.1	11	10	2
2001/02	23	19	25	17	12	8	5	4
Sun hours	176.5	167.2	174.9	178.6	173.0	196.6	215.7	237.5
2000/01	124.2	137.3	149.1	183.8	163.1	**	**	**
2001/02	159.3	166.9	175.6	187.4	154.3	**	**	**

** - unavailable

3.2.2 Trial layout

Three cultivars were used in the trial, based on three recognised cultivar groups, *i.e.*, susceptible (SC206), medium susceptible (PAN6568) and resistant (SC627) (Ward *et al.*, 1996; Ward, personal communication)[6]. Three treatments, consisting of an unsprayed control, a single spray and a double spray treatment, were used. The same number of treatments and cultivars were retained for the 2001/02 season.

[6] Dr J.M.J. Ward, Crop Protection, Cedara, Department of Agriculture and Environmental Affairs, Private Bag X9059, Pietermaritzburg, South Africa, 3200.

For both seasons the trial design was a randomised block design. Gross plots were four rows by six metres long. Net plot size was two rows by 5.2 metres long. The trial was surrounded by two border rows of maize to reduce fungicide spray drift.

Table 3.3 Trial layout of Cedara maize fungicide trial, 2000/01 season

I 1 SC206 NS	II 5 PAN6568 1S	II 6 SC627 NS	III 4 SC206 2S
I 2 SC206 2S	II 4 SC206 2S	II 7 SC206 1S	III 5 PAN6568 1S
I 3 SC206 1S	II 3 SC627 2S	II 8 SC627 1S	III 6 SC206 1S
I 4 PAN6568 NS	II 2 PAN6568 NS	II 9 PAN6568 2S	III 7 PAN6568 NS
I 5 SC627 2S	II 1 SC206 NS	III 1 PAN6568 2S	III 8 SC627 NS
I 6 SC627 NS	I 9 PAN6568 1S	III 2 SC627 1S	III 9 SC627 2S
I 7 PAN6568 2S	I 8 SC627 1S	III 3 SC206 NS	

Table 3.4 Trial layout of the 2001/02 Cedara maize fungicide trial

III 7 SC206 1S	III 8 PAN6568 NS	III 9 PAN6568 1S						
III 6 SC627 1S	III 5 SC627 2S	III 4 PAN6568 2S	III 3 SC206 NS	III 2 SC206 2S	III 1 SC627 NS
II 4 SC627 1S	II 5 PAN6568 1S	II 6 SC206 1S	II 7 SC206 NS	II 8 SC206 NS	II 9 PAN6568 NS
II 3 SC627 NS	II 2 SC627 2S	II 1 SC206 2S	I 9 SC627 1S	I 8 PAN6568 2S	I 7 SC206 1S
I 1 SC206 NS	I 2 SC206 2S	I 3 PAN6568 NS	I 4 SC627 2S	I 5 PAN6568 1S	I 6 SC627 NS

3.2.3 Land preparation

Immediately before planting, fertilizer was band applied by means of a John Deere 7200 series No-till planter. All plots received 19.3 kg N ha^{-1}, 28.9 kg P ha^{-1}, 38.6 kg K ha^{-1} and 2.9 kg Zn ha^{-1} (as a compound fertilizer 2:3:4 (30) + 1% Zn). For both seasons, fertilizer was applied for an 8 ton ha^{-1} yield.

Rows were created with the John Deere 7200 planter at 0.75 m. The 2000/01 trial was hand-planted on 22 November 2000 and on 11 November 2001 for the 2001/02 trial. Two seeds were planted per planting station 0.3 m apart using "jab planters".

Plant counts were taken to ensure full emergence and to check for gaps in the plant stand. Thinning to one plant per planting station was carried out to ensure a uniform plant stand of approximately 44 000 plants ha^{-1}. The 2001/02 trial was grown on a land with a high rat population, with the result that the plant stand was affected and the gaps in the row had to be filled twice by replanting with the "jab planters". The post emergent herbicide and insecticide treatments were applied when the crop was "knee height" (approximately 0.6 m tall).

For both seasons, the same pre-emergent herbicide was applied after planting with 549g s-metolachlor (Dual S Gold 915 EC, Syngenta, RSA), 761.25 g atrazine 507.5 g metolachlor 761.25 g terbuthylazine (Gardomil 700 SC, Novartis, RSA). A post-emergent herbicide was applied on 21 December 2000 and 2001 using 360 g atrazine 150 g sulcotrione (Galleon, Syngenta, RSA), 525 g acetochlor (Wenner 700 S EC, Dow AgroSciences, RSA) and 120 g 2,4-D (2,4-D Amine 480, Dow AgroSciences, RSA).

The trial was topdressed on 21 December 2000 and 2001 with 100 kg N ha^{-1} (as limestone ammonium nitrate; 28%N). Stalkborer control was achieved with 300 g monocrotophos (Nuvacron, Novartis, RSA) on 21 December 2000 and 2001.

3.2.4 Fungicide applications

Fungicide treatments were applied with a CO_2-pressurised back-pack sprayer fitted with a vertically mounted spray-boom. Whirlrain $^1/_4$" WRW2-20° nozzles were spaced one metre apart on a vertical boom. Fungicide sprays were applied in 450 l ha^{-1} (Ward *et al.*, 1996). The standard fungicide used was azoxystrobin (Amistar, Syngenta, RSA) at 75g ha^{-1} active ingredient.

Fungicides were applied on 15 February 2001 (SC206 and PAN6568) and 15 March 2001 (SC206 only, because disease had not progressed on the other cultivars) for the 2000/01 trial. The 2001/02 trial was sprayed on 12 February and 26 March, regardless of disease progress and cultivar. Fungicide treatments were initiated at 2% level of observed disease (Ward *et al.,* 1997), when the basal five leaves of the crop showed GLS lesions. Rating of disease was by whole plot, using standard diagrams developed by (Ward *et al.,* 1997) and by single leaf rating of the fifth basal leaf. Single leaf area diagrams were developed by sampling the fifth basal leaf of each cultivar in the trial. This was then photo-reduced onto an A4 page and scanned into an image analysis software package (AnalySIS®, Soft Imaging System, Münster, Germany). Leaf area was measured with the software and diagrams depicting 0.25%, 0.5%, 0.75% and 1% leaf area infected were designed (Appendix 3.1, 3.2 and 3.3).

3.2.5 Disease assessments

Visual disease ratings were conducted and use was made of a disease prediction model (Chapter 1.5) to simulate disease spread through the field. This model used a weather file generated by an automatic weather station (AWS), which was situated on the edge of the trial area, outside the maize canopy. Data were recorded using an Adcon Telemetry A720 AddIT (Agrotop, Stellenbosch, South Africa). Parameters measured were temperature, RH, rainfall and leafwetness. Sensors were read every three minutes and recorded in datalogger memory every 15 minutes. A weather file with the daily maximum and minimum air temperature, total rainfall and number of hours of RH above 90% was generated daily (see Chapter 4) and used in the simulation model.

The prediction model (Chapter 1.5) was run on the same dates as the visual disease ratings were conducted. Residue cover of the crop was estimated at 10% in the 2000/01 and 5% in the 2001/02 seasons and incorporated into the model.

Area under disease progress curve (AUDPC) was calculated from visual disease rating data. The AUDPC was calculated using a trapezoidal integration program (Berger, 1981). Rate of disease progress was determined with Vanderplank's (1963) logistic equation:

$$X_1 = X_0.e^{rt}.(1-x)$$

where

X_1 is final disease;

X_0 is initial disease; **e** is natural log e;

r is the rate of disease progress;

t is time and

(1-x) is the correction factor.

3.2.6 Harvesting

Trials were hand-harvested on 20 June 2001 and 3 June 2002 from 6 m of the centre two rows of each plot. The harvested ears were weighed in the field. The plots were yielded and moisture and shelling percentage calculated. A Datatec moisture meter (Sinar Africa, Edenvale, South Africa) was used for moisture analysis. The moisture curve used was for "wet maize", *i.e.* 17 - 24% moisture. Shelling percentage was calculated by shelling a sub-sample of six randomly collected cobs from the net plot. The grain and shelled cobs were weighed separately and the shelling percentage calculated. Grain yield was expressed in ton ha^{-1} and adjusted to 12.5% grain moisture content.

3.2.7 Statistical analysis

Data were analysed using Genstat 5 release 4.2 for Windows (Anonymous, 2000). A significance level of 5% was used (LSD = 5 %). An analysis of variance (ANOVA) test was used. An angular transformation was used to normalise the coefficient of variation in the disease rating data. Disease severity ratings were analysed as area under disease progress curve (AUDPC) (Berger, 1981) at a 5 % level of significance (LSD), to determine differences in disease severity between treatments. The AUDPC values were standardized (SAUDPC) for comparison across seasons by dividing the AUDPC by the number of days the disease was observed.

3.2.8 Historical data

Historical data from when GLS started being investigated up to the 2000/01 season at Cedara was collated. This data was taken from the physical data sheets of various trials. Only cultivars that had been grown for the entire period and/or that were in the trial were used. Most of the data was compiled from Dr J.M.J Ward's notes on his trials that were conducted at Cedara over that time.

3.3 Results

Emergence was more than 50% on both 28 November 2000 and 3 December 2001.

Weather during the growing period was favourable and no extended drought periods existed to cause significant yield loss. No visible symptoms of phytotoxicity was observed after any of the fungicide applications.

3.3.1 Residue cover

The residue cover for the 2000/01 trial was low as the trial followed a maize silage trial where, of necessity, all maize was removed, leaving very little residue. For the 2001/02 trial the land used followed a dry bean crop, which left even less residue on the soil than the maize silage trial. Residue cover was estimated as 10% and 5% in the 2000/01 and 2001/02 trials, respectively.

3.3.2 Timing of fungicide applications

Fungicides were applied when visually rated disease on the maize was at 2%. This meant that in the 2000/01 trial, SC627 did not receive any fungicide sprays, as no GLS symptoms were observed and PAN6568 only received one spray application due to a lower disease severity. To prevent a re-occurrence of this, in the 2001/02 trial all cultivars were fungicide treated when SC206 (susceptible) reached the critical 2% level of disease. This ensured that even though SC627 did not develop GLS symptoms in the 2001/02 trial either, it was sprayed with fungicides to ensure all treatments received the same number of fungicide applications.

3.3.3 Disease assessments

Rating for disease started on 23 January 2001 and 29 January 2002. At this stage, no disease was observed in plots other than the occasional lesion (1 lesion on every 10

plants) on the susceptible cultivar (SC206). The last disease rating was on 9 April 2001 and 3 April 2002. Observed final disease percentage on unsprayed SC206 was 80% in 2000/01 and 93.3% in 2001/02. No GLS was observed on SC627 in either of the trials, while PAN6568 had a final disease percentage of 25% in 2000/01 and 11.7% in 2001/02.

In the 2000/01 season, GLS was the most significant fungal pathogen. However, maize rust (*Puccinia sorghi* Schwein) was also present on all three cultivars. At physiological maturity *Phaeosphaeria maydis* (P.Henn.) Rane, Payak and Renfro became more pronounced. No control measures were carried out against these diseases. The most prevalent diseases in 2001/02 were GLS and maize rust.

An angular transformation was applied to these disease ratings, to reduce the high coefficient of variation. SC206 had the highest level of disease in both the 2000/01 (63.43%) and 2001/02 (75.24%) trials.

No visible disease was observed at any stage on SC627. For the cultivar PAN6568 unsprayed final visible disease was 29.53% (2000/01) and 19.89% (2001/02) (Tables 3.5 and 3.6).

Table 3.5 Mean of observed whole plot percentage disease rating (angular transformation) for three cultivars, Cedara trial 2000/01

Rating Date	Treat	23/1	29/1	01/2	12/2	16/2	19/2	05/3	15/3	22/3	29/3	9/4
SC206	0s[1]	0.60	1.81	1.81	3.31	9.55	9.55	18.43	26.57	38.24	50.77	63.43
SC206	1s[2]	1.21	1.21	1.21	3.31	5.97	5.97	8.13	10.34	15.23	17.47	26.82
SC206	2s[3]	0.60	1.88	1.88	3.31	7.33	7.33	7.33	11.32	13.78	13.78	17.40
PAN6568	0s	0	1.21	1.81	1.81	3.31	3.31	9.73	13.78	16.21	23.36	29.53
PAN6568	1s	0	1.81	1.81	2.56	5.97	5.97	6.54	7.33	7.95	7.95	9.36
PAN6568	2s	0	0.60	0.60	1.81	2.56	2.56	4.05	4.62	6.54	6.54	8.47
SC627	0s	0	0	0	0	0	0	0	0	0	0	0
SC627	1s	0	0	0	0	0	0	0	0	0	0	0
SC627	2s	0	0	0	0	0	0	0	0	0	0	0
LSD spray		0.551	0.837	0.628	0.977	1.731	1.326	1.185	2.012	3.151	4.014	4.738
LSD cultivar		0.551	0.837	0.628	0.977	1.731	1.326	1.185	2.012	3.151	4.014	5.738
LSD spray X cultivar		0.954	1.450	1.088	1.692	2.999	2.296	2.053	3.485	5.458	6.953	8.206
CV %		205.4	94.7	85.2	52.6	44.9	37.6	19.7	24.5	29.0	30.4	27.5

(1) - Zero fungicide sprays

(2) - One fungicide spray

(3) - Two fungicide sprays

Table 3.6 Mean of observed whole plot disease (angular transformation) rating for three cultivars, Cedara trial 2001/02

Rating Date	Treatment	29/1	06/2	12/2	19/2	27/2	06/3	13/3	18/3	26/3	3/4
SC206	0s[1]	1.46	2.56	5.18	12.92	19.89	32.02	43.08	52.74	61.22	75.24
SC206	1s[2]	1.81	3.31	4.05	10.96	13.73	13.73	15.57	17.40	21.56	25.00
SC206	2s[3]	1.27	2.56	5.18	10.34	11.94	13.73	14.76	14.76	18.05	18.05
PAN6568	0s	1.21	1.81	2.56	4.62	6.54	12.92	14.76	14.76	17.82	19.89
PAN6568	1s	1.21	1.21	2.56	4.05	7.01	4.05	4.62	4.62	4.62	5.74
PAN6568	2s	1.81	1.81	3.31	4.05	4.05	4.05	4.62	4.62	6.17	8.93
SC627	0s	0	0	0	0	0	0	0	0	0	0
SC627	1s	0	0	0	0	0	0	0	0	0	0
SC627	2s	0	0	0	0	0	0	0	0	0	0
LSD spray		0.585	0.762	0.783	0.929	1.931	1.735	1.951	1.579	3.094	3.143
LSD cultivar		0.585	0.762	0.783	0.929	1.931	1.735	1.951	1.579	3.094	3.143
LSD spray X cultivar		1.014	1.320	1.357	1.609	3.345	3.005	3.379	2.734	5.359	5.444
CV %		60.1	51.8	30.9	17.8	27.5	19.4	18.2	13.1	21.5	18.5

(1) - Zero fungicide sprays

(2) - One fungicide spray

(3) - Two fungicide sprays

Log transformed AUDPC of the two trials is shown in Table 3.7. The purpose of the log conversion was to straighten the line and reduce the effect of variation among the three replicates in the trial.

Table 3.7 Log transformed AUDPC of three cultivars, Cedara 2000/01 and 2001/02 trials

Treatment	Cultivar					
	SC206		PAN6568		SC627	
	2000/01	2001/02	2000/01	2001/02	2000/01	2001/02
0 spray	7.355	7.584	6.000	5.494	0.000	0.000
1 spray	5.674	5.974	4.504	3.705	0.000	0.000
2 spray	5.341	5.666	3.887	3.746	0.000	0.000
	2000/01			2001/02		
LSD spray	0.3046			0.2339		
LSD cultivar	0.3375			0.2339		
LSD spray X cultivar	0.5276			0.4051		
CV %	8.4			6.5		

Table 3.8 presents the disease progress of the three cultivars in the 2000/01 and 2001/02 seasons. Actual observed disease ratings are presented, as well as the results of the simulation model. SC627 is included in the Table even though no disease was observed on this cultivar in both the 2000/01 and 2001/02 trials. The prediction model predicted the development of disease on SC627 in both seasons. For the 2000/01 trial, an estimated residue cover of 10% was used and emergence date as day 333/2000, while for the 2001/02 season an estimated residue cover of 5% was used and emergence date as day 326/2001.

The results of the observed disease and the predicted disease were analysed using regression analysis:

SC206:

2000/01	Intercept = 4.55	Slope of the fitted line = 0.6387
2001/02	Intercept = -3.21	Slope of the fitted line = 0.6870

PAN6568:

2000/01	Intercept = 0.681	Slope of the fitted line = 0.2064
2001/02	Intercept = -0.065	Slope of the fitted line = 0.2145

SC627: As no disease was observed, data were not analysed.

For the relationship between observed and predicted disease the slope and intercept are as follows:

2000/01	Intercept = 1.724	Slope of the fitted line = 0.5164
2001/02	Intercept = -2.14	Slope of the fitted line = 0.5445

Table 3.8 Mean values of the predicted and actual observed disease levels on three maize cultivars in the 2000/01 and 2001/02 seasons, using an estimated residue cover of 10% and day of emergence as 333 for 2000/01 and estimated residue cover of 5% and day of emergence as 326 for 2001/02

Predicted																	Observed													
DOY*	DOY*	SC206						PAN6568					SC627				SC206						PAN6568					SC627			
		2000/01			2001/02			2000/01		2001/02			2000/01	2001/02			2000/01			2001/02			2000/01		2001/02			00/01	2001/02		
2000/01	2001/02	NS*	1S*	2S*	NS	1S	2S	NS	1S	NS	1S	2S	NS	NS	1S	2S	NS*	1S*	2S*	NS	1S	2S	NS	1S	NS	1S	2S	NS	NS	1S	2S
23	29	0.6	0.6	0.6	0.1	0.1	0.1	0.5	0.5	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0	0.1	0	0.1	0.1	0.1	0	0	0.1	0.1	0.1	0	0	0	0
29	37	1.2	1.2	1.2	0.4	0.4	0.4	0.8	0.8	0.3	0.3	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0	0	0	0
32	43	1.6	1.6	1.6	0.5	0.4	0.4	1.1	1.1	0.3	0.3	0.3	0.5	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.5	0.8	0.1	0.1	0.2	0.2	0.4	0	0	0	0
43	50	4.6	4.6	4.6	1.1	0.4	0.4	2.8	2.8	0.6	0.3	0.3	1.0	0.2	0.1	0.1	0.4	0.4	0.4	5.0	3.7	3.3	0.1	0.2	0.7	0.5	0.5	0	0	0	0
47	58	6.3	5.6	4.6	3.0	0.4	0.4	3.7	3.3	1.5	0.3	0.3	1.2	0.4	0.1	0.1	1.2	1.2	1.7	11.7	5.7	4.3	0.4	1.2	1.3	2.0	0.5	0	0	0	0
50	65	8	5.6	4.6	8.6	0.4	0.4	4.5	3.3	3.9	0.3	0.3	1.4	0.7	0.1	0.1	1.2	1.2	1.7	28.3	5.7	5.7	0.4	1.2	5.0	0.5	0.5	0	0	0	0
64	72	33.5	5.6	4.6	14.9	0.4	0.4	14.6	3.3	6.3	0.3	0.3	3.2	1.0	0.1	0.1	10	2	1.7	46.7	7.3	6.7	3	1.3	5.7	0.7	0.7	0	0	0	0
74	77	79.6	5.6	4.6	30.1	0.4	0.4	38.4	3.3	12.0	0.3	0.3	6.5	1.7	0.1	0.1	20	3.3	4	63.3	9.0	6.7	6	1.7	6.7	0.7	0.7	0	0	0	0
81	85	100	5.8	4.6	80.8	0.6	0.4	55.7	3.5	32.3	0.4	0.3	8.9	3.4	0.1	0.1	38.3	7.7	6	76.7	14.0	10.0	8.3	2	9.7	0.7	1.2	0	0	0	0
88	93	100	6.0	4.6	95	0.6	0.4	93.4	3.7	38.8	0.4	0.3	14.3	4.0	0.1	0.1	60	10	6	93.3	18.3	10.0	16.7	2	11.7	1.0	2.7	0	0	0	0
99		100	7.0	4.6				100	4.1				22.7				80	21.7	9				25	2.7				0			

* DOY-Day Of Year NS-No Spray 1S-1 Spray 2S-2 Spray

The differences between the observed and the predicted incidence of disease are shown in Figures 3.1 to 3.4.

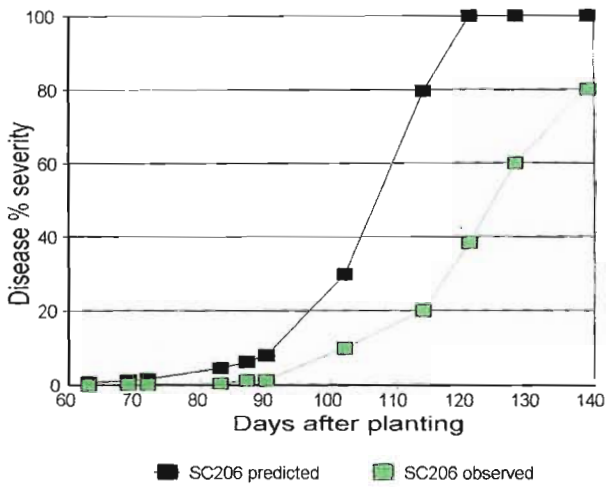

Figure 3.1 Unsprayed control SC206 (susceptible) showing observed and predicted disease severity, Cedara 2000/01

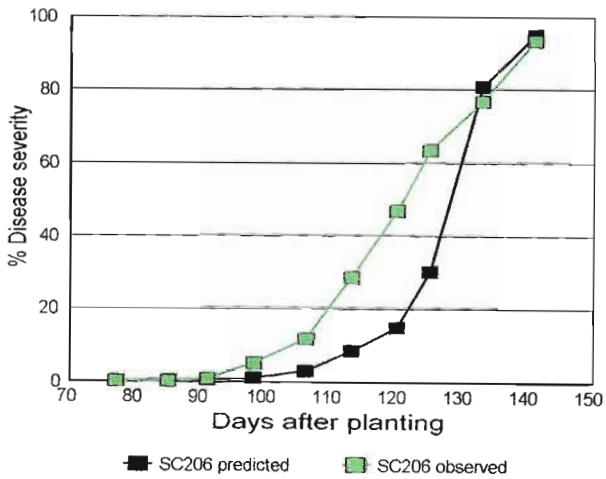

Figure 3.2 Unsprayed control SC206 (susceptible) showing observed and predicted disease severity, Cedara 2001/02

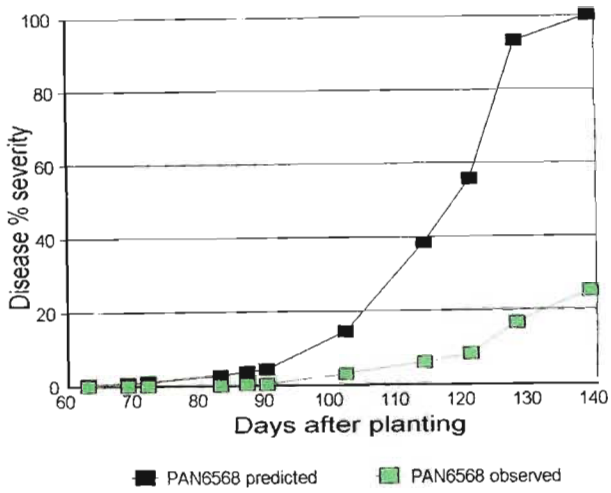

Figure 3.3 Unsprayed control PAN6568 (medium tolerant) showing observed and predicted disease severity, Cedara 2000/01

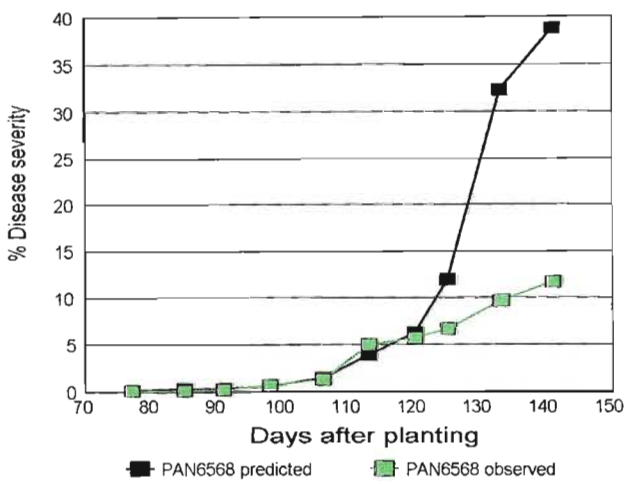

Figure 3.4 Unsprayed control PAN6568 (medium tolerant) showing observed and predicted disease severity, Cedara 2001/02

A different approach to show the result and the speed at which GLS progresses would be to use Vanderplank's (1963) logistic equation for apparent infection rate. These graphs are presented in Figures 3.5 to 3.8, using the rate of infection of the cultivar SC206 and PAN6568. Treatments applied to SC206 and PAN6568 include no spray, 1 spray and 2 sprays.

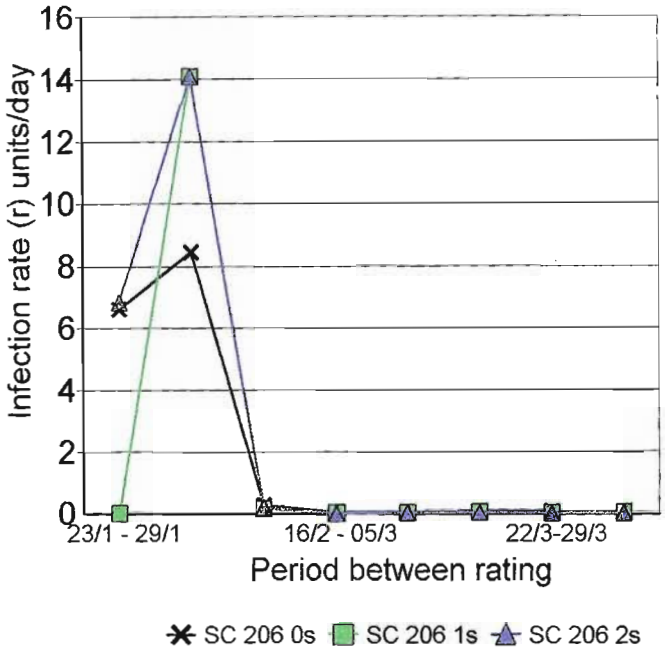

Figure 3.5a Apparent rate of infection (r) for SC206 for the 2000/01 season using zero (0s), one (1s) and two (2s) fungicide sprays

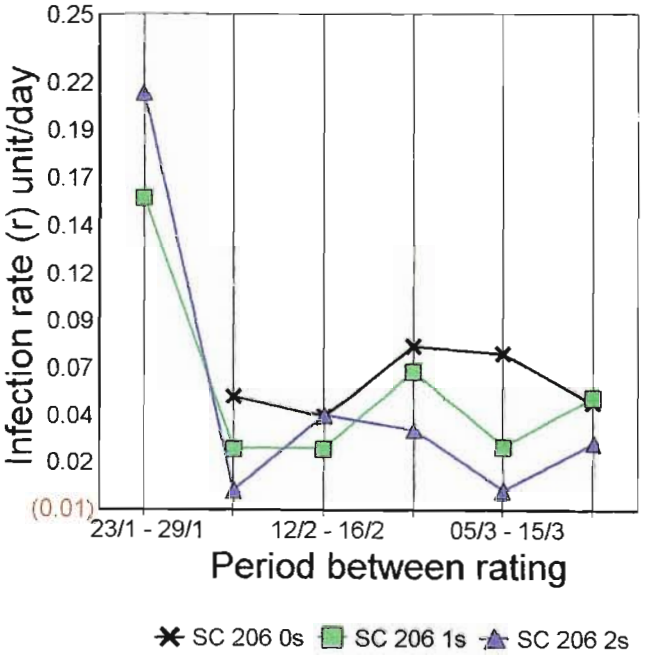

Figure 3.5b Close-up of Fig. 3.5a showing the fluctuations in "r" for SC206 in the 2000/01 season

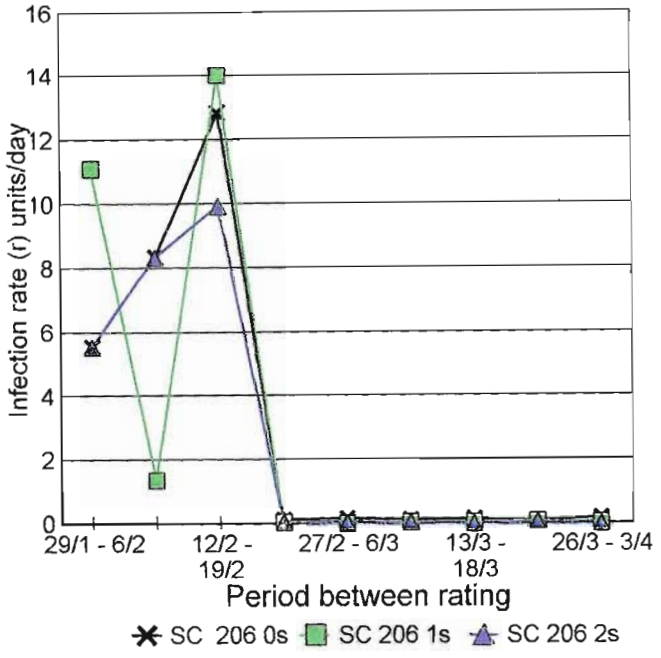

Fig 3.6a Apparent rate of infection (r) for SC206 for the 2001/02 season using zero (0s), one (1s) and two (2s) fungicide sprays

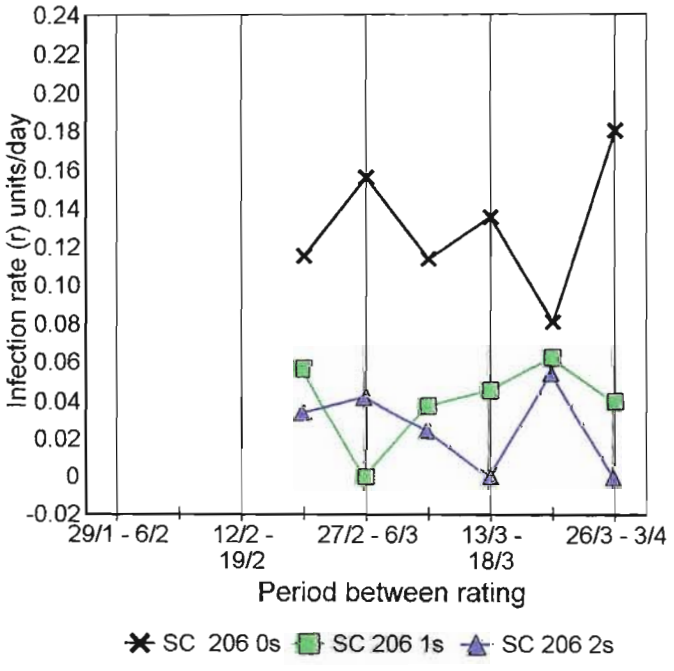

Figure 3.6b Close-up of Fig. 3.6a showing the fluctuations in "r" for SC206 in the 2001/02 season

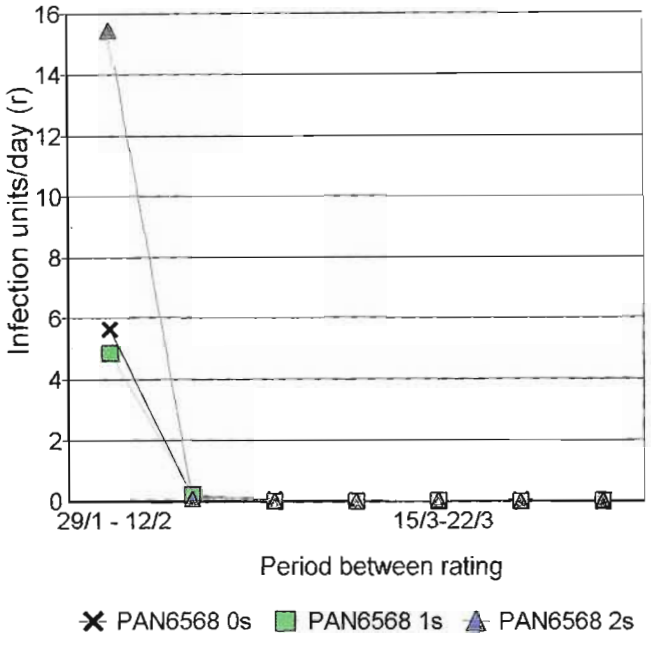

Figure 3.7a Apparent rate of infection (r) for PAN6568 for the 2000/01 season using zero (0s), one (1s) and two (2s) fungicide sprays

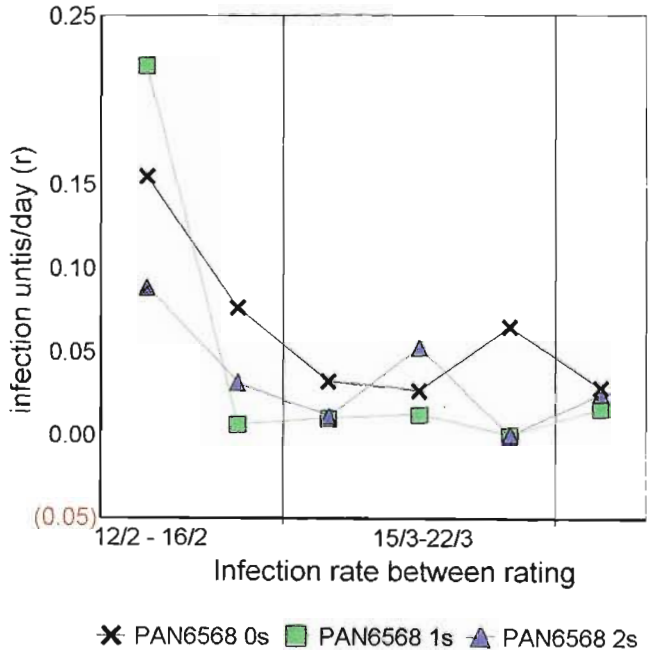

Figure 3.7b Close-up of Fig. 3.7a showing the fluctuations in "r" for PAN6568 in the 2000/01 season

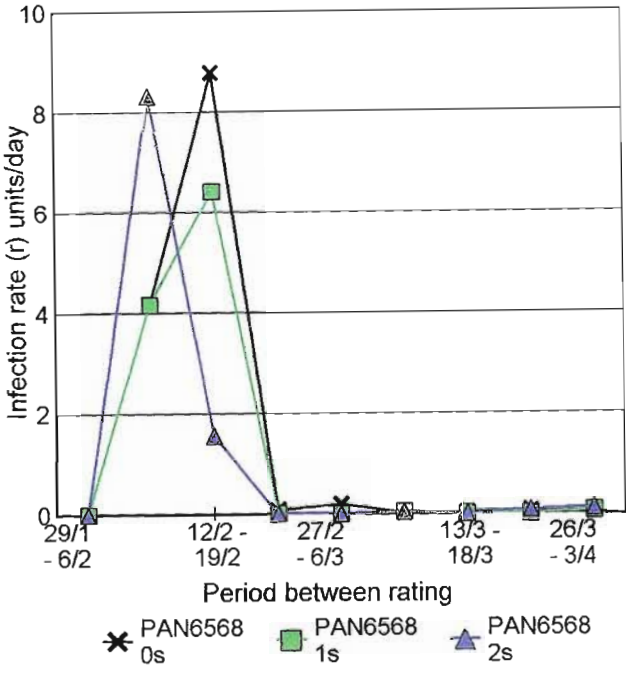

Figure 3.8a Apparent rate of infection (r) for PAN6568 for the 2001/02 season using zero (0s), one (1s) and two (2s) fungicide sprays

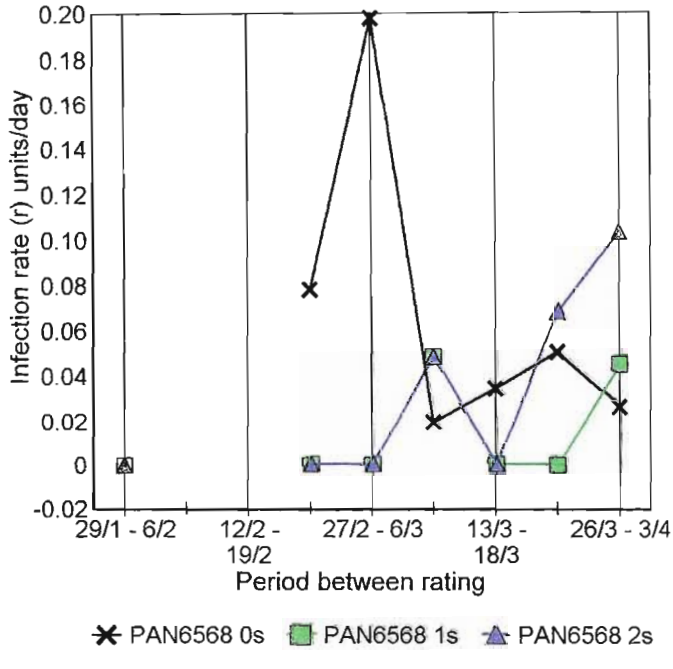

Figure 3.8b Close-up of Fig. 3.8a showing the fluctuations in "r" for PAN6568 in the 2001/02 season

3.3.4 Yield

Cultivar SC206 produced fewer cobs than there were plants in both the 2000/01 and 2001/02 seasons. There are no significant differences between the three SC206 treatments, *i.e.*, unsprayed, 1 and 2 sprays.

In both seasons, more cobs were produced than there were plants for PAN6568. In the 2001/02 season there was a significant difference between unsprayed and sprayed treatments. There was also a significant difference between the unsprayed treatment and sprayed treatments plant count at harvest.

There is no clear pattern of cob and plant number for SC627 compared to the other two cultivars (Table 3.9).

Table 3.9 Final plant count and harvested cobs for three cultivars, Cedara trial 2000/01 and 2001/02 seasons

	Cultivar											
	SC206				PAN6568				SC627			
	2000/01		2001/02		2000/01		2001/02		2000/01		2001/02	
Treatment	P*	C**	P	C	P	C	P	C	P	C	P	C
0 spray	35.33	32.00	36	34.3	37.67	43.33	36.3	37.7	37.67	39.00	37.7	37.3
1 spray	32.67	32.00	37	34.3	37.33	43.33	39	44.7	32.00	39.33	35.3	34.7
2 spray	36.33	31.00	35.7	34.3	34.33	46.67	39	42	37.67	39.00	33.7	32

	2000/01		2001/02	
	Plant number	Cob number	Plant number	Cob number
LSD spray	3.114	3.916	1.769	3.216
LSD cultivar	3.114	3.916	1.769	3.216
LSD spray X cultivar	5.393	6.783	3.064	5.570
(CV) %	8.7	10.2	4.8	8.8

* Number of plants; ** Number of cobs

Yields for cultivars are not typical, e.g., the susceptible cultivar SC206 was expected to show a linear increase in yield. Cultivar PAN6568 performed as would be expected of a medium resistant cultivar, in that a yield increase was visible after the first fungicide spray, with the effect levelling off after the second fungicide application. The resistant cultivar SC627 does not behave as would be expected as there was a yield decrease with increasing fungicides in both years. Usually the yield response curve of a resistant cultivar is level. There was a significant difference between the unsprayed treatment and the two spray treatments in the 2000/01 trial (Table 3.10, Figures 3.9 and 3.10).

Table 3.10 Total yield in ton ha^{-1} corrected to 12.5% moisture, for three cultivars with three different spray treatments at Cedara in the 2000/01 and 2001/02 seasons

Treatment	Cultivar					
	SC206		PAN6568		SC627	
	2000/01	2001/02	2000/01	2001/02	2000/01	2001/02
0 spray	7.90	6.32	9.30	6.95	8.87	7.72
1 spray	9.97	8.37	9.93	9.02	8.37	7.85
2 spray	10.00	8.22	10.10	8.71	7.93	6.88
	2000/01			2001/02		
LSD spray	0.712			0.920		
LSD cultivar	0.712			0.920		
LSD spray X cultivar	1.233			1.594		
CV %	7.8			11.8		

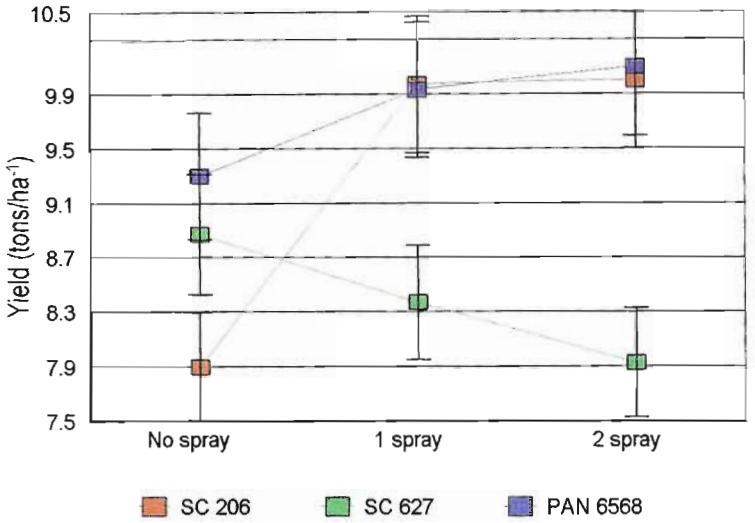

Figure 3.9 Yield (ton ha^{-1}) of three cultivars with three spray treatments at Cedara, 2000/01 trial

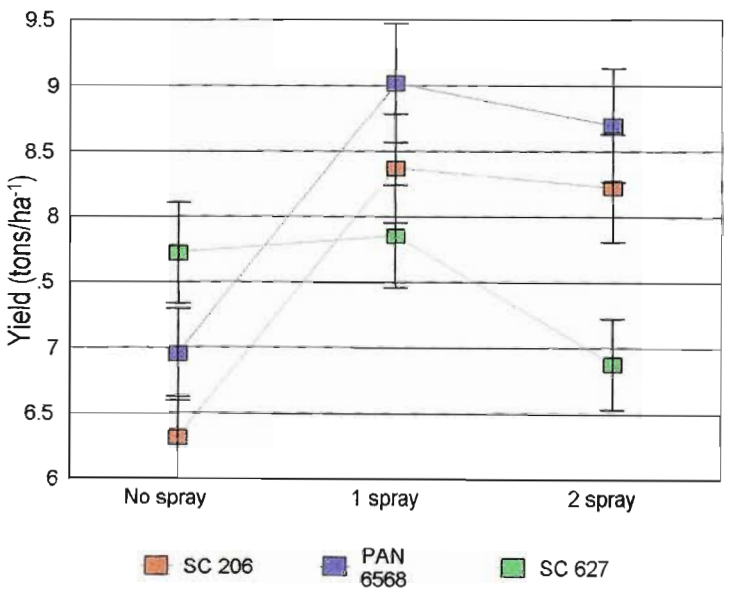

Figure 3.10 Yield (ton ha^{-1}) of three cultivars with three spray treatments at Cedara, 2001/02 trial

The yield response curve of SC627 did not fit the expected response of a cultivar resistant to GLS. Soil samples from around the net plot were taken in an attempt to explain the variation. Although SC627 had no fungicide sprays at all in the 2000/01 trial there is a negative effect in three replicated plots. Therefore there must be a soil effect, but the questions as to why no block effect exists is not answered. The high soil fertility around the unsprayed treatment in replicate two may have increased the yield (Table 3.11).

Table 3.11 Post-harvest soil samples (samples from SC627 zero spray and two spray treatments) for the 2000/01 maize trial at Cedara

Rep & treatment	Sample density (g/ml)	P	K	Ca	Mg	Acidity (Al+H) cmol/L	Total cations cmol/L	Acid sat. (%)	pH (KCl)	NIRS clay (%)
		--------(mg/L)---------								
I-Ns	1.04	22	121	833	109	0.36	5.72	6	4.46	38
II-Ns	1	33	192	1147	140	0.30	7.67	4	4.48	41
III-Ns	1.02	18	182	882	107	0.59	6.34	9	4.39	39
I-2s	1.06	20	118	1095	129	0.36	7.19	5	4.49	34
II-2s	1.04	20	139	1051	128	0.33	6.98	5	4.51	36
III-2s	1.01	22	150	934	113	0.53	6.50	8	4.41	39

Even though SC627 had no disease it yielded less than PAN6568, which ended the season with approximately 28% and 8% in the 2000/01, 2001/02 seasons respectively. The general trend for PAN6568 was that as disease increased (thick dark line) so yield decreased (thin line) (Figure 3.11 and 3.12).

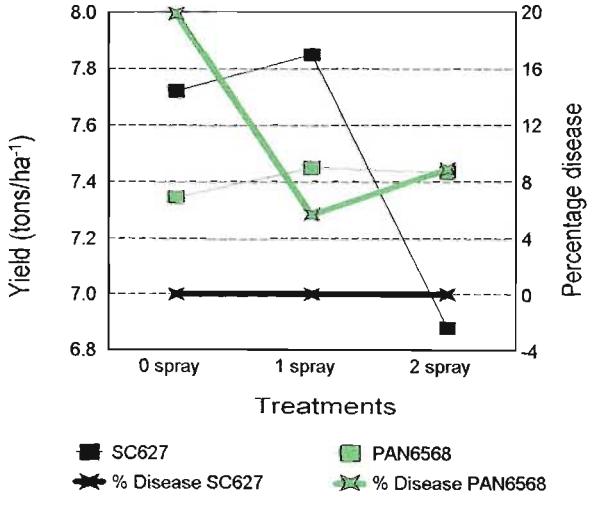

Figure 3.11 Differences between yield obtained and final percentage disease level for SC627 and PAN6568, using an angular transformation, in the Cedara 2000/01 trial

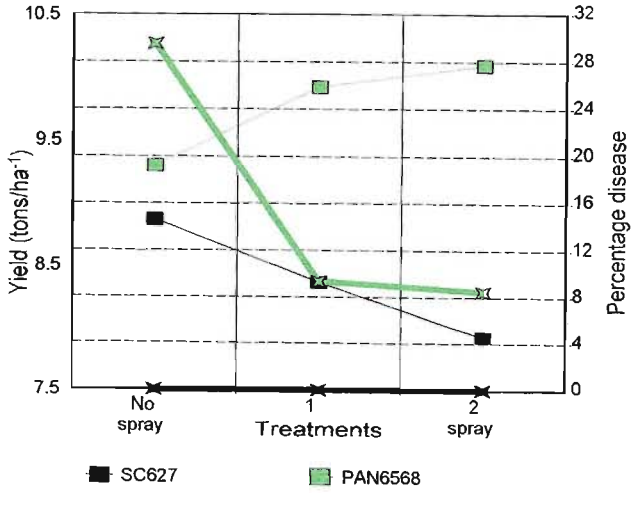

Figure 3.12 Differences between yield obtained and final disease level for SC627 and PAN6568, using an angular transformation, in the Cedara 2001/02 trial

3.3.5 Fluctuating disease severity over seasons

Figure 3.13 shows the decrease in apparent infection rate for a number of cultivars and the influence of rainfall on the development of disease from 1991 - 2002. There is no visible pattern between apparent rate of infection and rainfall in the growing season over these years. Figure 3.14 shows the standardised area under disease progress curve (SAUDPC) for the same cultivars and period, with rainfall included.

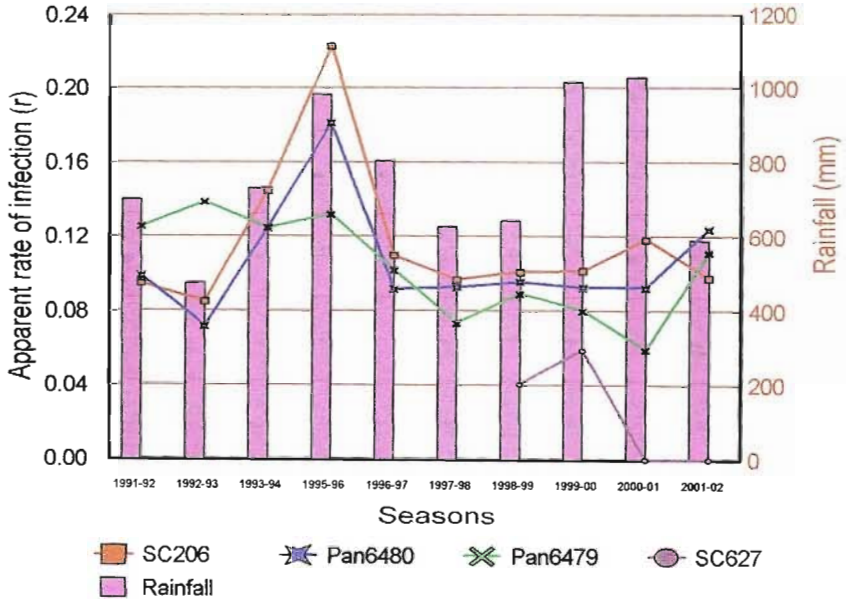

Figure 3.13 Apparent infection rate ('r') from 1991-2002 at Cedara for a susceptible (SC206), two medium resistant (PAN6480 and PAN6479 slightly more resistant) and a resistant cultivar (SC627) from 1998-2002 and total rainfall per season.

Figure 3.15 shows the disease progress curves from the 1992-93, 1995-96, 1998-99 and 2000-01 seasons. These graphs have been standardised across time and show the delayed reaction from infection to 90% leaf area infected, across the seasons.

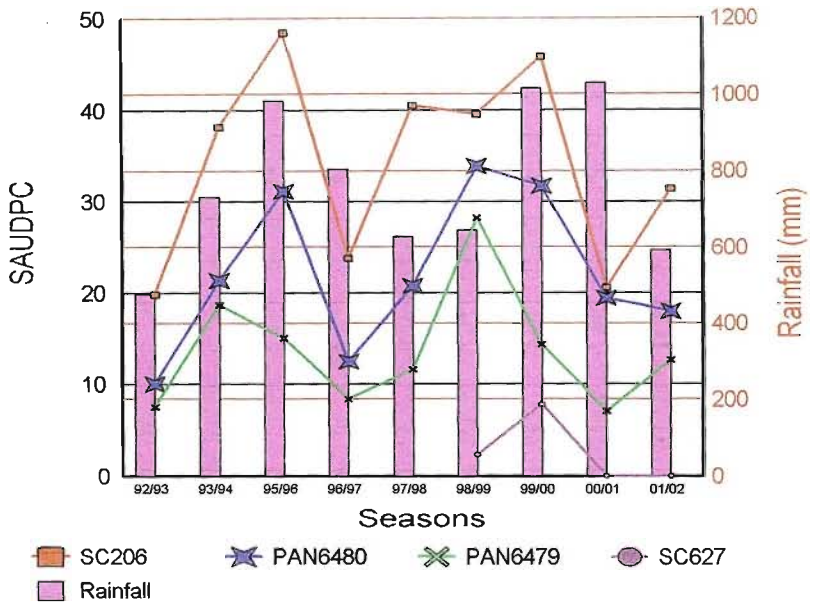

Figure 3.14 Standardised area under disease progress curves (SAUDPC) at Cedara for a susceptible (SC206), two medium resistant (PAN6480 and PAN6479 slightly more resistant) and a resistant cultivar (SC627) from 1998-2002 and total rainfall per season.

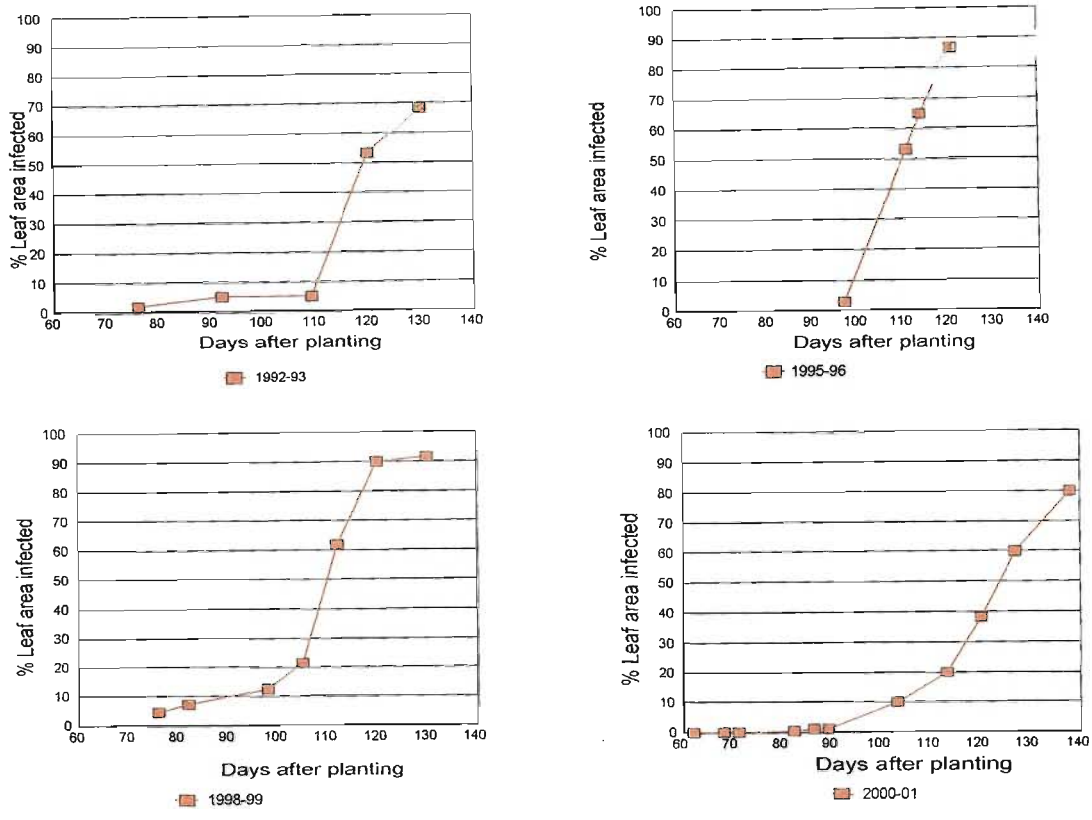

Figure 3.15 Disease progress curves from the 1992-93, 1995-96, 1998-99 and 2000-01 seasons, showing the effect of X_0 (initial inoculum) on progress of disease

3.4 Discussion and conclusion

For the 2000/01 trial, the effect of the reduced inoculum (from the previous maize crop harvested for silage) was evident in the delay of the initial onset of the epidemic. While the trial below the site on which this trial was planted had a higher level of disease earlier in the season, it had a high maize stover level (Lawrance, personal communication)[7]. The 2001/02 trial was planted after a dry bean crop with low residue counts and also exhibited a delayed onset of disease.

[7] K.L. Lawrance, Agricultural Research Council - Grain Crops Institute, Cedara, Private Bag X9059, Pietermaritzburg, South Africa 3200.

The higher the residue cover, the faster GLS symptoms spread up the plant. This effect is due to the higher initial inoculum associated with higher residue cover (Beckman and Payne, 1982; Ward *et al.*, 1999).

The estimated residue cover in both the 2000/01 and the 2001/02 trial were incorrect. The estimations were too high and the effect of this is discussed in Chapter 1 (Figures 1.3 and 1.5). These exaggerated levels of initial inoculum caused the model to simulate a faster spread of disease than actually occurred. This impacted negatively on the timing of fungicide sprays, as forecast by the model, and the predicted disease severity (Table 3.8 and Figure 3.1). However, for the 2001/02 trial the error level was not as great and the prediction was closer to the observed spread of disease. This error serves to show the sensitivity of the model to the residue input and the importance of initial infected inoculum in the rate of disease progress.

A suggestion for the improvement of the model is that the quantity of infected residue is used as an input to the model and not the total percentage of crop residue on the surface. The reason for this is that when the model was designed (Berry *et al.*, 1995) in the early-mid 1990's, the GLS epidemic was at its peak and there was a lower level of commercially available genetic resistance (Figure 3.13). This effectively meant that the model assumed that most commercial crops, if left unsprayed, would end the season with close to 90-100% leaf blighting and that all the residue on the field at planting was infected. The relatively high levels of current genetic resistance means that at the end of the season some fields have no GLS and others are below 40% (Table 3.8).

To input the actual level of infected residue is simple, provided that the final level of disease is known on the crop from the previous season. For instance, if the previous season ended with 50% leaf blighting and the field had 10% residue at planting then only 5% would be passed to the model as half of the available residue is not infected.

The 1998/99, 1999/00, 2000/01 and 2001/02 seasons were analysed (Figure 3.15, 3.16, 3.17, 3.18) using observed disease progression data, total residue at planting and infected residue at planting, based on the previous season's final incidence of disease.

By using infected residue at planting the model becomes more dynamic, as it receives feedback from season to season.

For the 1998/99 season, predicted disease progression curves, regardless of feedback of amount of infected residue or total residue, initially predicted lower disease incidence than observed levels of disease. Using infected residue did give a better fit than using total amount of residue at planting (Figure 3.15).

In the 1999/00 season, total residue gave a good fit to observed disease in the beginning of the season but disease progression is over-predicted at the end of the season. Using the amount of infected residue gives a better overall visual fit to the observed disease progression curve (Figure 3.16).

For the 2000/01 season, the amount of infected residue gives an excellent fit of predicted disease progression to observed disease throughout the season (Figure 3.17).

In the 2001/02 season, total residue at planting gave a better fit to observed disease progression than using the amount of infected residue (Figure 3.18). The infected residue disease progression curve tends to under-predict for the beginning half of the season. This may be due to the incorrect estimate of residue at planting for this trial.

From the four seasons analysed, using the amount of infected residue (feedback) at planting, rather than the total amount of residue at planting, gives a better fit to the observed disease progression in three of the seasons. The recommendation, therefore, is that feedback needs to be included in the model inputs, as it allows the model to be more dynamic and slow down the speed of disease progression, which tends to be a problem when using total amount of residue at planting.

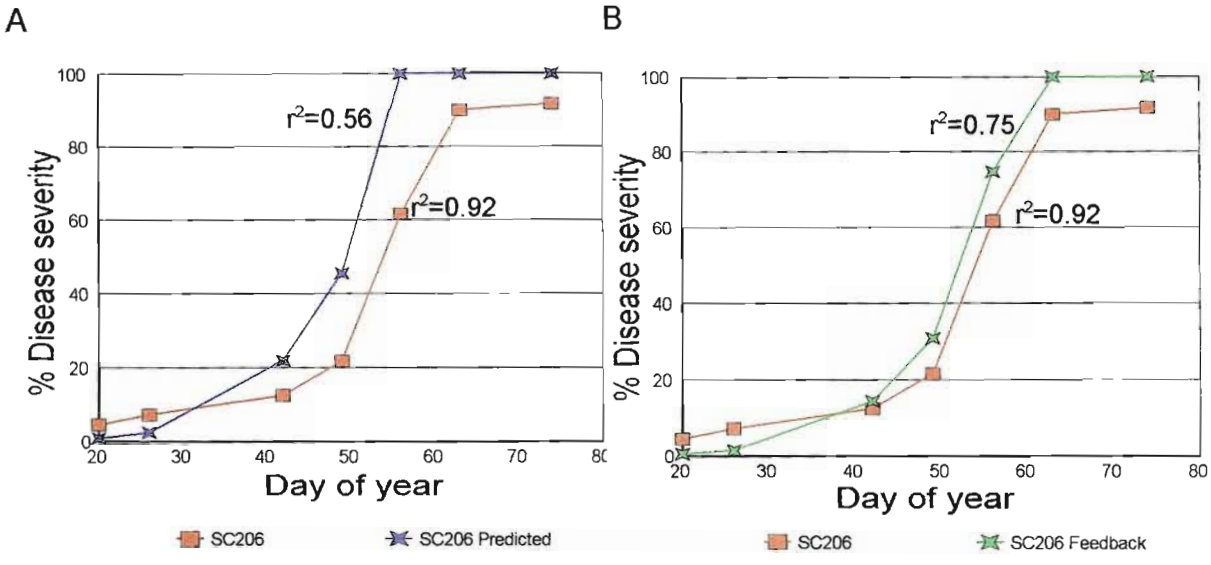

Figure 3.15 1998/99 season with total residue at planting (A) and with the previous season's final disease incidence used to calculate infected residue at planting (B) for the cultivar SC206.

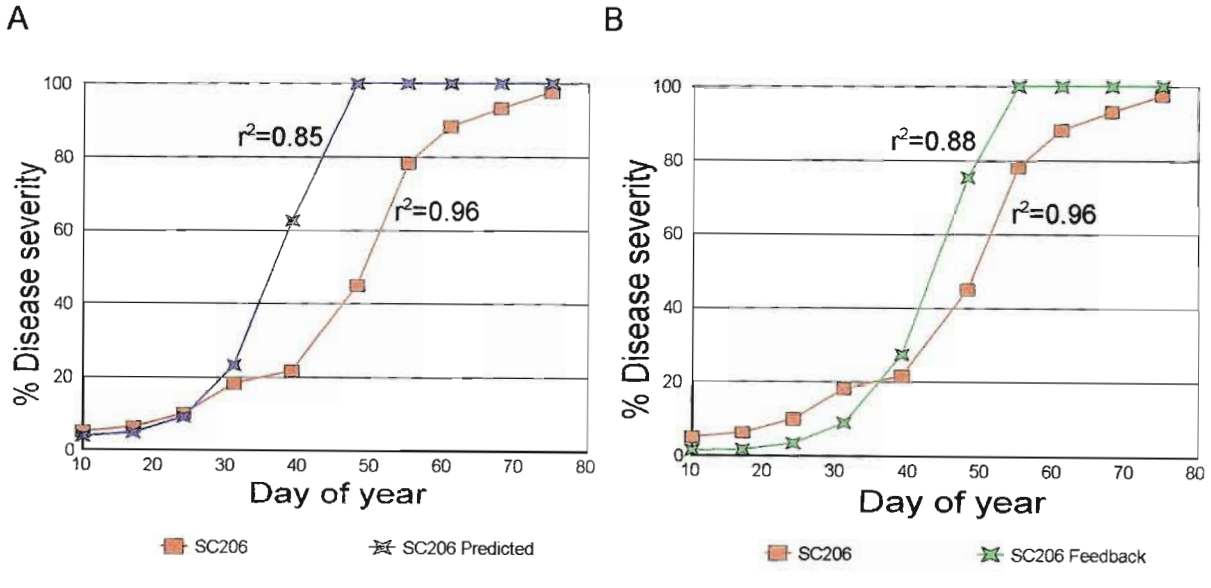

Figure 3.16 1999/00 season with total residue at planting (A) and with the previous season's final disease incidence used to calculate infected residue at planting (B) for the cultivar SC206.

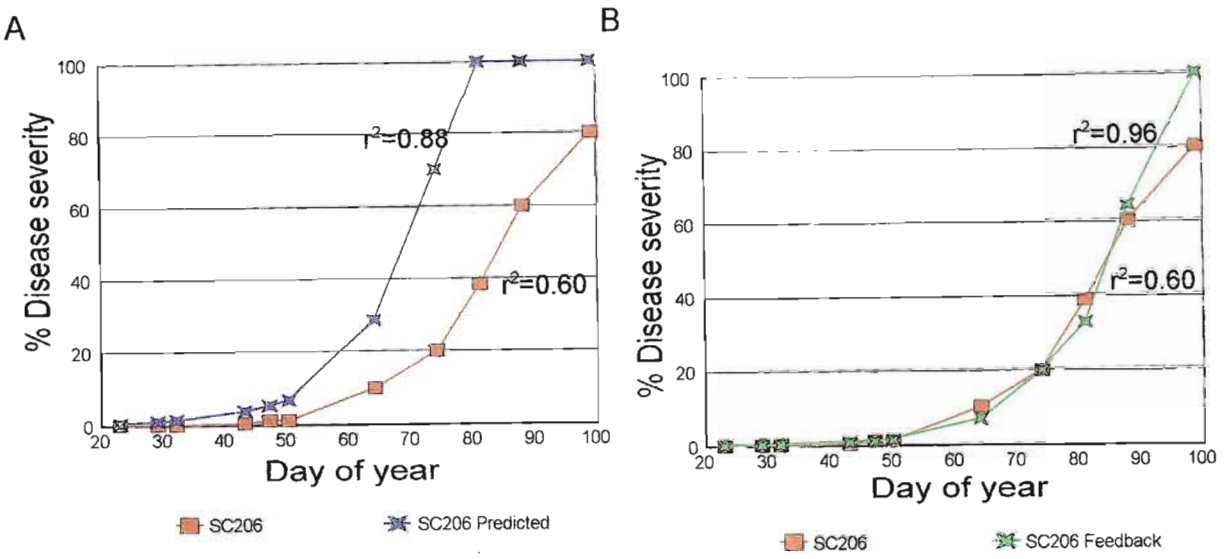

Figure 3.17 2000/01 season with total residue at planting (A) and with the previous season's final disease incidence used to calculate infected residue at planting (B) for the cultivar SC206.

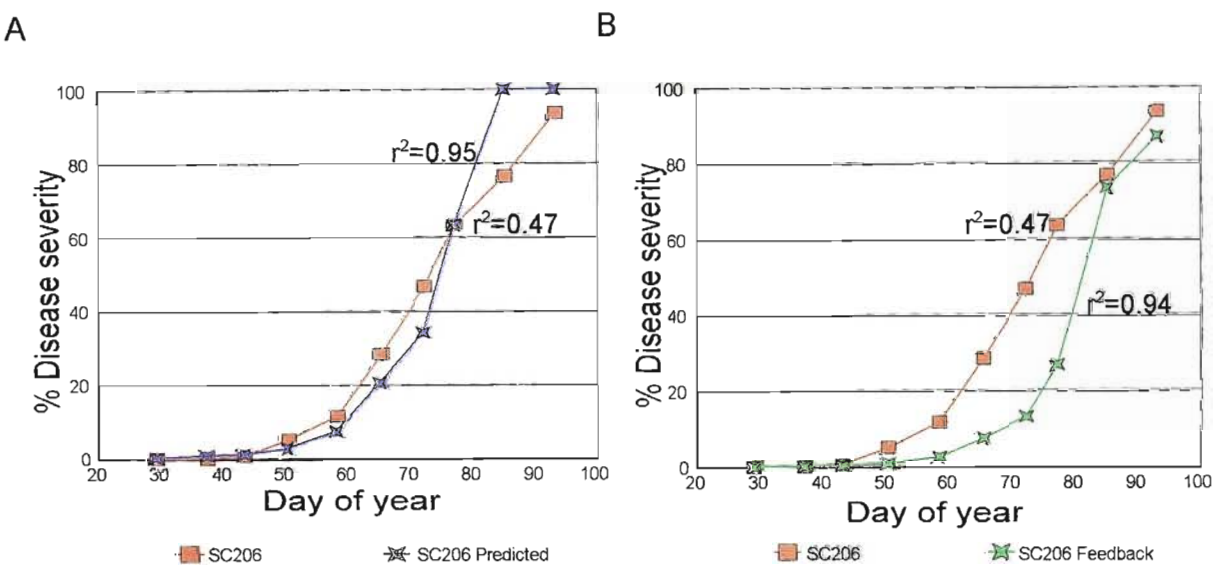

Figure 3.18 2001/02 season with total residue at planting (A) and with the previous season's final disease incidence used to calculate infected residue at planting (B) for the cultivar SC206.

Using the model the timing of fungicide sprays was examined. It was assumed that the spray application was applied when the model predicted 2% disease severity. For the 2000/01 trial the model exaggerated the spread of disease but this would have been better than the 2001/02 trial where the spread of disease was under-predicted. For

example, in 2000/01 (Table 3.8), when the model predicted disease levels of 1.6% on day of year 32, and if a fungicide spray was applied, a better preventative control would have been achieved compared to the 2001/02 trial. In the 2001/02 trial (Table 3.14), when the model predicted 3% leaf blighting, if a fungicide spray had been applied when actual observed disease was 11.7%, there would have been an epidemic in the field concerned and significant yield losses, as the disease would be much harder to control when starting off at such high levels. Therefore, while over-prediction is incorrect, it may sometime be better to err on the side of caution.

In the trials SC627 showed no GLS symptoms, even though it generally does develop disease, as shown in Figure 3.13 (although, depending on the season, GLS is normally too late to cause significant yield loss).

The question to be asked is, why did SC627 exhibit no GLS symptoms during the 2000/01 and 2001/02 trials ? Was this a function of lower initial inoculum pressure, increased resistance, or a weaker virulence of the pathogen ?

A hypothesis is that these results were the result of a reduction in the amount of initial inoculum. In Figure 3.13, over a 10 year period, there was a peak after four years in the level of severity of GLS and a gradual decline thereafter. This can best be explained by the diligent use of fungicide by maize farmers and the increasing availability of high levels of genetic resistance, resulting in the level of initial inoculum declining steadily. The level of disease occurring on specific cultivars has not increased. For example SC206, a standard susceptible check, was recorded with a 90% disease severity at the end of the 1993/94 season (Ward *et al.*, 1997). Final percentage disease levels in the 2000/01 and 2001/02 trials were 80% and 93%, respectively, showing no change in susceptibility, nor weaker virulence in the pathogen. A further point to strengthen the case for lower initial inoculum is the level of disease of SC627. Disease was observed on the cultivar in both the 1998/99 and 1999/00 seasons, yet no disease was observed on SC627 in the 2000/01 and 2001/02 trials, showing a probable decline in presence of initial inoculum.

The lower amount of initial inoculum and the effect of good genetic resistance, is leading to the resistant cultivars exhibiting low to non-existent levels of leaf blighting. If disease does occur then it is usually late in the season, causing no significant yield loss.

Regression analysis of the disease assessment data (Table 3.8) shows that the prediction of the model is better for the more susceptible cultivar SC206 than for the medium tolerant PAN6568. It also shows the differences between two seasons where, in the first season, the model did not predict as well as in the second season.

PAN6568 is a prolific variety, whereas the two SC varieties usually only have a single cob per plant (Table 3.9). Yields obtained were not as expected. For SC206, a linear increase in yield with fungicide applications was as expected (Ward *et al.*, 1997), whereas for PAN6568 there was no significant yield increase after the first fungicide spray. For SC627, a nil response to spraying was expected (Ward, personal communication)[8]. Even though the variety was not sprayed due to absence of disease there was a negative response. The difference among the three treatments of SC627 are not significant. From Table 3.9 and 3.11 it is difficult to explain the variation in yield. Taking into account the number of plants in the row and number of harvested cobs, the data cannot explain the decreased yields. Following this a decision was taken, in the 2001/02 trial, that all the treatments would be sprayed, even if no GLS was visible, and at the same time as the most susceptible variety.

An interesting point to note in Figure 3.9 and 3.10 is the difference in yield among the medium susceptible, and resistant cultivars. The medium susceptible cultivar (PAN6568) had a higher disease severity at the end of the season than the resistant cultivar (SC627) did. PAN6568 is tolerant to disease and able to yield in the presence of disease (Anonymous, 2002). Figure 3.11 and Figure 3.12 show the difference between PAN6568 and SC627 according to yield and transformed percentage disease

[8] Dr J.M.J. Ward, Crop Protection, Cedara, Department of Agriculture and Environmental Affairs, Private Bag X9059, Pietermaritzburg, South Afica 3200.

progress. The graphs show how the tolerant cultivar yielded more than the resistant cultivar. This increase in yield is better for both seasons of the trial and can not only be ascribed to other factors, for instance better drought tolerance.

Figure 3.13 shows the seasonal epidemic using Vanderplank's apparent rate of infection for most of the period that GLS has been present at Cedara, from 1991 to 2001. The 1994-95 season's data is missing due to drought affecting disease rating. The same susceptible hybrid was used to show the disease progress through the seasons. There was an apparent increase in the rate of disease progress in the 1993-94 and 1995-96 season (Figure 3.13). This is ascribed to the explosion of the epidemic during that time, resulting in widespread production of inoculum and high levels of initial inoculum. The data from 2000 to 2002 is from a different individual rater than the previous years. This provides a possible explanation for the higher apparent rates of infection in these two seasons. In addition, the last two seasons were from data sets with more than 10 disease ratings, whereas all the other seasons were from data sets with about 6 ratings only. Initial disease severity was as high as 4% for the ratings taken prior to 2000, which affects the slope of the disease progress line and the value of 'r' significantly.

The use of 'r' for comparisons across seasonal disease progress curves does not work well, because 'r' is essentially the slope of the disease progress curve, and the starting point of the epidemic varies each season, and cannot be standardised. Therefore AUDPC has been standardised (SAUDPC) to allow comparisons of amount of disease over more than a single season (Figure 3.14). This shows that the amount of disease has essentially not changed over the period 1992 - 2001. Unfortunately, SAUDPC is not able to show the duration of the epidemic. So, although similar amounts of disease are occurring, it is not possible to show if the length of the epidemic has changed, *i.e.*, infection may be occurring earlier in the season.

Another question that needs to be asked is: is there a general "slowdown" in the disease epidemic in KZN ? Does this exist or is it a function of climate ? Figure 3.15 shows the disease progress for a selected number of seasons. These progress curves

have been plotted using an XY scatter graph to accurately show the progress of disease through the season. Using Vanderplank's logistic equation:

$\mathbf{X_1 = X_0.e^{rt}.(1-x)}$

where

$\mathbf{X_1}$ is final disease;

$\mathbf{X_0}$ is initial disease; **e** is natural log e;

r is the rate of disease progress;

t is time and

(1-x) is the correction factor.

It is possible to show that time, the interaction of rate of disease progress and initial disease influence final disease. Therefore, to answer the question of what is causing the general "slowdown" in the disease epidemic in KZN the logistic equation must be examined. Time is not a factor in slowing down the increase in disease. Weather affects the rate of disease progress. Using Figure 3.15 it can be seen that final disease levels are generally similar across seasons. The cultivar (SC206) has been shown to have the same level of susceptibility as when GLS was first diagnosed in KZN. The initial disease or inoculum is the only factor left, as ploughing in of residue is a control practice not normally used in the KZN Midlands. However, the use of systemic fungicides and resistant cultivars is widespread. These two control practices reduce the amount of initial disease or inoculum available to start an exsodemic. This is the main reason for the "slowdown" in the disease epidemic. The final level of disease is still essentially the same, but the time taken to reach 5% level of disease is a lot longer.

The use of models to time fungicide applications seems to have merit for cultivars with a higher susceptibility to GLS. This would be expected because, if a cultivar has a linear response in yield to fungicide applications and it is possible to predict the optimum timing of the applications, then benefits will be realised. For cultivars without a linear response to fungicide applications, either fungicide applications need to be limited or the cultivars should not be sprayed.

This trial has highlighted the apparent stabilisation in the GLS epidemic. From the data presented it would appear as if this stabilisation is due to lower initial inoculum in the spring. This reflects favourably on the KwaZulu-Natal maize industry, farmers and maize breeders alike, as it would appear that the levels of initial inoculum have been reduced through the use of genetic resistance and fungicide applications.

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CHAPTER 4

EVALUATION AND COMPARISON OF TWO PREDICTED FUNGICIDE SPRAY PROGRAMMES WITH TWO COMMERCIALLY USED CALENDAR-BASED FUNGICIDE SPRAY PROGRAMMES IN CONTROLLING POTATO LATE BLIGHT

Abstract

Fungicides are an important control measure for late blight (LB) (caused by *Phytophthora infestans* (Mont.) de Bary) and early blight (EB) caused by *Alternaria solani* Sorauer of potatoes (*Solanum tuberosum.* L.) in KwaZulu-Natal (KZN). Standard commercial practice is to apply fungicides on a calendar basis. Applications start approximately three weeks after emergence and continue until the crop is mature or the crop is "burnt off" with a non-selective contact herbicide. Two disease prediction models were compared to two calendar-based fungicide spray programmes. Results showed no significant yield differences between the predicted fungicide and calendar-based fungicide spray programmes. This was based on strict adherence to the model recommendations in the 2000/01 and in the 2001/02 season by delaying fungicide applications until LB was confirmed nearby (<50 km away). However, with known inoculum concentrations and disease incidence, it should be possible to time the start of the spray programme more effectively and so reduce the number of sprays in a season. The EB model was only evaluated in the second season (2001/02), yet shows potential for further use in KZN.

4.1 Introduction

Potatoes are an important crop in KwaZulu-Natal (KZN), in terms of economic importance, in 2003 KZN produced about 5% of the national potato crop (summer crop: 7 531 300 10kg pockets from 2243 hectares)[9]. This equates to a gross value of R89.4 million based on an average price of R1 188 ton^{-1} in 2001 (Anonymous, 2003)

Fungicides are an integral part of late blight (LB) (caused by *Phytophthora infestans* (Mont.) de Bary) control in the KwaZulu-Natal Midlands. In KZN the crop is commercially sprayed from 3-4 weeks after emergence until maturity at 16 weeks. This near total reliance on fungicides is cause for concern regarding fungicide resistance and costs.

Traditionally, fungicides are applied on a calendar basis, or on the advice of an agrochemical representative. However, in Gauteng and the Western Province, it is more economical to apply fungicides based on LB disease prediction models (McLeod and Denner, 1998).

The objectives of this study were:

- To evaluate the feasibility of using LB disease prediction models to time fungicide sprays, as opposed to the standard calendar-based schedules currently in use in KZN.
- To determine whether predicting and timing fungicide applications according to disease-favourable conditions is less expensive and more cost-effective than calendar-based sprays,
- To determine the most cost-effective fungicide programme for commercial and small-scale farmers,

[9] Mr J.P.Mostert, Potatoes South Africa, Private bag X135, Pretoria, 0001, South Africa.

- To determine the suitability of an early blight (EB) (*Alternaria solani* Sorauer) model, currently being developed for use in South Africa, by the Vegetable and Ornamental Plant Institute of the Agricultural Research Council, at Roodeplaat, Gauteng Province.

4.2 Materials and methods

4.2.1 Trial site

Trials were conducted at the Cedara Research Station, of the KZN Department of Agriculture and Environmental Affairs (KZNDAE), approximately 20 kilometres north of Pietermaritzburg, KZN, South Africa. It is 1076 m above mean sea level, in Bioclimatic Zone 3 (Phillips, 1969), which is classed as Mistbelt. This area is highly conducive to the development of fungal diseases, due to frequent misty conditions, causing prolonged duration of leaf wetness, which aids fungal germination and development. Generally, the climate is hot and wet, with high RH during the summer growing season and cold and dry conditions during the winter. Long-term weather data for the spring planting season are shown in Table 4.1.

Table 4.1 Long-term averages for Cedara (average of 30.5 years) and averages from the potato trial growing seasons for 2000/01 and 2001/02

	Sept	Oct	Nov	Dec	Jan	Feb
Max. Temp. (°C)	22.2	22.3	23.4	24.8	25.2	25.3
2000/01	23.3	22.4	21.7	25.2	24.9	24.6
2001/02	22.3	23.7	25.5	25.9	28.0	25.3
Min. Temp. (°C)	9.0	10.8	12.6	14.1	15.3	15.2
2000/01	4.9	11.4	12.1	14.0	13.8	14.4
2001/02	7.1	11.5	13.3	13.2	14.9	13.9
Rain (mm)	55.6	89.3	106.3	127.8	139.6	115.9
2000/01	68.5	65.9	166.4	131.8	117.6	111.2
2001/02	106	116.2	125.5	157.5	159.4	58.2
Rain days						
2000/01	5.7	11	12.6	13.8	13.6	11.1
2001/02	8	23	19	25	17	12
Sun hours	192.2	176.5	167.2	174.9	178.6	173.0
2000/01	204.3	124.2	137.3	149.1	183.8	163.1
2001/02	212.7	159.3	166.9	175.6	187.4	154.3

The 2000/01 trial site soil was a deep red Hutton form (MacVicar, 1991), with a depth of approximately 1 m and a clay content of 55%. The trial site for the 2001/02 season had an approximate soil depth of 0.9 m and 50 % clay. Thorough soil sampling was carried out. Forty cores, 0-150 mm deep, were taken from the trial site. Samples were mixed and air-dried before analysis for phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), acid saturation and pH, by the Cedara Fertilizer Advisory Service (Farina and Channon, 1988). Soil analyses for the 2000/2001 and 2001/02 trial sites are presented in Table 4.2.

Table 4.2 Soil analysis of trial site at the Cedara for the 2000/01 and 2001/02 trial

Year	Sample density (g/ml)	P	K	Ca	Mg	Acidity (Al+H)	Total cations	Acid sat. (%)	pH (KCl)	NIRS clay (%)
		---------(mg/L)---------								
2000/01	0.9	12	191	721	156	0.51	5.88	9	4.47	55
2001/02	0.97	5	234	1009	243	0.09	7.72	1	4.79	51

4.2.2 Design and layout

The 2000/01 trial design used was a randomised blocks design, with split plots, replicated four times. The main plots comprised six treatments:

Treatment 1 (T1) Plant-*Plus* LB prediction model and the Plant-*Plus* EB prediction model (The Plant-*Plus* LB model was the main model used). Advice from the Plant-*Plus* EB model was only followed if the crop was unprotected by fungicides used against LB. This effectively meant that no sprays were applied against EB, as the LB fungicides were effective against EB.

Treatment 2 (T2) Winstel LB prediction model (Winstel, 1992)

Treatment 3 (T3) Standard calendar-based spray schedule with a fixed fungicide schedule (Schedule 1)

Treatment 4 (T4) Standard calendar-based spray schedule with a different fixed fungicide schedule (Schedule 2)

Treatment 5 (T5) A fixed schedule with fortnightly sprays of a contact fungicide commencing after flowering (Control 1)

Treatment 6 (T6) A weekly spray of a contact fungicide, defined as the minimum measures a farmer would take to control LB (Control 2).

For the 2001/02 season the trial design was a randomised blocks design, with split plots, replicated three times. The main plots comprised nine treatments:

Treatment 1 (T1) Plant-*Plus* LB prediction model (Plant-*Plus*)

Treatment 2 (T2) Winstel LB prediction model (Winstel) (Winstel, 1992)

Treatment 3	(T3) Standard calendar-based spray schedule with a fixed fungicide schedule (Schedule 1)
Treatment 4	(T4) Standard calendar-based spray schedule with a different fixed fungicide schedule (Schedule 2)
Treatment 5	(T5) A fixed schedule with fortnightly sprays of a contact fungicide commencing after flowering (Control 1)
Treatment 6	(T6) A weekly spray of a contact fungicide, defined as the minimum measures a farmer would take to control LB (Control 2).
Treatment 7	(T7) An unsprayed control (Control 3).
Treatment 8	(T8) Plant-*Plus* EB prediction model (Plant-*Plus* EB)
Treatment 9	(T9) An EB unsprayed control, where LB was controlled without products that affect EB (Control 4).

The split plots were planted to a cultivar moderately susceptible to LB (BP 1, four rows) and a cultivar moderately resistant to LB (Hertha, four rows).

The main plots were 8 rows by 5 m. The inner 2 rows of the plot were the net plot. Tables 4.3 and 4.4 show the trial layout for the 2000/01 and 2001/02 trials at Cedara.

Table 4.3 Cedara 2000/01 season trial layout

REP I	T 4 (Schedule2) BP1 Hertha	T 2 (Winstel) BP1 Hertha	T 5 (Control 1) BP1 Hertha
	T 1 (Plant-*Plus*) Hertha BP1	T 3 (Schedule 1) Hertha BP1	T 6 (Control 2) BP1 Hertha
REP II	T 1 (Plant-*Plus*) BP1 Hertha	T 2 (Winstel) BP1 Hertha	T 5 (Control 1) Hertha BP1
	T 3 (Schedule 1) Hertha BP1	T 4 (Schedule2) BP1 Hertha	T 6 (Control 2) Hertha BP1
REP III	T 5 (Control 1) Hertha BP1	T 3 (Schedule 1) Hertha BP1	T 2 (Winstel) BP1 Hertha
	T 4 (Schedule2) BP1 Hertha	T 1 (Plant-*Plus*) BP1 Hertha	T 6 (Control 2) BP1 Hertha
REP IV	T 2 (Winstel) Hertha BP1	T 5 (Control 1) Hertha BP1	T 3 (Schedule 1) Hertha BP1
	T 4 (Schedule2) Hertha BP1	T 1 (Plant-*Plus*) Hertha BP1	T 6 (Control 2) Hertha BP1

T = treatment (see page 95)

Table 4.4 Cedara 2001/02 season trial layout

Rep I	T 6 (Control 2) BP1 Hertha	T 3 (Schedule 1) Hertha BP1	T 9 (Control 4) Hertha BP1
	T 1 (Plant-*Plus*) Hertha BP1	T 7 (Control 3) Hertha BP1	T 4 (Schedule 2) BP1 Hertha
	T 2 (Winstel) BP1 Hertha	T 5 (Control 1) BP1 Hertha	T 8 (Plant-*Plus* EB) Hertha BP1
Rep II	T 4 (Schedule 2) BP1 Hertha	T 1 (Plant-*Plus*) BP1 Hertha	T 6 (Control 2) Hertha BP1
	T 5 (Control 1) BP1 Hertha	T 2 (Winstel) BP1 Hertha	T 8 (Plant-*Plus* EB) Hertha BP1
	T 3 (Schedule 1) Hertha BP1	T 9 (Control 4) Hertha BP1	T 7 (Control 3) Hertha BP1
Rep III	T 1 (Plant-*Plus*) BP1 Hertha	T 5 (Control 1) BP1 Hertha	T 6 (Control 2) Hertha BP1
	T 2 (Winstel) BP1 Hertha	T 8 (Plant-*Plus* EB) Hertha BP1	T 3 (Schedule 1) Hertha BP1
	T 7 (Control 3) Hertha BP1	T 9 (Control 4) BP1 Hertha	T 4 (Schedule 2) BP1 Hertha

T = treatment (see page 95/96) list of treatments

4.2.3 Production practices

Immediately before planting, fertilizers were applied by hand in the row and covered with a layer of soil before the tubers were planted. All plots received 52.8 kg N ha^{-1} (as 2:3:4 (30) + 1 % Zn), 80 kg P ha^{-1} (as 2:3:4 (30) + 1 % Zn), 244.2 kg K ha^{-1} (as 2:3:4 (30) + 1 % Zn and potassium chloride 50 %) and 8 kg Zn ha^{-1} (as 2:3:4 (30) + 1 % Zn) for both years of the trial.

The trial was planted on 13 September 2000 and 21 September 2001, in 90cm ridged rows. The tubers were pre-sprouted in sprouting boxes three weeks before planting. Due to the size of the seed supplied in the 2000/2001 season, tubers were quartered and treated with a 50:50 mixture of cement and mancozeb (Dithane M45, Algro-Chem, South Africa). The cement helps to dry the wounds quickly, while the Dithane M45 protects against fungal pathogens prophylactically.

No pre-emergent herbicide was applied for the 2000/01 trial, but paraquat (Gramoxone, Syngenta, South Africa) was applied at 4 l ha^{-1} on 3 October, to even out the emergence and kill off any weeds that had emerged since planting. In the 2001/02 trial, pre-emergent herbicides were applied immediately after planting with 1056 g metribuzin (Sencor 480 SC, Bayer, South Africa) and 1189.5 g s-metolochlor (Dual S Gold 915 SC, Syngenta, South Africa).

No post-emergent herbicide was applied for the 2000/01 trial, but 1440 g bendioxide (Basagran, BASF, South Africa), was applied at a rate of 3 l ha^{-1} on 26 October for the 2001/02 trial.

The crop was topdressed with 186.2 kg N ha^{-1} (as limestone ammonium nitrate 28%) on 23 October 2000 and 31 October 2001. At the same time the potatoes were ridged by hand hoeing.

Recommended insect control practices were applied, using a knapsack sprayer. Deltamethrin (Decis, AgrEvo, South Africa) was applied on 18 December 2000/01 for bollworm control. The 2001/02 trial was sprayed with 5 g lambda-cyhalothrin (Karate, Syngenta, South Africa) on 26 October 2001 for bollworm control. In addition, the trial was sprayed on 30 November 2001 with 10.8 g abamectin (Nuvomec, Novon, South Africa) to control a leaf mining fly, *Liriomyza huidobrensis* (Blanchard).

The trial was irrigated during dry periods, to ensure that the crop received approximately 12 mm of water per week. The 2000/01 trial was harvested on 7 February 2001, after being sprayed on 22 January 2001 with 800 g paraquat (Gramoxone,

Syngenta, South Africa). The 2001/02 trial was harvested on 13 and 14 February 2001, after being sprayed on 22 January 2001 with 800 g paraquat (Gramoxone, Syngenta, South Africa).

4.2.4 Fungicide application

For both seasons, fungicides were knapsack-applied. In the 2000/01 season, a 3.5 metre boom, equipped with seven hollow cone nozzles (Lurmark 30HCX12, Spraynozzles, Johannesburg) was used to apply fungicides. This gave a spray width of 3.5m and applied 600 to 700 l/ha water volume. For the 2001/02 season, a 2m boom equipped with four hollow cone nozzles (Lurmark 30HCX12) was used, to increase inoculum pressure, as only two out of four lines per plot were sprayed. This gave a spray width of 2m and applied between 600 and 700 l ha^{-1} water, depending on the plant stand in the plot. Generally the height of the plant canopy and its density affected the walking speed of the fungicide applicator.

4.2.5 Disease assessment

Early blight was assessed from flowering onwards, using percentage disease severity. Late blight severity was assessed weekly, using standard leaf area diagrams (James, 1971) and the Horsfall-Heuberger Index (HHI) (Horsfall and Heuberger, 1942). The two methods were used to determine differences between the two assessment methods.

The HHI rating is based on the relative proportion of total leaf area on the plant killed by fungal attack.
Infection categories are as follows:
0 = infection-free or nearly so
1 = trace to 25 % leaf area killed
2 = 26 to 50 % leaf area killed
3 = 51 to 75 % leaf area killed
4 = 76 to 100 % leaf area killed.

Data were calculated using the following formula:
Infection index = Sum of category numbers / (number of plants [10] X 4) X 100. The 4 in the denominator represents maximum infection and 100 is used to convert to a percentage. In dealing with fungicides, the infection index is subtracted from 100 to give percentage control (Horsfall and Heuberger, 1942).

Different cultivars and fungicide programmes, combined with the inclusion of an unsprayed control, contributed to variable disease ratings and high coefficients of variation. AUDPC values are thus presented as log transformed. However, in the case of the HHI AUDPC, the coefficient of variation was higher when using the log transformed data. To give a meaningful comparison it was included to show the difference between the whole field rating and the HHI. Unlike the 2000/01 season, where the early blight ratings were extremely variable and not presented, the 2001/02 season's data are shown as log transformed data.

Results were analysed using Genstat 5 Version 4.1 for Windows (Anonymous, 2000 b). Disease severity ratings were analysed as area under disease progress curve (AUDPC) at a 5 % level of significance (LSD), to determine differences in disease severity among treatments. Yields were analysed for variations among treatments.
Various assumptions were made for the 2000/01 trial, *i.e.*,

- fungicide prediction models were correct;
- complete disease control was desirable at any cost;
- all produce was first grade, as the second and third grade potatoes were sorted and discarded as unmarketable and
- interplot interference would result if an unsprayed plot was included.

Assumptions for the 2001/02 trial were:

- it was necessary to have baseline yield data and so an unsprayed control was added to the trial;
- all produce was first grade as the second and third grade potatoes were sorted and discarded as unmarketable;
- prices were fixed at the same prices used for the 2000/01 season and

- to limit interplot interference, the split plot border rows were left unsprayed to ensure all plots were equally surrounded by two lines of unsprayed potatoes.

4.3 Results

The plants were fully emerged by 10 October 2000 and 12 October 2001. All net plots had full emergence. Total plant counts for the net plots were 16 plants/row. All fungicide and insecticide sprays were rainfast before precipitation occurred. No visible symptoms of phytotoxicity was observed after any of the fungicide applications.

During the 2001/02 trial, a new insect pest, on potato a leaf mining fly (*L. huidobrensis),* arrived in South Africa, causing serious damage to the trial. A single spray of abamectin was used to control the fly. In the 2000/01 season no EB AUDPC was available, as disease levels were too low. However, in the 2001/02 season, an AUDPC was calculated.

4.3.1 Fungicide applications

Fungicide application timing and frequencies are presented in Tables 4.5 and 4.6. In the 2000/01 trial, the Plant-*Plus* model treatments were applied exactly as the model required, which was with an earlier start of fungicide applications, as compared to the calendar-based programmes. In the 2001/02 trial, the Plant-*Plus* model was not followed as strictly and the result was synchronised fungicide applications for the first four weeks.

Acrobat was applied early to Treatment four (T4) in the 2000/01 season due to high predicted disease pressure. For the 2001/02 season this was not carried out.

Table 4.5 Application dates of fungicide treatments 1 - 6, showing fungicides applied for the 2000/01 Cedara trial for BP 1 and Hertha

	Application date and fungicides applied (no additives shown)																	
Treat	**19/10**	**24/10**	**28/10**	**31/10**	**03/11**	**07/11**	**08/11**	**09/11**	**17/11**	**24/11**	**29/11**	**01/12**	**10/12**	**18/12**	**22/12**	**01/01**	**08/01**	**12/01**
1	D	A	**	A	**	B	**	B	D	B	B	**	B	T/D	B	B	**	T/D
2	**	**	T/D	**	**	**	**	B	T/D	**	T/D	**	A	**	D	T/D	**	**
3	**	D	T/D	**	T/D	**	D	**	D	T/D	**	T/D	D	T/D	D	T/D	T/D	**
4	**	D	A	**	B	**	**	B	AM	B	**	AM	B	AM	B	AM	B	**
5	**	**	**	**	**	**	**	D	**	D	**	**	D	**	D	**	D	**
6	**	D	**	D	**	D	**	D	D	D	**	**	D	D	D	D	D	**
Week number	2	2	3	3	4	4	5	5	6	7	8	8	9	10	11	12	13	14

Week 1 10 - 17/10	Week 2 17 - 24	Week 3 24 - 31	Week 4 31 - 7/11	Week 5 7 - 14	Week 6 14 - 21	Week 7 21 - 28	Week 8 28 - 5/12	Week 9 5 - 12	Week 10 12 - 19	Week 11 19 - 26	Week 12 26/12 - 2/01/01	Week 13 2 - 9	Week 14 9 - 16	Week 15 16 - 23
10/10 Emergence		23/10 Topdress, ridge							18/12 Apply Decis					22/01 Paraquat burndown

A - Acrobat, AM - Amistar, B - Bravo, D - Dithane,T/D - Tanos/Dithane ** - No spray applied

The length of the trial and the number of weeks in the trial are shown in a simple time line. Application of fungicides can be linked to different weeks and stages in the crop with the time line. Full rates and adjuvants used are shown in Appendix 4.1.

Table 4.6 Application dates of fungicide treatments 1 - 9, showing fungicides applied for the 2001/02 Cedara trial for BP 1 and Hertha

Application date and fungicides applied (no additives shown)																		
Treatment	**2/11**	**09/11**	**16/11**	**22/11**	**29/11**	**30/11**	**5/12**	**07/12**	**11/12**	**13/12**	**18/12**	**21/12**	**24/12**	**27/12**	**31/12**	**03/01**	**07/01**	**11/01**
1	D	D	D	D	D	**	D	D	D	**	T/D	**	D	**	D	**	D	T/D
2	D	D	D	D	**	D	**	**	**	**	T/D	**	**	D	**	**	D	T/D
3	D	D	D	D	D	**	**	**	**	T/D	**	D	**	D	**	D	**	T/D
4	B	B	B	B	B	**	**	A	**	B	**	A	**	B	**	A	**	B
5	**	**	**	**	**	**	**	D	**	**	**	D	**	**	**	D	**	**
6	D	D	D	D	D	**	**	D	**	D	**	D	**	D	**	D	**	D
7	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
8	**	P	D	D/PN	P	D	**	D/P/PN	D	P/PN	D/P/PN	P/PN	D	P/PN	D	P/PN	D	P/PN
9	**	P	P	PN	P	**	**	P/PN	**	P/PN	P/PN	P/PN	**	P/PN	**	P/PN	**	P/PN
Week number	3	4	5	6	7	7	8	8	9	9	10	10	11	11	12	12	13	13

Week 1 12 - 19/10	Week 2 19 - 26/10	Week 3 26 - 2/11	Week 4 2 - 9/11	Week 5 9 - 16	Week 6 16 - 23	Week 7 23 - 30/11	Week 8 30 - 7/12	Week 9 7 - 14	Week 10 14 - 21	Week 11 21 - 28	Week 12 28/12 - 4/01/02	Week 13 4 -11	Week 14 11 - 18	Week 15 18 - 25
Emerge	Basagran Karate					Nuvomec	Topdress							Burndown

A - Acrobat, AM - Amistar, B - Bravo, D - Dithane, P - Phosguard PN - PrevicurN, T/D - Tanos/Dithane** - No spray applied

Application of fungicides can be linked to different weeks and stages in the crop with the time line. The length of the trial and the number of weeks in the trial are shown below in a simple time line. Full rates and adjuvants used are shown in Appendix 4.2.

4.3.2 Disease progression

For the 2000/01 trial, progression of LB for cultivar BP1 was rapid on T5 (small-scale farmer) and T6 (weekly contact fungicide application). For T5 it is possible to see the effect of the two contact fungicide sprays and how the rate of disease was slowed down (Figure 4.1). The same effect is not visible in the 2001/02 trial. However, the speed of progression was rapid. All other treatments in both the 2000/01 and 2001/02 trials show the effect of systemic fungicides on the rate of disease progression. Only T5 (small-scale farmer) and T7 (Control 3) showed signs of disease in the 2001/02 trial (Figure 4.2).

For the cultivar Hertha, a similar pattern is revealed. In the 2001/02 trial only the T7 (unsprayed) treatment showed any sign of LB progression (Figure 4.3 and 4.4).

In both seasons the level of LB was high for BP1, reaching a maximum of approximately 65% for T5 (2000/01) and 100% for T7 (2001/02). In comparison, for T5 final percentage disease severity was approximately 65% for both seasons. In the 2000/01 trial T6 was approximately 65%, while in 2001/02 T6 was close to 0% disease. With Hertha (2001/02) the only treatment with a high disease severity at the end of the season was T7, which was unsprayed.

For EB on BP1 in 2000/01 all the treatments except T5 and T6 had more than two percent EB disease severity. In the 2001/02 season, T2, 4, 5, 6, 7 and 9 had an EB disease percentage higher than 5%. Treatment 7 was the highest (approximately 65%) and T5 was second highest (approximately 35%) (Figure 4.5 and 4.6). These findings were similar for Hertha, except that final levels of disease were higher than for BP1 (Figure 4.7 and 4.8).

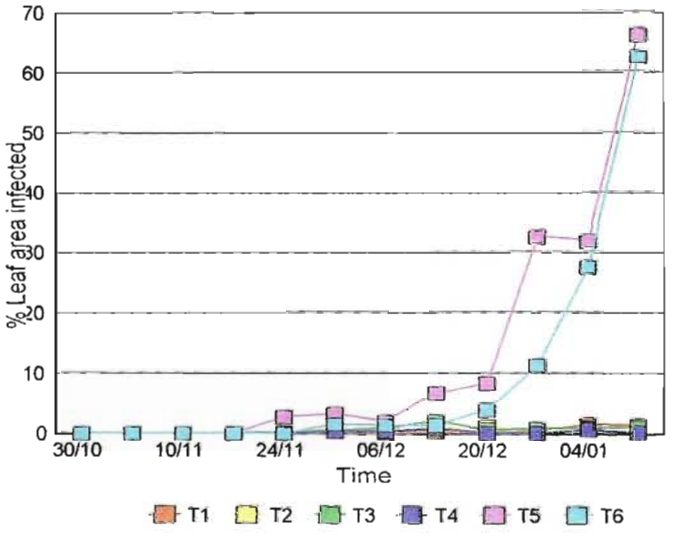

Figure 4.1 Late blight progression for cultivar BP1 (2000/01, Cedara).

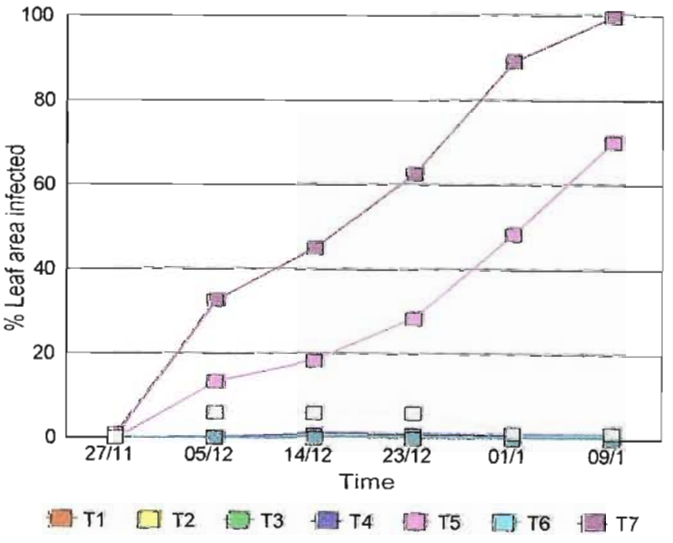

Figure 4.2 Late blight progression for cultivar BP1 (2001/02, Cedara).

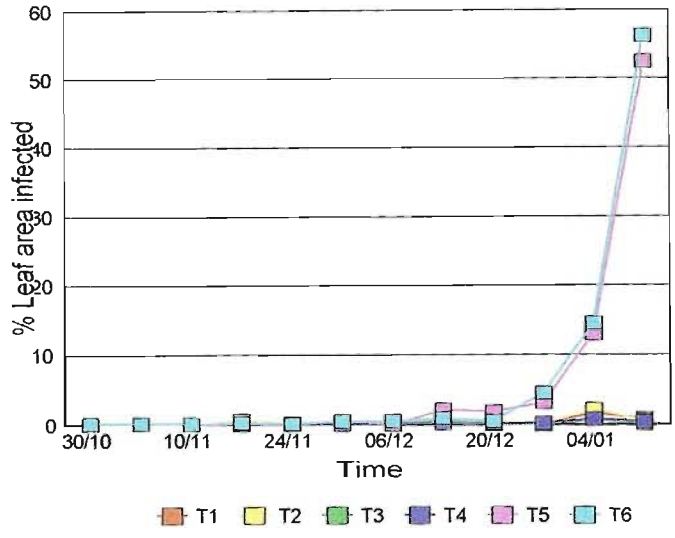

Figure 4.3 Late blight progression for cultivar Hertha (2000/01, Cedara).

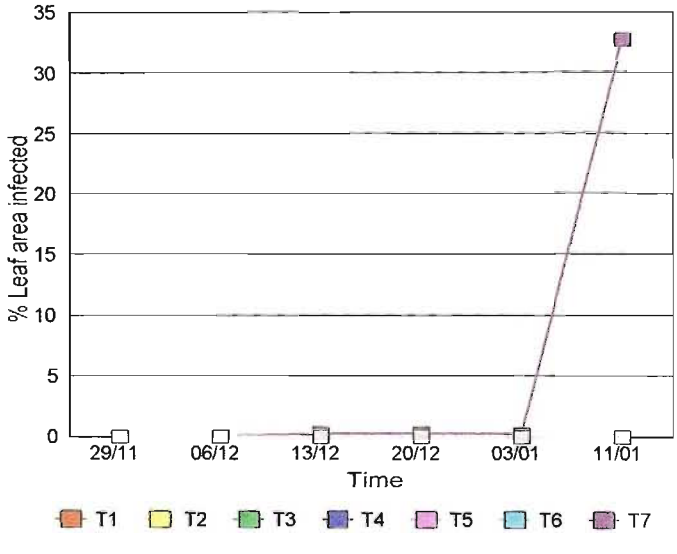

Figure 4.4 Late blight progression for cultivar Hertha (2001/02, Cedara).

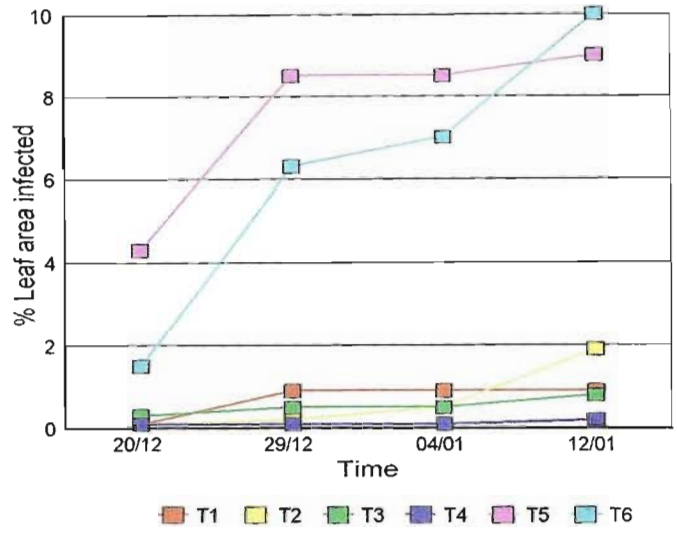

Figure 4.5 Early blight disease progress curve for the cultivar BP1 (2000/01, Cedara).

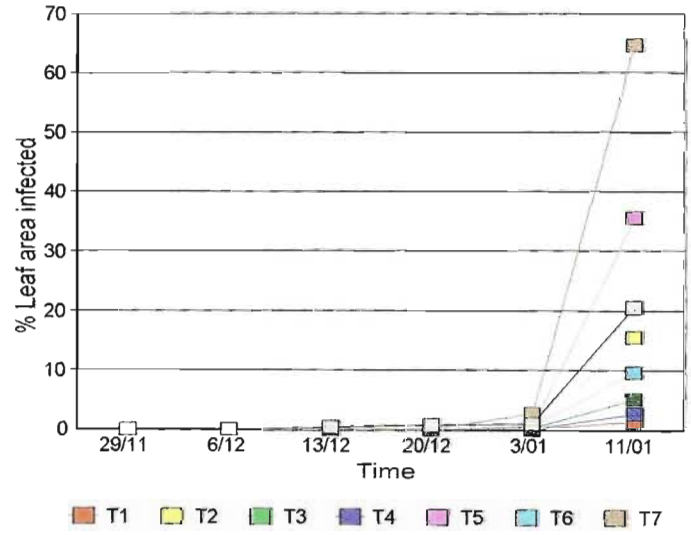

Figure 4.6 Early blight disease progress curve for the cultivar BP1 (2001/02, Cedara).

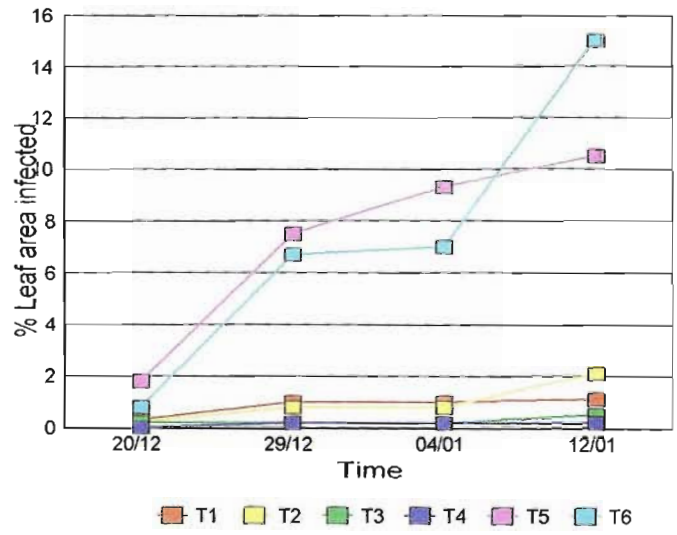

Figure 4.7 Early blight disease progress curve for the cultivar Hertha (2000/01, Cedara).

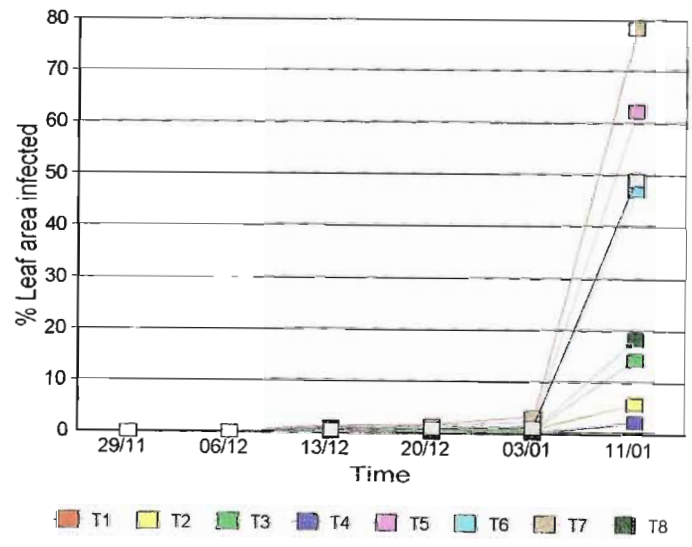

Figure 4.8 Early blight disease progress curve for the cultivar Hertha (2001/02, Cedara).

4.3.3 Disease assessment

Two visual disease rating systems were used, *viz.* percentage leaf area infected and the HHI. Only once in the 2000/01 data did the HHI have a lower AUDPC than the percentage leaf area infected system. In the 2001/02 data this was reversed and the percentage leaf area infected system had more plots with higher AUDPCs than the HHI (Table 4.7 and 4.8).

In 2000/01, using the percentage leaf area infected AUDPC, Plant-*Plus* LB model (T1) had the lowest disease severity, while the small-scale farmer's treatment (T5) had the highest disease severity. For Hertha's disease severity, Schedule 1 (T3) resulted in the lowest AUDPC, while the small-scale farmer's treatment (T5) again produced the highest AUDPC (Table 4.7).

In 2001/02, using the percentage leaf area infected AUDPC, for BP1 the Winstel model (T2) resulted in the lowest AUDPC, and control 1 (T5) unexpectedly resulted in the highest AUDPC. For Hertha in the same trial the highest AUDPC was for the Control 3 (T7) and other than zero was Schedule 1 (T3) (Table 4.8).

An EB AUDPC was calculated for all the cultivars and treatments in the 2001/02 trial. The AUDPC values for Hertha were mostly higher than for BP1. The highest AUDPC for Hertha resulted from Control 1 (T5) (Table 4.9).

Table 4.7 Log transformed Area Under Disease Progress Curve (AUDPC) values of late blight (caused by *Phytophthora infestans*) for two disease rating systems for the 2000/01 growing season at Cedara

Treatment	Plant-*Plus* (T1)		Winstel (T2)		Schedule 1 (T3)		Schedule 2 (T4)		Control 1 (T5)		Control 2 (T6)	
Cultivar	**BP1**	**Hertha**	**BP1**	**Hertha**	**BP1**	**Hertha**	**BP1**	**Hertha**	**BP1**	**Hertha**	**BP1**	**Hertha**
AUDPC % leaf area infected	2.42 ab*	3.07 ab	3.52 b	3.12 ab	3.54 b	2.42 a	2.77 ab	2.10 a	6.57 c	5.57 c	6.14 c	5.77 c
AUDPC HHI***	3.16 abc	4.50 cde	4.04 bc	4.19 c	4.28 cd	2.05 ab	2.15 ab	1.86 a	7.01 f	6.32 ef	6.57 f	6.23 def

LSD (5%) % leaf area infected treatment X variety	1.29
LSD treatment	1.12
LSD variety	0.42
CV %	17.6
LSD 5% Horsfall-Heuberger Index (HHI) treatment X variety	2.03
LSD treatment	1.48
LSD variety	0.89
CV %	32.8

* Means with the same letter are not significantly different ($P \leq 0.05$)

** Horsfall-Heuberger Index

Table 4.8 Log transformed Area Under Disease Progress Curve (AUDPC) values of late blight (caused by *Phytophthora infestans*) for two disease rating systems for the 2001/02 growing season at Cedara

Treatment Cultivar	Plant-*Plus* LB(T1)		Winstel (T2)		Schedule 1 (T3)		Schedule 2 (T4)		Control 1 (T5)		Control 2 (T6)		Control 3 (T7)		Plant-*Plus* EB (T8)		Control 4 (T9)	
	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha
AUDPC % leaf area infected	1.50	0.00	0.55	0.05	1.45	0.27	2.60	0.08	7.17	0.00	1.81	0.00	6.64	2.39	0.71	0.00	4.96	0.00
AUDPC HH index	0.00	0.00	0.00	0.00	1.60	0.00	3.86	0.00	7.27	0.00	1.75	0.00	6.85	2.00	6.62	0.00	0.00	0.00

LSD (5%) % leaf area infected treatment X variety	1.93
LSD treatment	1.56
LSD variety	0.59
CV %	61.7
LSD 5% HH Index treatment X variety	2.63
LSD treatment	1.99
LSD variety	0.88
CV %	92.2

Table 4.9 Log transformed Area Under Disease Progress Curve (AUDPC) for early blight (caused by *Alternaria solani*) percentage plot ratings for the Cedara trial 2001/02 growing season

Treatment	Plant-*Plus* LB (T1)		Winstel (T2)		Schedule 1 (T3)		Schedule 2 (T4)		Control 1 (T5)		Control 2 (T6)		Control 3 (T7)		Plant-*Plus* EB (T8)		Control 4 (T9)	
Cultivar	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha	BP1	Hertha
AUDPC % leaf area infected	0.33	2.40	2.66	2.06	1.56	3.19	0.71	0.52	3.38	5.87	2.81	5.41	0.31	5.71	1.60	3.31	4.20	5.46
LSD (5%) treatment x variety				1.619														
LSD treatment				1.333														
LSD variety				0.628														
CV %				38.1 %														

The results of the comparison between rating methods show that in the 2000/01 trial, the HHI gave a higher estimated level of disease compared to the mean of the ten plants used in the HHI and the percentage leaf area infected rating. For the 2001/02 trial, the HHI gave a higher level of disease than the percentage leaf area infected rating and the mean of the ten plants for the HHI (Table 4.10).

Table 4.10 Means of the rating methods used for late blight in the Cedara 2000/01 and 2001/02 trial

Method	Mean 2000/01	Mean 2001/02
Horsfall-Heuberger Index (HHI)	69.25 a	12.14 a
% Plot disease	59.38 b	10.52 b
Mean of 10 plants	61.06 b	10.09 b
LSD (5%)	4.046	0.707
CV %	8.8%	16.9%

* Means with the same letter are not significantly different ($P \leq 0.05$)

4.3.4 Yield

Total yields were different in each year across all treatments. The best yields were in the 2000/01 trial, where plots under T4 achieved the highest yield, of 75.0 tons ha^{-1}. In the 2001/02 trial T4 did not produce the highest yield although it was one of the highest. In the 2001/02 trial, T3 (Schedule 1) produced the highest yield.

According to grading there were more large tubers in the 2000/01 than in the 2001/02 trial. For the medium size there was no clear pattern, but there seemed to be more medium sized tubers in the 2001/02 compared to the 2000/01 trial. Generally, more small tubers were produced in the 2000/01 than the 2001/02 season (Table 4.11).

Table 4.11a Yield (tons ha^{-1}) obtained for graded and sorted tubers in four classes: large, medium, small, unmarketable and total yield for the 2000/01 and 2001/02 Cedara trial

Treatment	Cultivar	Large (t ha^{-1})		Medium (t ha^{-1})		Small (t ha^{-1})		Unmarketable (t ha^{-1})		Total (t ha^{-1})	
		2000/01	2001/02	2000/01	2001/02	2000/01	2001/02	2000/01	2001/02	2000/01	2001/02
Plant-*Plus* (T1)	BP1	32.9	24.08	25.8	28.05	11.9	7.74	3.3	2.95	74	62.82
Plant-*Plus* (T1)	Hertha	25.7	17.89	25.5	24.1	13.5	14.74	2.4	2.89	67.2	59.62
Winstel (T2)	BP1	31.7	23.46	25.4	26.79	11.3	8.47	2.5	3.84	70.9	62.56
Winstel (T2)	Hertha	21.2	19.05	24.5	27.38	13.4	9.81	2.4	3	61.6	59.24
Schedule 1 (T3)	BP1	35	29.03	23.8	24.44	10.6	10.56	2.6	3.36	71.9	67.39
Schedule 1 (T3)	Hertha	21.2	16.06	28.2	22.45	14.6	8.91	1.8	2.72	65.9	50.14
Schedule 2 (T4)	BP1	37.8	24.57	22.3	26.99	12.3	10.73	2.7	3.28	75	65.57
Schedule 2 (T4)	Hertha	29.1	17.65	25.8	24.48	14.3	10.59	3.9	5.1	73.2	57.82
Control 1 (T5)	BP1	21.9	13.12	23.4	18.09	12.7	11.56	2.8	2.94	60.9	45.71
Control 1 (T5)	Hertha	20.6	16.07	22.7	26.91	13.7	11.04	1.8	2.92	58.9	56.94
Control 2 (T6)	BP1	21.8	18.7	22.8	20.79	13.9	7.63	4.7	6.18	63.2	53.3
Control 2 (T6)	Hertha	20.4	18.11	19.5	22.11	11.2	13.76	2.4	2.76	53.6	56.74
Control 3 (T7)	BP1	**	5.48	**	17.32	**	11.27	**	1.2	**	35.27
Control 3 (T7)	Hertha	**	14.28	**	23.68	**	11.02	**	2.69	**	51.67
Plant-*Plus* EB (T8)	BP1	**	26.86	**	23.93	**	9.84	**	4.53	**	65.16
Plant-*Plus* EB (T8)	Hertha	**	13.17	**	21.58	**	15.32	**	4.27	**	54.34
Control 4 (T9)	BP1	**	17.5	**	21.98	**	9.65	**	4.77	**	53.9
Control 4 (T9)	Hertha	**	14.18	**	23.77	**	12.92	**	1.63	**	52.5

Table 4.11b Statistics for yield (tons ha^{-1}) obtained for graded and sorted tubers in four classes: large, medium, small, unmarketable and total yield for the 2000/01 and 2001/02 Cedara trial

2000/01				2001/02			
LSD 5% large (spray x variety)	7.57 t ha^{-1}	Large tubers CV %	22.4	LSD 5% large (spray x variety)	9.733 t ha^{-1}	Large tubers CV %	29.4
LSD 5 % medium (spray x variety)	6.86 t ha^{-1}	Medium tubers CV %	18.7	LSD 5 % medium (spray x variety)	6.164 t ha^{-1}	Medium tubers CV %	4.8
LSD 5% small (spray x variety)	4.65 t ha^{-1}	Small tubers CV %	29.8	LSD 5% small (spray x variety)	5.693 t ha^{-1}	Small tubers CV %	28.2
LSD 5% total (spray x variety)	10.37 t ha^{-1}	Total tubers CV %	9.1	LSD 5% total (spray x variety)	7.392 t ha^{-1}	Total tubers CV %	6.5
LSD 5% unmarketable (spray x variety)	1.52 t ha^{-1}	Unmarketable CV %	34.6	LSD 5% unmarketable (spray x variety)		Not analysed	

** not planted

When total yields from each treatment are ranked in descending order, the two models and the two calendar-based programmes all achieve high yields, with no significant differences between them (Table 4.12).

Table 4.12 Total yield (tons ha^{-1}) from the 2000/01 and 2001/02 Cedara trial

Treatment	Cultivar	Total tons ha^{-1} yield	Treatment	Cultivar	Total tons ha^{-1} yield
2000/01			**2001/02**		
Schedule 2 (T4)	BP1	75.0 a*	Schedule 1 (T3)	BP1	67.39 a
Plant-*Plus* (T1)	BP1	74.0 a	Schedule 2 (T4)	BP1	65.57 ab
Schedule 2 (T4)	Hertha	73.2 ab	Plant-*Plus* EB (T8)	BP1	65.16 abc
Schedule 1 (T3)	BP1	71.9 ab	Plant-*Plus* (T1)	BP1	62.82 abcd
Winstel (T2)	BP1	70.9 ab	Winstel (T2)	BP1	62.56 abcd
Plant-*Plus* (T1)	Hertha	67.2 abcd	Plant-*Plus* (T1)	Hertha	59.62 bcde
Schedule 1 (T3)	Hertha	65.9 abcd	Winstel (T2)	Hertha	59.24 bcde
Control 2 (T6)	BP1	63.2 bcd	Schedule 2 (T4)	Hertha	57.82 cdef
Winstel (T2)	Hertha	61.6 cde	Control 1 (T5)	Hertha	56.94 def
Control 1 (T5)	BP1	60.9 cde	Control 2 (T6)	Hertha	56.74 def
Control 1 (T5)	Hertha	58.9 de	Plant-*Plus* EB (T8)	Hertha	54.34 ef
Control 2 (T6)	Hertha	53.6 e	Control 4 (T9)	BP1	53.9 ef
			Control 2 (T6)	BP1	53.3 efg
			Control 4 (T9)	Hertha	52.5 efg
			Control 3 (T7)	Hertha	51.67 fg
			Schedule 1 (T3)	Hertha	50.14 fg
			Control 1 (T5)	BP1	45.71 g
			Control 3 (T7)	BP1	35.27 h

2000/01		2001/02	
LSD (5%) yield	10.368 t ha^{-1}	LSD (5%) yield	7.392 t ha^{-1}
LSD treatment	8.671 t ha^{-1}	LSD treatment	6.223 t ha^{-1}
LSD same level of treatment	8.979 t ha^{-1}	LSD same level of treatment	6.286 t ha^{-1}
LSD variety	3.666 t ha^{-1}	LSD variety	2.095 t ha^{-1}
Yield CV %	9.1	Yield CV %	6.5

* Means followed by the same letter are not significantly different

Marketable yield is the most important measure of success. This is the bottom line value. For BP1, T4 (75.09 ton ha^{-1}) produced the highest yield, while T3 (64.03 ton ha^{-1}) produced the highest yield in the 2000/01 trial. There were no significant differences between the top four yielding treatments in both years (Figure 4.9).

For Hertha, T4 (74.15 ton ha^{-1}) was the most effective treatment in the 2000/01 and T1 (56.73 ton ha^{-1}) in 2001/02. For BP1 there were no significant yield differences resulting from the top four treatments (Figure 4.10).

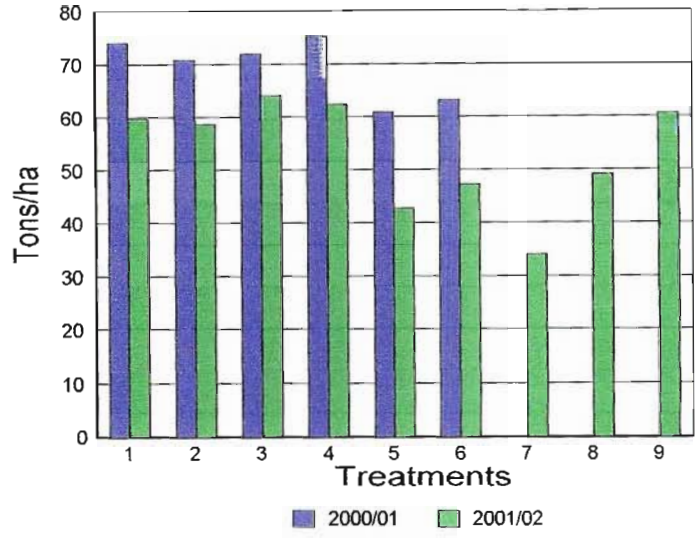

Figure 4.9 Marketable yields for the 2000/01 and 2001/02 Cedara trial for the cultivar BP1.

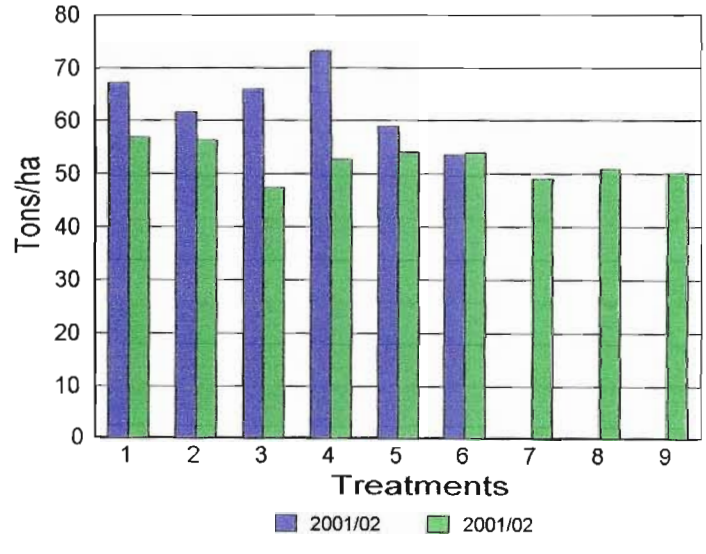

Figure 4.10 Marketable yields for the 2000/01 and 2001/02 Cedara trial for the cultivar Hertha.

The effect of LB on BP1's potential yield can be as high as 32 tons ha-1. This is reduced to just over 14 tons ha^{-1} when contact fungicide sprays are applied weekly. For Hertha, the effect of LB on potential yield is approximately eight tons ha^{-1}. If weekly sprays of contact fungicides are applied, this is reduced to just under three tons ha^{-1} (Table 4.13).

The effect of EB on yield is similar. Unfortunately there was no sprayed control, but only an EB modelled spray treatment compared to an EB unsprayed treatment. The effect of EB on BP1 is higher than on Hertha, although it may seem in the field that Hertha is more susceptible to EB than BP1 (Table 4.13).

Table 4.13 Yield differences between sprayed and unsprayed treatments, Cedara 2001/02

Disease	Cultivar	Sprayed (S)	Unsprayed control (UC)	Sprayed control (SC)	Difference S - SC (S - UC)
Late blight	BP1	67.39	35.27	53.3	14.09 (32.12)*
Early blight	BP1	65.16	53.9	-	11.26
Late blight	Hertha	59.62	51.67	56.74	2.88 (7.95)
Early blight	Hertha	54.34	52.5	-	1.84

* Figures in parenthesis are the difference between the sprayed and unsprayed control

4.3.5 Economics

The total value of the various treatments was calculated using four different grading classes:

large	> 250 grams/tuber
medium	150 - 250 grams/tuber
small	< 150 grams/tuber
unmarketable	all damaged tubers and smaller than the sieve size of 3cm.

All produce was first grade, as the second and third grades were sorted and discarded as unmarketable. Prices were based on Pietermaritzburg Fresh Market prices, obtained in the first week of February 2001. The values for the different grades were as follows:

Large	R11/10 kg pocket
Medium	R10/10kg pocket
Small	R9/10kg pocket

The cost of fungicide applications include the cost of agrochemicals, spray equipment depreciation and the driver cost. The total cost of application is for one hectare, using a 55 KW tractor, with a 10 m boom spray at 6km hr^{-1}, and paying a driver R8/hour = R30/ha (Anonymous, 2000 b). This figure of R30/ha was added to the chemical cost to obtain a total cost for each treatment (Table 4.14).

In the 2000/01 trial T4 was the cheapest option of the calendar-based fungicide programmes and T2 of the modelled fungicide programmes. In 2001/02 T3 was the cheapest calendar-based programme, while T2 was still the cheapest modelled programme.

Treatment Nine was the most expensive of all treatments tested. However, this is not a valid fungicide programme because it is solely to prevent LB without affecting EB (Table 4.14).

Table 4.14 Fungicide costs per treatment for the 2000/01 and 2001/02 trials at Cedara

Treatment	2000/01	20001/02
Plant-*Plus* (T1)*	R2148.54**	R1742.20***
Winstel (T2)	R1639.45	R1370.40
Schedule 1 (T3)	R2329.19	R1463.10
Schedule 2 (T4)	R1547.33	R1713.20
Control 1 (T5)	R272.65	R278.10
Control 2 (T6)	R708.63	R989.70
Control 3 (T7)	****	R0
Plant-*Plus* EB (T8)	****	R834.30
Control 4 (T9)	****	R6576.00

* T = Treatment

** R1500 for Plant-*Plus* based on ten plantings. R3200 for a single planting, as of August 2001.

*** R1500 for Plant-*Plus* based on ten plantings. R3600 for a single planting, as of August 2002.

**** Not in trial

The gross economic returns of each treatment was calculated as

Gross economic return = gross crop yield - fungicide application - cost of fungicides

This was to determine the most cost-effective fungicide LB spray programme. For BP1, T4 (R72 991) was the highest gross value in 2000/01 and T3 (R39 998) in 2001/02 (Figure 4.10).

For Hertha, T4 (R68 759) was the most cost-effective LB fungicide programme in 2000/01 and Treatment Six (R31 337) in 2001/02. The closest non-control treatment was T1 (R31 226) (Figure 4.11).

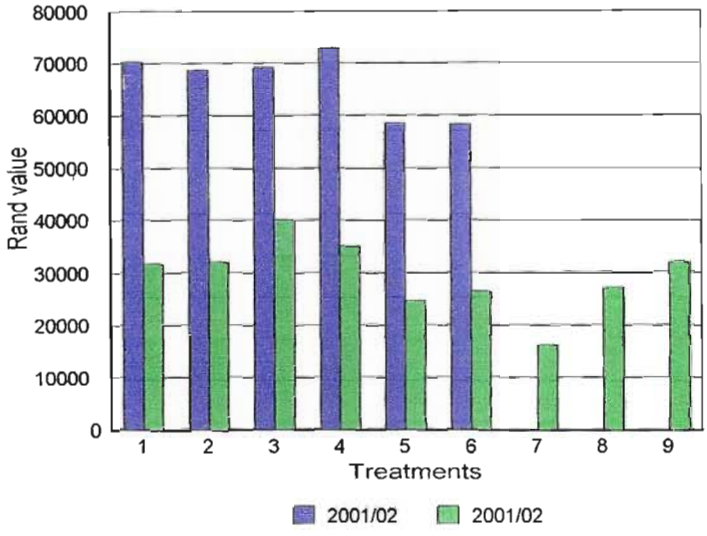

Figure 4.11 Gross economic return of each treatment less the cost of fungicide and application costs, Cedara 2000/01 and 2001/02 for cultivar BP1.

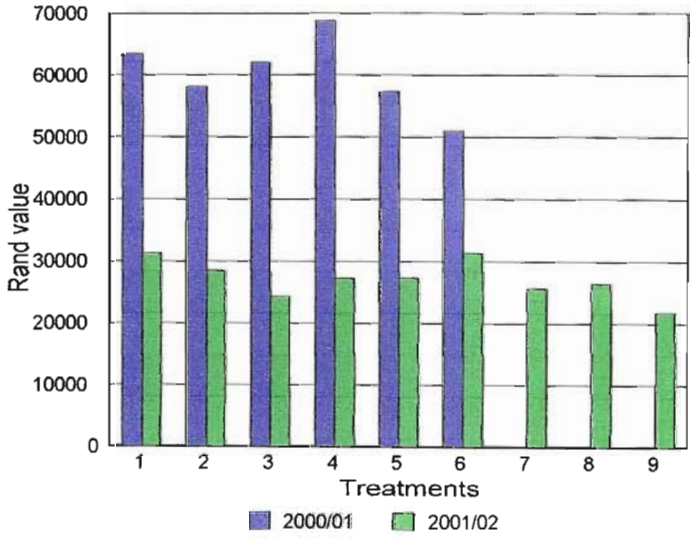

Figure 4.12 Gross economic return of each treatment less the cost of fungicide and application costs, Cedara 2000/01 and 2001/02 for cultivar Hertha.

4.4 Discussion and conclusions

For the 2000/01 trial, the Plant-*Plus* model was strictly followed, resulting in systemic fungicides being applied early in the season. This unnecessarily influenced the cost of the treatment, as there was no disease present when the first sprays were applied. To avoid this in the 2001/02 trial, fungicide spray applications were delayed until LB was confirmed within a 50 km radius of Cedara. By doing this, early application of expensive systemic fungicides was avoided, while the same level of control was obtained.

If prediction models are to be used to time fungicide sprays economically, it is imperative to determine when and where LB is present. This is due to the inherent nature of simulation models. Most models assume that the pathogen is constantly present and only the host and favourable climate need to be present to cause disease.

Based on the need to determine when and where LB is present in KZN, a KZN Late Blight Incidence Map has been set up and is available at http://agriculture.kzntl.gov.za. This map is a joint effort of all the role-players in the potato industry and includes producers, agricultural representatives, industry bodies and the KZNDAEA. It is hoped that, with the map as a decision aid, better use will be made of systemic fungicides in a preventative rather than a curative approach to controlling LB (van Rij, 2002).

Evaluation of the EB model (Plant-*Plus* EB, T8) was separated from the Plant-*Plus* LB model (T1) during the 2001/02 season. Unlike the LB model (T1), where the systemic fungicide Tanos was used, the EB model (T8) only had Dithane sprays. However, it did have Phosguard and Previcur N sprays to control the LB. According to Table 4.8, the Plant-*Plus* EB model (T8) did not control EB significantly better than the Plant-*Plus* LB model (T1). In practice, it would be best to combine the two models. A reason for the lower AUDPC for the Plant-*Plus* LB model (T1) was the inclusion of a systemic fungicide in the spray programme for the LB model. However, the Plant-*Plus* EB model (T8) does predict when infection chances for EB are high or low.

With the inclusion of the EB model and an unsprayed EB (Control 4) treatment (T9), it has been possible to show the effects of EB on potato yield. The effect of EB on the AUDPC of Hertha (Table 4.9) was not as marked as on BP1. This cannot be attributed to BP1 being more resistant to EB than Hertha. There may be an explanation in that *Liriomyza huidobrensis* affected BP1 more than Hertha. However, using AUDPC data from Table 4.9, it is difficult to support this hypothesis, because the AUDPC values for EB were consistently higher on the unsprayed EB control (T9) and the Plant-*Plus* EB treatment (T8). The differences are, however, not significant at the 5 % level.

During the 2001/02 season, on average, the model treatments had lower AUDPC values than the calendar-based programmes. Nevertheless, as in 2000/01, there was no statistical difference between the treatments.

In the 2001/02 season there did not appear to be the same marked difference between the rating methods used. There was a significant difference between the means of the methods, with the HHI being significantly better than the % disease severity rating. This was opposite to the previous season's results. A suggestion may be that this difference was due to a different disease intensity between seasons. If the HHI, as hypothesised, has too few infection categories, then in a year favouring high levels of disease, the HHI would tend to overestimate levels of disease while in a year which does not favour high disease levels it would be more accurate.

In the 2000/01 season, disease was first found on 10 November 2000. In the 2001/02 season, disease was found later, on 29 November. By 29 November LB was estimated at 2 % in the unsprayed control plot. The only other plot infected had very low levels, estimated at less than 0.1 %. These levels suggest an earlier infection, most probably later than 10 November. During the 2000/01 season, fungicide spray applications before 3 November were unnecessary. The 2001/02 season's results support the statement.

The effect of EB on total yield caused yield losses of 11.26 tons ha^{-1} (BP1) and 1.84 tons ha^{-1} (Hertha) for the 2001/02 season (Table 4.12). This shows that Hertha has a

higher tolerance to EB than BP1, explaining the higher yield with Hertha, even though it has a higher final percentage disease severity than BP1 had.

The Plant-*Plus* EB model (T8) seems to warrant further research and a recommendation may be to include an EB sprayed treatment into the trial to determine differences between a standard control programme and a predicted programme.

The suggestion from the 2000/01 season trial results, namely that an unsprayed control was necessary to verify the effects of LB on yield loss, appear to be valid. However, the unsprayed plots did introduce more variability into the trial because leaving the border rows unsprayed introduced additional inoculum into the trial area.

With the addition of the LB unsprayed control it was possible to see that a 50% yield loss is possible (Table 4.13). The variation in weather at Cedara, is often the cause of the effect of greater variation between years than between treatments. For instance in 2001/02 LB was not as severe as in 2000/01. This was supported by the higher yields and higher AUDPC values in the trial. Generally, a more favourable blight year translates into higher plant yields, as the same factors influencing LB affect potato growth.

Unlike the 2000/01 season, there is a significant difference between Control 1 option (T5) and the 2001/02 season. The Control 1 option (T5) was used to experiment with control options for resource-poor and small-scale farmers. In the 2000/01 season, the Control 1 option (T5) was statistically just as good as the Control 2 option (T6). For the 2001/02 season there was no significant yield difference between Hertha Control 1 (T5) and 2 (T6). There was, however, a difference in the composition of the total yield, with Control 2 (T6) having a higher number of large tubers (Table 4.11), giving a better economic return (Figure 4.9 and 4.11). For BP1 the same was true. Unfortunately for small-scale farmers who plant less than a hectare of potatoes the potential of a predicted fungicide programme may be limited in terms of the investment required to run the model. This is the reason for the recommendation that small-scale farmers either

grow resistant varieties or combine moderate resistance with timed applications of protectant fungicides (Fry, 1977).

The 2001/02 yields were lower than the 2000/01 yields. In the 2001/02 season the Plant-*Plus* LB model (T1) yielded fourth highest. This is lower than the 2000/01 season, where it was the second highest yielding treatment. As before, there is no significant difference between the two calendar-based sprays and the two LB prediction models. The cost of the Plant-*Plus* LB model (T1) was R1740.20 ha^{-1}. The cheapest calendar-based spray (T4) (which included systemic products) worked out at R1463.10 and gave the highest yield, with the highest gross value for BP1. The reason for the high economic value was the high proportion of large tubers obtained. For Hertha, the predicted spray programme was better than the calendar-based programmes. Control 2 (T6) gave the highest gross value for Hertha. A possible explanation may be that Dithane has an effect on EB or, as hypothesised earlier, Hertha is more disease tolerant. For the Plant-*Plus* LB model (T1), where 13 Dithane sprays were applied, Hertha gave the second highest gross value. In terms of total tons ha^{-1}, the predicted spray programmes gave the highest yields of all treatments, yet net value was not the highest, because of fungicide and application costs.

During the 2001/02 season the calendar-based treatments unexpectedly produced higher yields and economic returns for BP1. This reflects the dynamic nature of LB at Cedara, where an unfavourable year affected the models negatively. As in the 2000/01 season, the most cost-effective fungicide treatment was a calendar-based programme. Treatment 3, and not T4, was the best treatment for BP1. An explanation for the better performance of T3 was a change in approach to using Tanos. The applications of Tanos were restricted and Dithane was applied at 2 kg ha^{-1}, rather than 2.5 kg ha^{-1}. For Hertha, T6 was best, followed closely by T1. Whereas the calendar-based programmes were best for BP1, the predicted programmes were best for Hertha. This may be a function of resistance, possibly suggesting that the models need to include more systemic fungicides in their recommendations.

During the 2001/02 season, the importance of foreknowledge of when LB is present was shown. By using the 2000/01 recommendations to avoid spraying until LB was confirmed in the area, T2 became the cheapest treatment in terms of fungicide costs and applications. However, it did not have the highest yield and it had a lower proportion of large tubers than T3 (the most cost-effective BP1 fungicide treatment).

In conclusion, the importance of information regarding the early status of the seasonal LB epidemic is crucial and serves as a decision aid in itself. This knowledge will be provided by the Internet "Late Blight Incidence Map", discussed earlier. Use of either a model or calendar-based programme for fungicidal control of potato LB gives results that are not significantly different in terms of yield. Based on two years' data it is difficult to determine conclusively which is the optimum system for KZN. Another season's trials are in progress (2002/03 at the time of writing). With the data currently available, it is possible to say that as long as systemic fungicides are included in a preventative spray programme, marketable yield is significantly improved over the minimum control option of using only preventative contact fungicides.

The timing of the systemic fungicide sprays in the programme does have an effect. In an intense blight season a modelled spray programme will be better than a calendar-based programme. However, in a low blight season, a calendar-based programme may offer better returns. It must be stressed however, that whether a calendar-based programme or a modelled programme is used, there is no significant difference in yield between low or intense blight seasons.

The most sustainable approach will be through using models, which help determine the optimum time for the use of systemic fungicides. By limiting exposure of *P. infestans* to systemic fungicides, the chance of resistance development may be reduced.

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CHAPTER 5

A REVIEW OF LITERATURE AND EXPERIENCES IN THE DEVELOPMENT AND MAINTENANCE OF AN AUTOMATIC WEATHER STATION NETWORK

5.1 Introduction

All research recorded in this thesis has dealt with weather, climatic data and suggestions of how to use this to the farmer's advantage. This chapter reviews the literature dealing with recording these data and practical experience of the design and maintenance of an automatic weather station network (AWSN).

Rarely in the public sector is the design of an AWSN a carefully planned event unless massive funds are budgeted for a donor funded project. Such funding is ever more scarce. The AWSN in the KwaZulu-Natal Department of Agriculture and Environmental Affairs (KZNDAEA) is a system which has been put together using a number of different technologies, *viz.* manual, wireless and cellular modem links for data downloading.

The system has grown from a single station at the end of 1996 to a network of 13 automatic weather stations (AWS) covering a large area of KwaZulu-Natal, with the eventual aim of covering every region in the province (Figure 5.1). During this period most of the growth in the number of AWS has been funded by the KZNDAEA at the end of the financial year, when funding is occasionally available. This makes the purchase of AWS uncertain and unplanned, with the result that there are three makes of AWS in the AWSN, each with specific advantages and disadvantages.

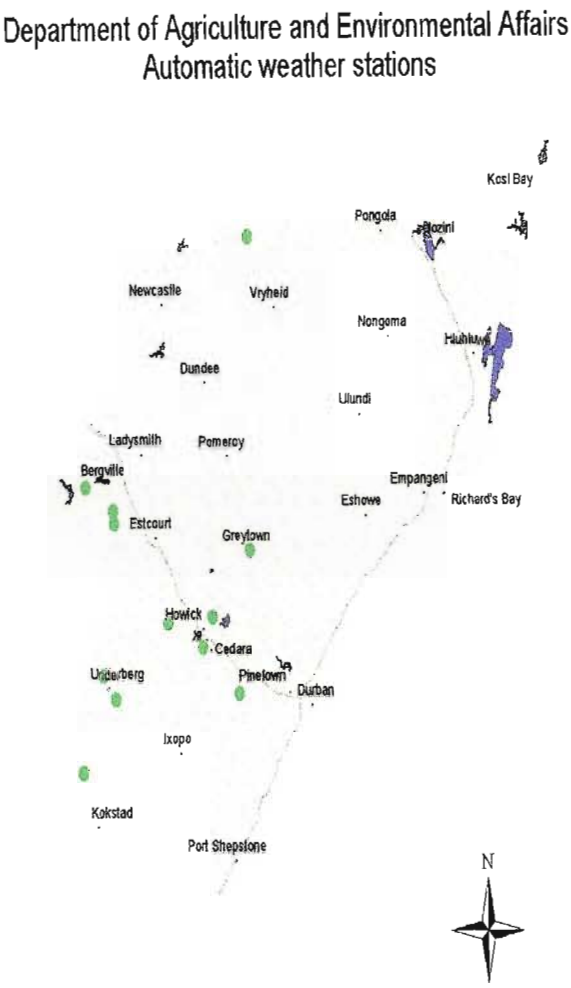

Figure 5.1 Layout of the Automatic Weather Station Network in KwaZulu-Natal.

5.2 Optimum layout and setup of an Automatic Weather Station

Agrometeorological weather stations are generally very similar to normal meteorological stations. The differences occur because the agricultural meteorologist requires information regarding the soil, the in-plant canopies, above canopies and generally wants a higher resolution, *i.e.,* a finer scale of measurement, the microclimate (Hubbard, 1994).

Parameters most commonly used in agriculture are:

- air temperature
- relative humidity or atmospheric water vapour content
- rainfall
- solar radiation, net radiation, albedo (global and reflected radiation)
- wind speed and direction
- soil temperature (Seeman *et al.*, 1979; Savage, 1998; Tanner, 1990).

The other parameters, such as duration of surface wetness (leaf wetness), air pressure, soil temperature and moisture content, are used with specialised disciplines such as Plant Pathology, which uses leaf wetness measurements extensively (Gillespie, 1994).

Siting and layout of the AWS are important. When using site specific data for a limited application, sensors should be placed according to the requirements of the project. However, for long-term data collection, and when it is envisaged that the data will be used for a number of purposes, it is better to standardize sensor layout (Tanner, 1990).

There are a number of standard layouts in use, for instance the World Meteorological Organization (WMO), the American Association of State Climatologists (AASC)and the Environmental Protection Agency (EPA). Each of these organizations use weather data for different purposes and, accordingly, have different standards (Table 5.1).

Table 5.1 Weather measurement standards of the Environmental Protection Agency, the World Meteorological Organisation and the American Association of State Climatologists

Measurement	Measurement height (metres) or depth (centimetres)		
Organization	EPA	WMO	AASC
Wind	10m	10m	3m (within 0.1m) Optional 2m (within 0.1m) or 10m (within 0.5m)
Air Temperature & Relative Humidity	2m temperature only 2m and 120m for temperature difference	1.25 to 2.0m	1.5m (within 1m)
Solar radiation	pyranometer should be located to avoid any shadow on the sensor; height is not critical	pyranometer should be located to avoid any shadow on the sensor; height is not critical	pyranometer should be located to avoid any shadow on the sensor; height is not critical
Precipitation	0.3 minimum close to the ground as possible but no rain splash	0.3 minimum close to the ground as possible but no rain splash	1.0m (within 1m) close to the ground as possible but no rain splash
Soil temperature	-	5, 10, 20, 50, 100cm	10cm (within 1cm)

(WMO, 1983; EPA, 1987; The State Climatologist, 1985)

In addition to Table 5.1, Seeman *et al.* (1979) state that the requirements for the siting of a net radiation meter/pyranometer is two metres high, on an outrigger arm, without shading and facing south (Northern Hemisphere).

These guidelines are subject to the availability of a suitable site. It is recommended by the EPA that, before the weather station site is chosen, if the conditions/guidelines, as laid out in their manuals, are unable to be met, then compromises may have to be made. The absolute ideal may not always be attainable, especially given that there are often two conflicting requirements. In the present case these requirements a secure site and adequate exposure of the sensors. Compromises have had to be made in the siting of certain of the AWS in the Cedara AWSN and of the sensors.

5.3 Actual layout of the Cedara Automatic Weather Station Network

The criteria for positioning the sensors have been based on the WMO guidelines (WMO, 1983). It is not always possible to satisfy all the requirements as laid down by the WMO and so the closest compromises have been used where the guidelines are not possible for the AWSN in its existing layout. Table 5.2 shows the sensor position norms used in the AWSN.

Table 5.2 Standard height and placement methods for sensors used in the Cedara Automatic Weather Station Network

Variable	Sensor	Height	Comments
Solar irradiance	Pyranometer	2 m	on cross arm Campbell on arm Adcon on rain gauge attatchment - Davis
Air temperature	Humitter	1,8 m	in 7 plate Gill shield
Relative humidity	Humitter	1,8 m	in 7 plate Gill shield
Wind speed	Wind speed 3 cup anemometer	2 m	on cross arm Campbell on separate arm Adcon Davis - 1.6 m high only on arm
Wind direction	Wind direction wind vane	2 m	on cross arm Campbell on separate arm Adcon Davis - 1.6 m high only on arm
Rainfall	Tipping bucket	2.2 m	unobstructed
Leaf wetness	Wet leaf sensor	0.5 m	Campbell and Davis 0.5 m (latex painted) Adcon 1.8 m (factory treated to obtain same effect of latex)

The height of the pyranometer has been set at 2m as this is the height that if a ladder is not available to climb up to the sensor a vehicle can be reversed up to the station and the technician servicing the sensor is able to work in some comfort. The height of the

humitter falls within the WMO guidelines; 1.8m was initially used as the standard height as this is the height of the technician who installed most of the AWS in the network.

For the most part it is impractical, with the funding available, to erect a wind mast 10m high and so the 2m height of the wind sensors was chosen. In the crops being worked on, 2m and lower is effectively the height of the crop canopies. The AWSN is concerned mostly with data for horticultural and agronomic uses.

Precipitation measurements for the Adcon equipment is at the top of the mast and so this is the reason for the other stations to be standardised at 2.2m. Due to the mix of AWS in the AWSN, it is not always possible for the sensors to be mounted at exactly the same height and location as sensors on another make of AWS. For example, on the older model Adcon Telemetry A730s, the leafwetness sensor is mounted above the radiation shield for the temperature and RH sensors. This has led to the problem that the leafwetness sensor of the of the Adcon equipment is set at 1.8m, which is the standard for temperature and RH and not for leafwetness.

To ensure that the data recorded by the AWS are accurate, a set of calibration norms has been established, based on personal experience and literature references. It is essential that a record of sensor calibrations is kept and this should include the date of purchase, the last time calibrated and the result of the previous calibrations. Once the sensor is consistently out of the calibration norms, as set out in Table 5.3, the sensor is discarded or sent off for repairs (Savage, 1998).

Table 5.3 Calibration norms in use for the Automatic Weather Station Network

Variable	Sensor example	Calibration period
Solar irradiance	Pyranometer	Annual or every 24 months
Air temperature	Humitter (CS 500)	Annual
Relative humidity	Humitter (CS 500)	Annual
Wind speed	R.M. Young wind sentry	Annual
Wind direction	R.M. Young wind sentry	Every 24 months
Rainfall	Tipping bucket	Annual, checked monthly for blockages
Leaf wetness	Model 237 leaf wetness	Every 6 months

5.4 Practical experience with Automatic Weather Stations

As stated previously, measuring weather variables without appropriate thought and consideration of specific objectives is uneconomical and foolish. A situation where no forethought and specific objectives have been drawn up results in a data set which is haphazard and very often inadequate for the eventual purpose of the weather station network.

It is preferable for an AWSN to be composed of a single make of AWS and that it uses standardized software. This allows for easy creation and programming of databases, *etc.* The Cedara AWSN has three types of AWS in it. They are the Campbell CR10X range, the Adcon Telemetry A730s and the Davis Vantage Pro stations. This mix is a result of the periodic purchase of AWS based on the lowest cost and also the purchasing of AWS by different people. This is not to say that the AWSN is not a valuable resource and investment. On the contrary, it has proved to be useful in a number of ways, for example the potato late blight incidence map (van Rij, 2002).

The key to welding the AWSN into a manageable whole is through the use of a central database. This database has been written in Microsoft Access. It provides a platform in which all raw data are entered and then, based on the type of AWS involved, data are converted and exported into different standard formats. For example, the primary format is that used by the grey leaf spot (GLS) model. It is an ASCII file, with the following daily records:

- Place
- Year
- Day of Year
- Solar radiation (MJ day^{-1})
- Maximum air temperature (°C)
- Minimum air temperature (°C)
- Rain (mm)
- Hours of relative humidity above 90% (hrs)
- Hours of leafwetness (hrs).

The second format used is for inclusion on the Cedara web page (http://agriculture.kzntl.gov.za). It is the same as the format for the GLS model, except that it is in Html format.

Retrieval of the data from the individual AWS is either radio-based or by using GSM enabled modems. Deciding which data retrieval method to use is important, as it will often define the ability of the AWSN to expand. The use of manual data retrieval, is by experience, not recommended, as it means that data are sometimes downloaded from the AWS too infrequently. If the AWSN is new and there are insufficient funds available for remote retrieval (either radio or GSM modem) then, as a last resort, manual downloading could be considered. However, if it is possible (as with the Campbell loggers), an optically isolated storage device should be attached. The reason for the backup data storage is that lightning can affect a logger and erase data, whereas, with a storage device attached, there is a better chance of retaining the data.

The use of GSM modems is currently a very cost-effective option. Before the introduction of data lines on pay-as-you-go packages, GSM communications was expensive and a contract with data lines cost R165.00 per month with a once-off cost of R150.00. This is now R5.00 per month on the data enabled pay-as-you-go packages with an initial start-up cost of approximately R300.00. Since calls are not made from the cellular modems and only calls are received on the modems, the price of airtime, *i.e.*, cost of making outgoing calls, is negligible.

A general problem for all the loggers is how to ensure a constant supply of power, a major issue at remote sites. In southern Africa, with the abundant solar energy available, solar panels recharging a battery are a logical option. Unfortunately, unless extreme measure are taken to secure the solar panels in place, they are easily stolen. Within the AWSN there are a number of different power solutions, stations that run on batteries alone, stations on AC current and a transformer with a battery as backup and stations on solar power and battery.

The individual loggers occasionally have design faults/quirks, which the user of AWSs needs to be aware of before the purchase of such equipment, bearing in mind the often prohibitive cost involved in AWS.

5.4.1 Campbell AWS

A practical problem with the Campbell CR10X is the actual physical set-up of the station. This is a time-consuming job and can take up to three hours for inexperienced operators. Another set-up delay is the programming of the logger to program the actual sensor wiring into the logger and the program and calculations for the data collected. This has already been catered for in the software package (Loggernet ver 2.1, Anonymous, 2002) from Campbell in the form of SCWin. This software enables the inexperienced user to specify the type of logger, the sensors and the calculations required from the AWS. A program is compiled based on the user's input and then downloaded to the logger. If users are unaware of this program, working out how to program the logger can take days.

The wiring of the individual sensors is just that, physical wiring which to some users may be a daunting task. However, if use is made of SCWin, then a wiring diagram is automatically generated for each compiled program.

The Campbell loggers which run solely on batteries, and with a modem for remote data download, use a lot of power. For a station with two 12V 7AH batteries in parallel and a GSM modem on continuously, the average battery life is a little over three weeks. With the CR10X there is a switched 12V channel. The modem is wired to this channel and programmed to switch on for a certain length of time per day. With this technique battery life is extended to approximately two months. In addition, the logger can be programmed not to switch the modem on if the station battery voltage is less than for instance, 10.8V. This would then allow the user to see a problem before the station's battery voltage is too low and the whole system shuts down.

5.4.2 Adcon Telemetry

The Adcon Telemetry AWS in the AWSN are the A720 AddIT, A730MD and the A733 AddWAVE. They are at the time of writing all using radio telemetry. The A720's are only "Disease Stations", *i.e.,* temperature, relative humidity, leaf wetness duration and precipitation sensors. The A730 and the A733 are mostly "ET stations", *i.e.*, windspeed and direction, leafwetness, relative humidity, temperature and precipitation. The system uses a small solar panel and five, 1.5V batteries that are charged by the panel.

The Adcon Telemetry System is a simpler and more user-friendly system than the Campbell system. However, the problem with this ease of use is the restriction on programming of individual sensors, as can be done with the CR10X. A licence is needed to operate the equipment in South Africa, because it uses wireless telemetry. This entails an annual cost of approximately R18 per station. The greatest problem with wireless is the range of the transmitters. For reliable communication, a maximum distance of 35 km is recommended by the manufacturers. This is not always possible in KZN and radio repeaters must be used. Without repeaters the AWSN is limited to as far as can be reached by the radio network.

Generally, repeaters are used in remote and unattended sites. The solar panels then become targets for petty theft. This is not only expensive but results in the loss of irrecoverable data. On the positive side, this is a system that is robust and able to be fully automated within the Dacom Plant-*Plus* system. This means it is much easier to use data from Adcon rather than from Campbell and Davis stations, where the data needs to be e-mailed manually.

The problem with the leafwetness sensor on the older models of the Adcon system is that the sensor is mounted above the radiation shield of the temperature and radiation shield and so is automatically at the height of the temperature and RH sensor. On the later models this has been corrected and users are able to set the height of the leafwetness sensor independently of the temperature and RH sensor.

The actual software used to run the Adcon dataloggers is not very user friendly and there are no help files in the version used in the AWSN (ADDvantage 3.5). The new software has not yet been evaluated within the AWSN. It is hoped that it is more user friendly. A new development by Adcon Telemetry is the introduction of GSM enabled A733s. This will bring a whole new element to the Adcon equipment. It will be possible with the new software, and an upgrade of the existing wireless base station (A730SD) to the A840 Gateway, to have both wireless and GSM enabled stations on the same network (Http://www.adcon.com, 2003).

5.4.3 Davis Vantage Pro

The Davis Vantage Pro Weatherlink loggers appear to be good value for money, as they offer all the sensors and GSM modem connection capabilities of the two dataloggers previously discussed, at half the price. There are two of these stations in the AWSN.

Initially there was a problem with the measurement of solar radiation, until the software supplied with the AWS (Weather Link 5.2) was upgraded and a beta version 5.3 was

released. Beta version 5.3 had the correct software settings available to enable interpretations of solar radiation data.

Another problem that required a firmware (the software the logger uses to operate) upgrade was the problem of the logger interpreting data from remote stations. Here it is necessary to explain the functioning of the Vantage Pro. The Vantage Pro AWS is set up on a modular structure. It has eight incoming radio channels available. On each of these channels a remote radio can be used and these are used for the measurements taken by the sensors. The basic remote sender is the ISS (integrated sensor suite). This contains the temperature and RH sensor, precipitation, solar radiation and ultra-violet sensors as optional and wind speed and direction. Additional ISS modules can be fitted to the Vantage Pro or a leafwetness station, soil moisture and temperature, wind speed and direction.

Before the firmware upgrade, the station would measure, in some instances over 100mm of rain a day, even though no rain had fallen. One of the fixes in the upgrade was the interpretation of data from the remote stations. If one of the remote stations had a low battery then low battery warnings are issued. Before the upgrade the main station was reading these warnings as rainfall measurements and not as low battery warnings. Since the firmware upgrade (Rev 1b Jan 2003), the stations appear to be measuring precipitation accurately and no further problems have been experienced.

5.5 Choice of a weather station

In the design of the perfect AWSN there is not really a right or a wrong choice. The choice of equipment is almost pre-determined by the objectives set for the AWSN and the funding available. Once the objectives for the AWSN have been determined, *i.e.*, will the AWSN be used mainly for crop modelling, modelling of energy fluxes, *etc.*, and the amount of funding is known, choices can be made. These choices will determine the limitations of the network. It is best to start with the correct equipment.

In the present research, the AWSN is to be used for disease modelling work. However, it is envisaged that the data collected from the AWSN may in the future be used to run crop growth models and irrigation scheduling. These objectives require that the individual AWS needs to be a full weather station, *i.e.,* have sensors to measure temperature, sunlight, wind speed and direction, relative humidity, precipitation, duration of leaf wetness, soil moisture and soil temperature.

If, however, the objectives are solely disease prediction, then the sensors are reduced to the following: temperature, relative humidity, precipitation and duration of leaf wetness.

The other considerations for the choice of AWS must be cost and reliability. The cheapest option has an expected lifespan of two years and the most expensive a lifespan of eight years. The prices are R30 000 (cheapest) and R60 000 (most expensive), giving a R30 000 difference between the two AWS.

One way to calculate the more cost-effective option is to reduce the cost to a per year basis (Table 5.3), with the equation:

Cost year^{-1} = cost of equipment/expected lifespan.

Table 5.3 Comparison of automatic weather stations, on a cost per year basis

Cost of equipment		**Expected lifespan (years)**	**Cost year^{-1}**
AWS 1	R30 000	2	R15 000
AWS 2	R60 000	8	R7 500

Using this system it is easy to see which is the more cost-effective weather station to purchase. The other consideration in terms of choice of AWS is the ability to expand

the sensors attached to the station. Can other external sensors, such as soil temperature probes, be attached ?

5.6 Future of the system and uses

The Cedara AWSN is a valuable asset and can be used for more than just disease prediction purposes. At the time of writing, the data is being used for the potato late blight incidence map and prediction of grey leaf spot.

It is envisaged that the data will further be used for validation of the Departmental GIS database. Once long-term trends can be calculated from the recorded data these data will be incorporated into the GIS database to substantiate data already present.

A maize rust fungicide timing model is being developed. This will be used to time initial fungicide sprays for the prevention of rust. The hypothesis behind the development of the model is that it is the climatic conditions early in the season that determine infection and rust symptoms. If the conditions are measured, and a preventative fungicide is applied before symptom development, then it should be possible to avoid symptoms altogether. If conditions suitable for infection should occur before the fungicide half life has passed, then no further sprays would be applied. However, if the conditions were to be suitable for infection after the fungicide half life, then a second fungicide spray would be applied.

A maize stalkborer model is being developed, using pheromone traps to count adult moths. Moth numbers are then correlated with prevailing weather conditions, probably temperature linked, as with the phenology models on the internet (Anonymous, 2003b). When the specific correlation is found, then using the weather data from the AWSN it will be possible to put out warnings regarding the timing of preventative insecticide sprays.

Further models and uses for the AWSN are limited only by the creativity of the users of the AWSN. Any pest (weed, insect or pathogen) which responds to environmental

triggers can be modelled and data from the AWSN can be used for prediction of these pests.

All existing models and any future models will be available on the Departmental internet site. It is envisaged that near realtime weather data will be available from the internet site and this will not only benefit farmers and advisers but be a source of interaction with the general public, who seem to be far removed from the realities of agriculture.

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CHAPTER 6

THESIS OVERVIEW

6.1 Why disease prediction ?

This study has highlighted the exciting possibilities of predicting disease. With the advent of the new automatic weather stations (AWS) and microchip technology, it is now possible to measure and record almost every conceivable climatic event influencing the life cycle of plants. These AWS have paved the way for a number of pest prediction models (Anonymous, 2003), through the ability to measure almost realtime climatic events.

With the ability to predict the development of pests on crops and the ability to move away from the use of calendar-based spray programmes, the possibility for extending the useful life of agrochemicals (before acute resistance builds up) exists.

The main limitation to the use of pest models lies in their acceptance by the farming community (*i.e.*, farmers and advisers). This is not always a poor reflection on the farmers, because many of the models currently in use are actually more academic than usable in practice. This is illustrated in the Cercospora leaf spot model (Shane and Teng, 1984) which, when used in practice, had a number of modifications by the users to fit into their farming practices, *e.g.*, the dropping of the intensive disease scouting component of the model and the change in the calculation of the Daily Infection Value by lowering the threshold value of the number of hours of relative humidity (RH) to 87% instead of 90% (Windels *et al.*, 1998). This emphasises the importance of developing prediction models (especially those meant for practical use) in conjunction with actual users or farmer advisers.

With the increasing use of disease prediction models to time fungicide applications, it is becoming easier to optimise fungicide applications. Normally, fungicides are applied

on a calendar-base or as a curative (not recommended), based on visual disease severity. The problem with visual disease estimates by untrained observers is the tendency to see disease only at an advanced stage (perception threshold). This threshold is normally at x (disease) = 0.05 (5%) severity, and for the trained observer between x = 0.0001 and x = 0.05 (Zadoks and Schein, 1979). This means that the disease is only observed in the logistic phase, by the layman. This results in fungicide applications after the disease has increased the most rapidly, *i.e.*, the increase from 0.0001 to 0.05 is far greater than the increase from 0.05 to 0.5. This is why fungicides are applied too late if they are applied simply on visual assessments alone (especially if the assessments are done by a layman).

The use of disease prediction models can reduce this risk of late fungicide applications by showing producers when infections conditions have occurred. In so doing the fungicides can then be applied in the absence of visual disease yet the producer knows that infection has occurred and the fungicide applications are economically justified.

6.2 The *Cercospora zeae-maydis* prediction model

Grey leaf spot (GLS) of maize, caused by *Cercospora zeae-maydis*, is a devastating foliar disease in the absence of genetic resistance and active disease management strategies. This is illustrated by the level of yield losses sustained with unprotected susceptible varieties used in the study's trial. With the susceptible maize variety SC206 for the 2000/01 season a yield loss of 2.1 tons ha^{-1} occurred.

Most commercial maize cultivars available on the market have good tolerance to GLS and will return reasonable yields (6.9-9.3 tons ha^{-1} for PAN6568 and 7.7-8.8 tons ha^{-1} for SC627), without fungicide applications. In contrast, SC206, a susceptible cultivar, yielded 6.3-7.9 tons ha^{-1} without fungicide applications.

For those producers growing susceptible cultivars the use of fungicides is still justified. The GLS model helps to time these applications. The model developed at Cedara by Berry *et al.* (1995) is still usable. The study did find that the model, since its inception

has drifted. But by introducing a correction factor to the calculations, the models lifespan has been extended.

The correction factor is essentially a departure from the assumption that all residue at planting is infected. When the model was designed this assumption was correct, as susceptible maize varieties were being grown. By 2002, cultivars with a much higher level of genetic resistance were being grown and this was reflected in the amount of infected residue at planting. The correction factor calculates the amount of infected residue based on the previous season's final disease rating and the estimated residue cover at planting. For example, if the previous season's final disease rating was 50% disease severity and it is estimated that there is a 30% residue cover on the soil, then the estimated amount of infected residue is 15%, using the equation below:

Infected residue = final disease severity X estimated residue cover/100

With the correction factor included, the model is far more accurate and dynamic because it is able to take into account the previous season's final disease incidence and show the effect of estimated infected residue rather than assuming that all residue is infected.

In addition, the model has been re-programmed into Borland Delphi Enterprise Version 5 (Inprise Corporation, Scott's Valley, California, USA) and renamed SprayAid32.

Additions to the model during the course of this study include the length of control of a fungicide. Fungicide Half Life and Fungicide Effective Period (FEP) are defined as the period of time it takes for the fungicide to become half as efficient as it was at application. Once a fungicide spray is applied, the model is halted until the FEP is past. After the FEP, the model is reset to 0 and the cycle is restarted.

SprayAid32 includes the ability to change the air temperature requirements at runtime. If a user wanted to test the effects of changing the simulated epidemiological requirement of the pathogen, it can be done without going into the actual program code.

The number of cumulative hours of RH needed for infection to start can be adjusted. The default value is 200 hours but, with this addition to the model, it is possible to simulate different scenarios. The study has contributed to the further evolution of the GLS model and the understanding of the dynamics of the pathogen/host interaction in KwaZulu-Natal.

6.3 Evaluation of the potato late blight and early blight prediction models

Potato late blight (LB), caused by the pathogen *Phytophthora infestans,* is one of the best known plant pathogens. It caused the Irish famine of 1845 by the total devastation of the potato crop and subsequent rotting of the tubers. It is an airborne foliar disease that, under optimal conditions, can defoliate an entire crop in less than four days (Agrios, 1997).

Without fungicide protection, a medium susceptible cultivar such as BP1 has the potential to lose close to 50% (2001/02 trial) of the potential yield. This is in a season that, from the results, can be classed as a medium disease pressure season. Because of this commercial producers need to spray fungicides regularly to prevent the spread of LB through their mostly susceptible cultivars.

With the demand for fungicide applications, there is a need to time these applications optimally. The two LB prediction models compared to the two commercial calendar-based fungicide programmes gave mixed results. There were no significant statistical differences between the treatments. There appeared to be an interaction between the cultivars and the type of spray programme, *e.g.*, Hertha gave higher yields with the predicted programmes than with the calendar-based programmes, whereas BP1 gave better yields with the calendar-based programmes. In economic terms the calendar-based programmes were the highest yielding.

Based on two years' data it is difficult to determine conclusively which is the optimum system for KZN. Another season's trials are in progress (2002/03). With the data currently available, it is possible to say that as long as systemic fungicides are included in a preventative spray programme, marketable yield is significantly improved over the minimum control option of using only preventative contact fungicides.

The timing of the systemic fungicide sprays in the programme does have an effect. In an intense blight season a modelled spray programme will be better than a calendar-based programme. However, in a low blight season, a calendar-based programme may offer better returns. However, it must be stressed that whether a calendar-based programme or a modelled programme is used, there is no significant difference in yield between low and intense blight seasons.

The most sustainable approach will be through using models which help determine the optimum time for the use of systemic fungicides. By limiting exposure of *P. infestans* to systemic fungicides, the chance of resistance development may be reduced.

The single year of evaluating the early blight (EB) (caused by *Alternaria solani*) prediction model showed that it is suitable for use in KwaZulu-Natal (KZN) (van der Waals *et al.*, 2003a). Only contact fungicides were used and with the model three contact sprays were saved (van der Waals *et al.*, 2003b).

The method of controlling LB without affecting EB was a direct result of this trial. The method is to use propamocarb-hydrochloride and phosphorous acid at 4-5 day intervals, to ensure that LB does not occur. Initially the propamocarb-hydrochloride was used as a drench on its own. This however, proved too cumbersome, so both fungicides were tank-mixed and sprayed onto the foliage. The level of EB in this treatment was high and the level of LB was lower than any of the calendar-based and predicted spray programmes.

The LB map was a direct result of the trial (van Rij, 2002; van Rij, 2003). The map attempts to show the seasonal progression of the LB epidemic across KZN. There has

been considerable interest shown in the map and in 2002 the map was updated ten times and the warnings e-mailed to a list of more than 60 users. This map will continue to be updated and is available on the Department's Website at: http://agriculture.kzntl.gov.za/crop_protection/late_blight/late blight incidence.htm.

6.4 Visual disease assessments

One of the objectives of the study was to compare different visual disease rating systems. For the maize trials, the idea was to assess the whole plant and then only the fifth leaf for disease and compare the two as a way of determining the need for fungicide applications. This did not work, as the fifth leaf died off too soon, and by the time disease was at a reasonable percentage severity on the whole plant, the leaf had dried out. However, fifth leaf rating scales have been developed and cater for very low lesions areas, *i.e.*, from 0.25% to 1% leaf area covered by lesions.

For the potatoes two rating systems were compared, *viz.* the Horsfall-Heuberger Index (HHI) (Horsfall and Heuberger,1942) and the percentage disease severity in the plot (% plot disease), based on the work of James (1971).

For the potato rating systems comparison it was found that the HHI can be used in seasons with low disease pressure, although it appears to be better in seasons with high disease pressure, as erratic results occur in seasons with low disease pressure. The study clearly showed that % plot disease, and even the mean of the ten plants' individual ratings used to calculate the HHI, are better estimates of disease incidence and severity than the HHI.

6.5 Automatic weather station network

While not initiating the AWSN, the study has certainly contributed to it, in that it has allowed the formalisation of norms and standards for the AWSN. The AWSN currently comprises 13 automatic weather stations (AWS) covering a large area of KwaZulu-

Natal. The study has highlighted the need for accurate and reliable data. Prior to the study an AWS was not considered permanent. It has now been recognised that for data to be useful to more than one user it needs to be accurate, and from the same single location, for as long as possible.

The data from the AWSN has been placed on the Departmental Internet site: http://agriculture.kzntl.gov.za/crop_protection/Weather records/weather.htm.

6.5 Future research needs

The ability to predict pathogen development, either at infection or in the developmental stages, is an advantage in the quest to secure food security. It is an aid in the decision-making process for the timing of disease control intervention. Problems facing the large-scale use of these decision aids are the lack of acceptance, both through ignorance of their existence, the lack of capital for the running of such aids, and prejudice against using them.

For the GLS maize model, work is currently under way to determine the time of release of initial inoculum from the previous season's infected maize residue. If this can be linked to prevailing weather patterns it will be possible to peg the start of the GLS season and quantify spore release and numbers. This may also show a trend in the release of spores over time and determine if there are differences in when spore release starts in the season.

Mapping of the seasonal progression of LB needs to continue, as it is providing a valuable service to farmers and advisers. Suggestions for the map and the whole concept of disease prediction models available from the Departmental Website are being expanded and work will be done on the development of models to aid in the timing of control measures, *i.e.*, agrochemicals, be they insecticides, fungicides or herbicides.

Visual disease rating systems are a necessity in Plant Pathology. This may not be a research need but a practical point. It is essential that people who do visual rating of disease have an understanding of the laws that apply to how the eye works and the fact that after a certain percentage blighting the eye is no longer seeing healthy tissue but rather dead tissue.

To resolve this problem, Crop Protection Section; Cedara is currently investigating the use of a solar radiometer, to measure reflectance from crop canopies. The use of this instrument is in its infancy in South Africa and research is being carried out to determine whether it is efficient or not. The obvious benefit of the machine is that if a surface reflects light it can be measured by the radiometer. As long as standards are established of how rating is to be done before the start of each trial, it will be fair to say that the radiometer is totally unbiased.

In conclusion, the challenge ahead is to develop disease prediction models to the point where they are able to be easily understood by most users. These models will then be effectively applied to optimize the timing of control intervention strategies. The ideal would be to be able to use models in an integrated approach, such that the use of agrochemicals would be a last resort and thus the effective lifespan of the different products may be lengthened.

6.6 Literature cited

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Appendix 2.1

```
unit fmain;
interface
uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs, Grids, ComCtrls, Menus, StdCtrls, TeEngine, Series, ExtCtrls, TeeProcs,
  Chart, Printers, StdActns, DBActns, ActnList, ImgList, Clipbrd;
type
  TForm1 = class(TForm)
    MainMenu1: TMainMenu;
    File1: TMenuItem;
    Open1: TMenuItem;
    N1: TMenuItem;
    Exit1: TMenuItem;
    Data1: TMenuItem;
    Analyse1: TMenuItem;
    StatusBar1: TStatusBar;
    PageControl1: TPageControl;
    TabSheet1: TTabSheet;
    StringGrid1: TStringGrid;
    OpenDialog1: TOpenDialog;
    TabSheet2: TTabSheet;
    GroupBox1: TGroupBox;
    Edit1: TEdit;
    Edit2: TEdit;
```

```
    Edit3: TEdit;
    Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    TabSheet3: TTabSheet;
    TabSheet4: TTabSheet;
    TabSheet5: TTabSheet;
    Edit4: TEdit;
    Edit5: TEdit;
    Edit6: TEdit;
    Edit7: TEdit;
    Edit8: TEdit;
    Label4: TLabel;
    Label5: TLabel;
    Label6: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    GroupBox2: TGroupBox;
    Chart1: TChart;
    GroupBox3: TGroupBox;
    Chart2: TChart;
    Series1: TPointSeries;
    Series7: TPointSeries;
    Print1: TMenuItem;
```

Blight1: TMenuItem;

Cumulate1: TMenuItem;

BlightCumulate1: TMenuItem;

N2: TMenuItem;

Label9: TLabel;

Label10: TLabel;

Label11: TLabel;

Edit9: TEdit;

Edit10: TEdit;

Edit11: TEdit;

Label12: TLabel;

Edit12: TEdit;

PrintDialog1: TPrintDialog;

Label13: TLabel;

StringGrid2: TStringGrid;

StringGrid3: TStringGrid;

Edit13: TEdit;

Label14: TLabel;

Analyse: TButton;

ActionList1: TActionList;

EditCopy1: TEditCopy;

EditCut1: TEditCut;

EditPaste1: TEditPaste;

EditSelectAll1: TEditSelectAll;

```
    Edit14: TMenuItem;
    Cut1: TMenuItem;
    Copy1: TMenuItem;
    Paste1: TMenuItem;
    SelectAll1: TMenuItem;
    Label15: TLabel;
    procedure Open1Click(Sender: TObject);
    procedure Analyse1Click(Sender: TObject);
    procedure FormCreate(Sender: TObject);
    procedure Exit1Click(Sender: TObject);
    procedure FormResize(Sender: TObject);
    procedure Chart1ClickSeries(Sender: TCustomChart; Series: TChartSeries;
      ValueIndex: Integer; Button: TMouseButton; Shift: TShiftState; X,
      Y: Integer);
    procedure Blight1Click(Sender: TObject);
    procedure Cumulate1Click(Sender: TObject);
private
    { Private declarations }
  public
    { Public declarations }
  end;
WeatherType = record
        maxtemp,
        mintemp,
```

```
      rainfall,
      solrad,
      humhrs: real;
  end;

var
  Form1: TForm1;
  DataFile: TFileName;
  day, year, emdoy, i, j: integer;
  weatherrec: weathertype;
  germinate, develop, plantup, infection: boolean;
  newfactor, cumulate, prevcum, rateincr, inoccoeff, gencoeff,
      percblight, meantemp, tempfac, humfac, rateinc : real;
  f: textfile;
  id: string[7];
  s: string;
  cumcounter: integer;  //row counter for cumulate grid
  blightcounter: integer; //row counter for blight grid;
  sd1, sd2, sd3, sd4, sd5: integer;
  mintmp, maxtmp, hmhrs, trigger: real;
  delay, delay1: integer;
  stopped: boolean;
```

```
implementation
{$R *.DFM}
procedure TForm1.Open1Click(Sender: TObject);
begin
  Opendialog1.Execute;
  DataFile := OpenDialog1.FileName;
  assignfile(f, Datafile);
  reset(f);
  j:=1;
  stringgrid1.Visible := false;
      while not eof(f) do
      with weatherrec do
      begin
            readln(f, id, year, day, solrad, maxtemp, mintemp, rainfall, humhrs);
            stringgrid1.RowCount := j;
            stringgrid1.cells[0,j] := id;
            stringgrid1.cells[1,j] := inttostr(year);
            stringgrid1.cells[2,j] := inttostr(day);
            stringgrid1.cells[3,j] := floattostr(solrad);
            stringgrid1.cells[4,j] := floattostr(maxtemp);
            stringgrid1.Cells[5,j] := floattostr(mintemp);
            stringgrid1.cells[6,j] := floattostr(rainfall);
            stringgrid1.Cells[7,j] := floattostr(humhrs);
```

```
            j:=j+1;
            Application.ProcessMessages;
        end;
        closefile(f);
        stringgrid1.visible := true;
        if stringgrid1.Cells[2,1] <> '' then edit1.text := stringgrid1.cells[2,1];
end;
procedure TForm1.Analyse1Click(Sender: TObject);
        function power(a, b: real):real;
        begin
            power:= exp(ln(a)*b);
       end;
begin
if (edit1.text <> '') and (edit2.text<>'') and (edit3.text<>'') and (Opendialog1.FileName<>'')then
begin
        StringGrid2.RowCount := 2;
        StringGrid3.RowCount := 2;
        series1.Clear;
        series7.clear;
        emdoy := strtoint(edit1.text);
        inoccoeff := strtofloat(edit2.text);
        gencoeff := strtofloat(edit3.text);

        maxtmp:= strtofloat(edit9.text);
```

```
mintmp:= strtofloat(edit10.text);
hmhrs:= strtofloat(edit11.text);
delay:= strtoint(edit12.text);
trigger:= strtofloat (edit13.text);
delay1:= delay;;

sd1:= strtoint(edit4.text);
sd2:= strtoint(edit5.text);
sd3:= strtoint(edit6.text);
sd4:= strtoint(edit7.text);
sd5:= strtoint(edit8.text);
assignfile(f, DataFile);
reset(f);
germinate:= false;
develop:= false;
cumulate:= 0.0;
rateincr:= 0.0;
percblight:= 0.0;
newfactor:= 0.0;
plantup:= false;
i:=1;
j:=1;
cumcounter:= 1;
blightcounter := 1;
```

```
stopped:= false;
while not eof(f) do
with weatherrec do
begin
    readln(f, id, year, day, solrad, maxtemp, mintemp, rainfall, humhrs);
    if (year < 70) then year:= year+2000 else year:= year+1900;
    if (day=emdoy) then plantup := true;
    if (day=151) then
    begin
        germinate:= false;
        develop:=false;
        prevcum:= 0.0;
        cumulate:= 0.0;
        rateincr:= 0.0;
        percblight:= 0.0;
        newfactor:= 0.0;
        plantup:= false;
    end;
    if (day=sd1) or (day=sd2) or (day=sd3) or (day=sd4) or (day=sd5) then
    begin
        germinate := false;
        develop := false;
        prevcum := 0;
        cumulate := 0;
```

```
        rateincr := 0;
        percblight := 0;
        newfactor := 0;
        delay1:= delay;
        stopped := true;
end;
if (delay1 = 0) then
begin
//glsprogress
if (plantup) then
with weatherrec do
begin
        meantemp := (maxtemp+mintemp)/2;
  if (meantemp > mintmp) and (meantemp<=maxtmp) then
        begin
              if (trigger > 0) then
              begin
                if (humhrs>=trigger) then germinate := true
              end else
              if (humhrs>=13) then germinate := true;

              if (germinate) then cumulate := cumulate+humhrs;

              if (germinate) and (cumulate<hmhrs) then
```

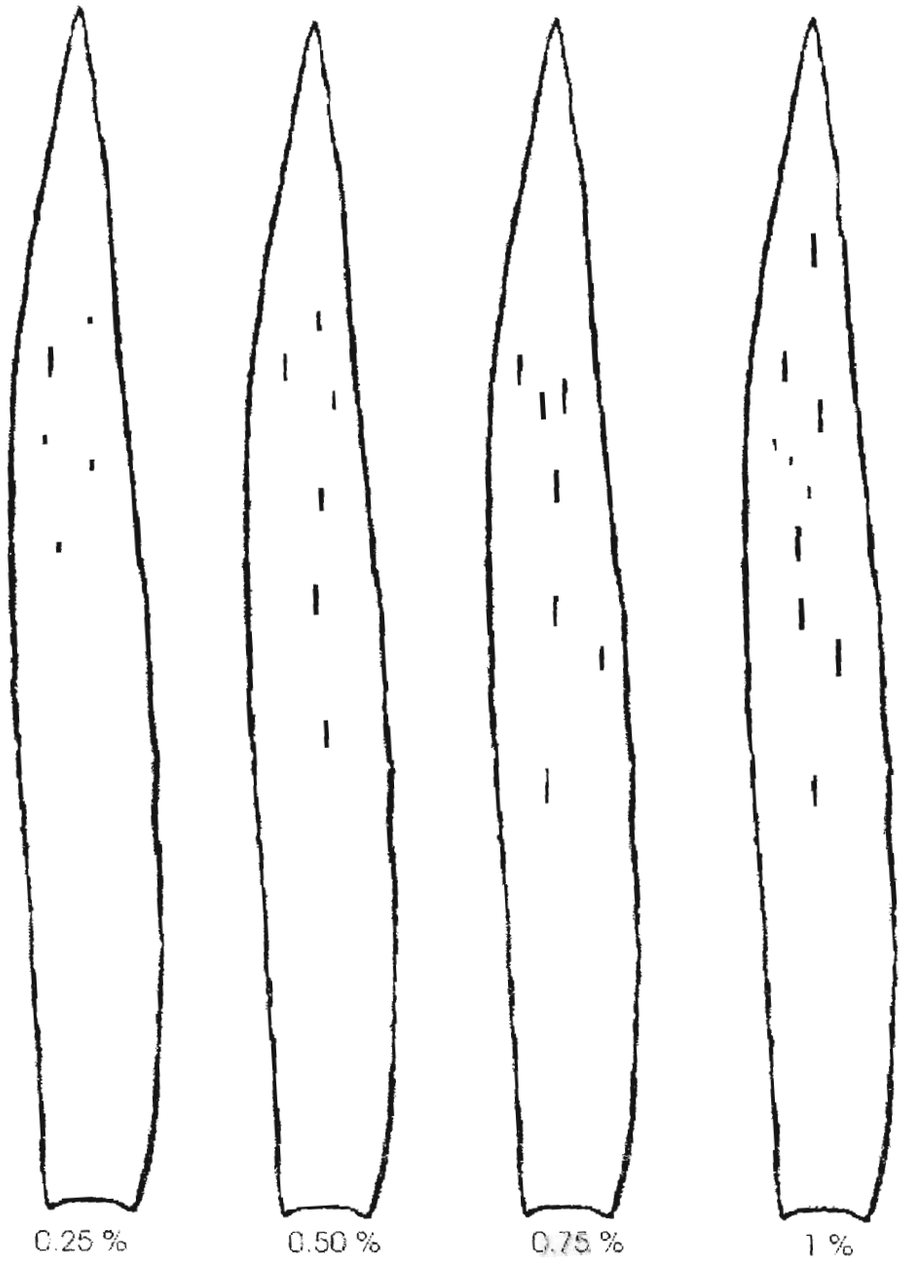
```
        begin
            //s := format('Date : %d   Cum : %f',[day,cumulate]);
            //memo1.lines.add(s);
            begin
                stringgrid2.Cells[0,cumcounter] := inttostr(day);
                s := format('%8.2f',[cumulate]);
                stringgrid2.cells[1,cumcounter] := s;
                cumcounter := cumcounter +1;
                stringgrid2.rowcount := cumcounter;
            end;

            with series1 do
                add(cumulate,inttostr(day),clred);

        end;

        if (cumulate >= 72) then infection := true;

        if (cumulate >= hmhrs) then develop := true;
end;

if (develop) then
begin
        if (meantemp <= 15) then tempfac:= 0;
```

```
        if (meantemp > 15) and (meantemp<22) then
            tempfac:= (meantemp-15)/7;
        if (meantemp>=22) and (meantemp<=30) then
            tempfac:= 1;
        //todo: verify this formula
        if (meantemp>30) then tempfac:= (37-meantemp)/7;
        if (humhrs<= 0) then humfac:= 0;
        if (humhrs > 0) and (humhrs<12) then humfac:= humhrs;
        if (humhrs>12) then humfac:= 12;
        newfactor:= newfactor+(tempfac*humfac);
end;
rateinc := newfactor-prevcum;
if (develop) then
begin
        percblight := power(100/(1+inoccoeff*exp(-gencoeff*newfactor)),1.243);
        if (percblight > 100) then percblight := 100;
        begin
            stringgrid3.Cells[0,blightcounter] := inttostr(day);
            s := format('%8.2f',[newfactor]);
            stringgrid3.cells[1,blightcounter] := s;
            s := format('%8.1f',[percblight]);
            stringgrid3.Cells[2,blightcounter] := s;
            blightcounter := blightcounter + 1;
            stringgrid3.rowcount := blightcounter;
```

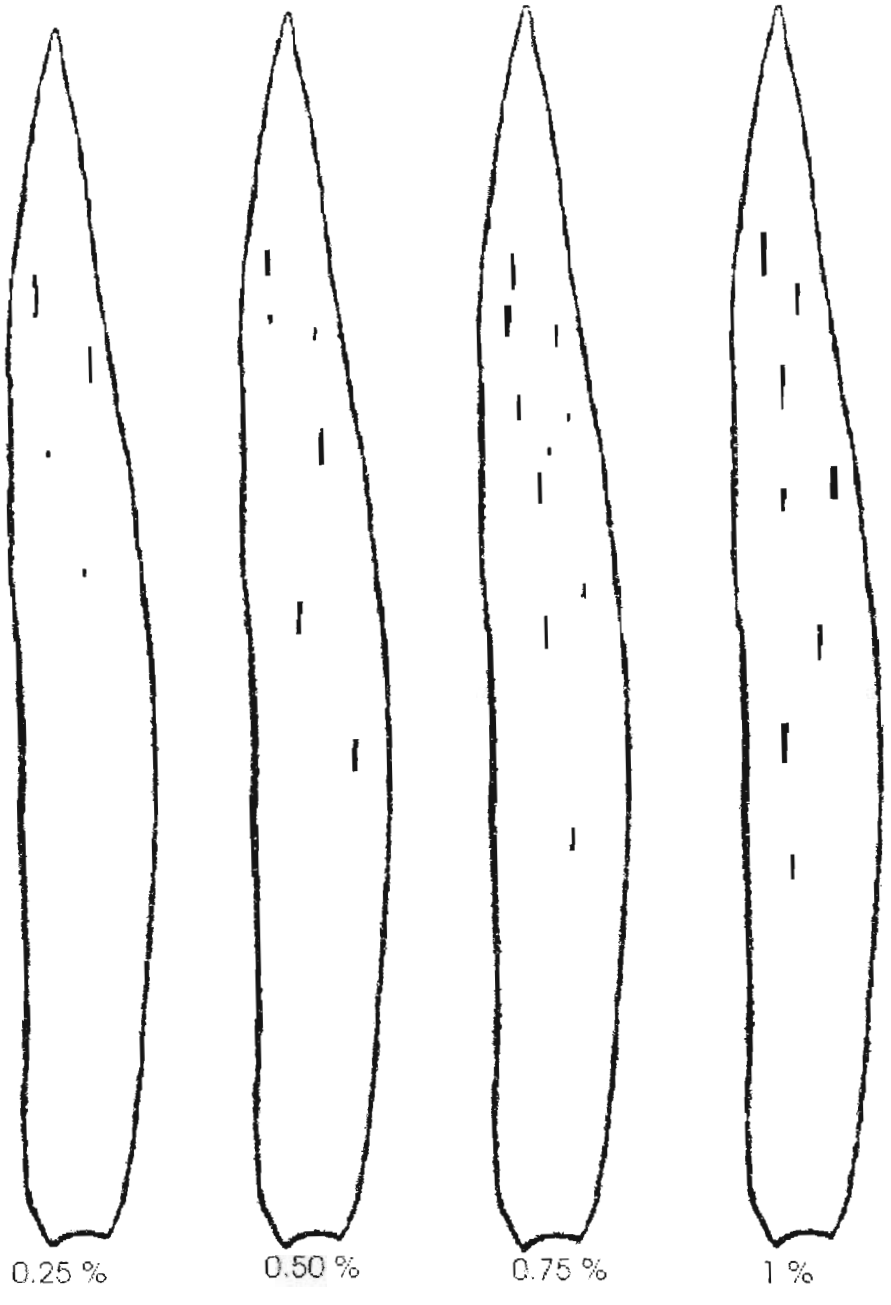
```
                    end;
                    with series7 do
                        add(percblight,inttostr(day),clgreen);
                end;
            end;
            end
            else
            delay1 := delay1-1;
        end;
        closefile(f);
        end;
end;
procedure TForm1.FormCreate(Sender: TObject);
begin
  stringgrid1.Cells[0,0] := 'STN';
  stringGrid1.Cells[1,0] := 'Year';
  stringgrid1.Cells[2,0] := 'Day';
  stringgrid1.cells[3,0] := 'Sol. Rad.';
  stringgrid1.cells[4,0] := 'Max. Temp.';
  stringgrid1.cells[5,0] := 'Min. Temp.';
  stringgrid1.cells[6,0] := 'Rainfall';
  stringgrid1.cells[7,0] := 'Hum. Hours';

  stringgrid2.Cells[0,0] := 'Day';
```

```
  stringgrid2.cells[1,0] := 'Cumulate';

  stringgrid3.Cells[0,0] := 'Day';
  stringgrid3.cells[1,0] := 'Temp X Hum Fac';
  stringgrid3.cells[2,0] := '% Blight';
end;
procedure TForm1.Exit1Click(Sender: TObject);
begin
  Close;
end;

procedure TForm1.FormResize(Sender: TObject);
begin
  groupbox2.Height := tabsheet5.Height div 2;
  groupbox3.Height := tabsheet5.Height div 2;
end;

procedure TForm1.Chart1ClickSeries(Sender: TCustomChart;
  Series: TChartSeries; ValueIndex: Integer; Button: TMouseButton;
  Shift: TShiftState; X, Y: Integer);
var
  s: string;
  yval: double;
```

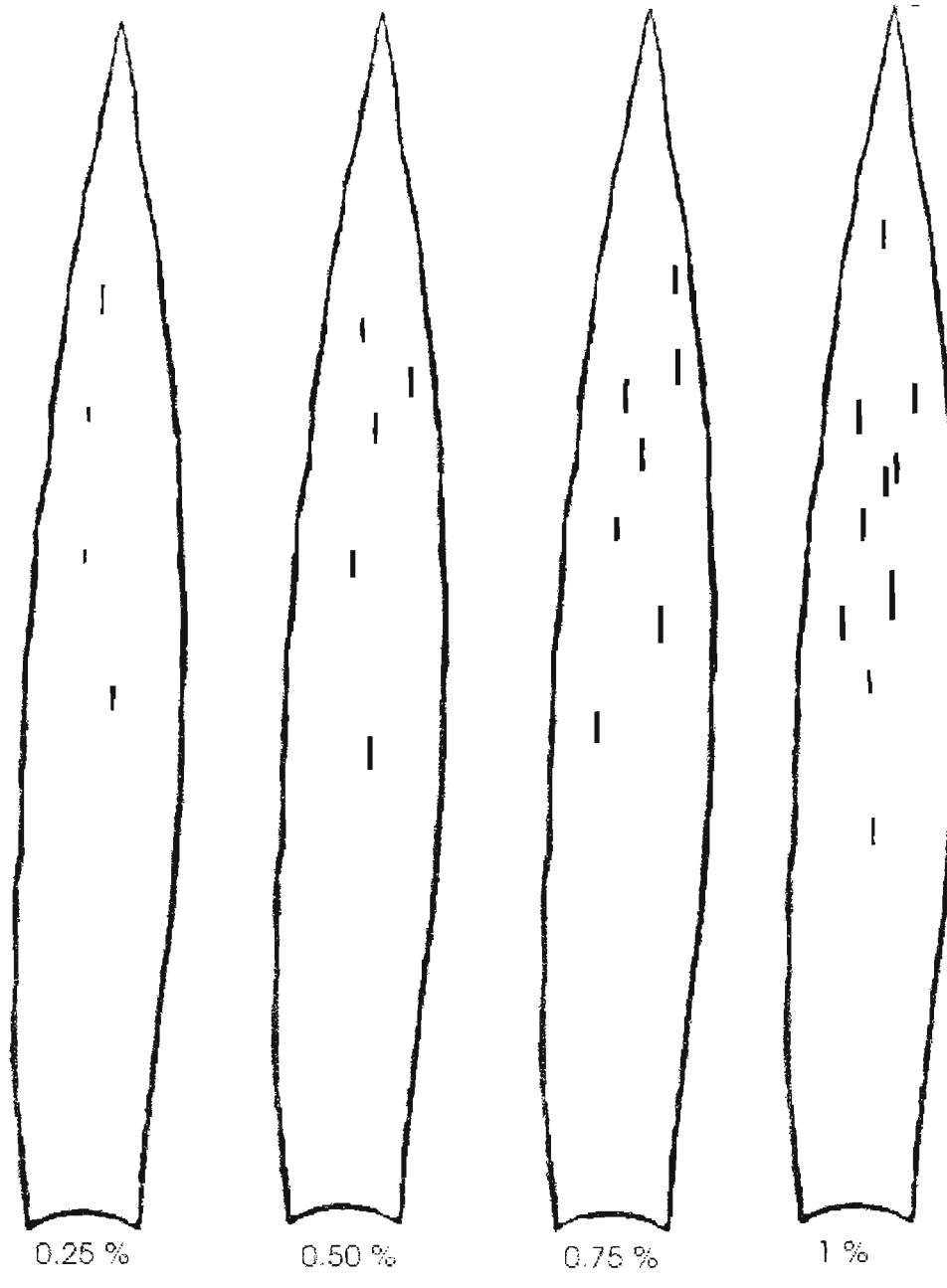
```
begin
  yval := series1.YValues.Value[valueindex];
  s:= format('Cumulate: %f',[yval]);
  label13.Caption := s;
  label13.Visible := true;
end;

procedure TForm1.Blight1Click(Sender: TObject);
begin
  chart1.PrintProportional := true;
  chart1.PrintLandscape;
end;

procedure TForm1.Cumulate1Click(Sender: TObject);
begin
  chart1.PrintProportional := true;
  Chart1.Height:=Round(Printer.PageHeight-20);
  chart2.PrintLandscape;
end;

end.
```



Appendix 3.1 SC206 leaf area diagrams depicting 0.25, 0.50, 0.75 and 1 % leaf area blighting, developed and used in the maize trials at Cedara.



Appendix 3.2 PAN6568 leaf area diagrams depicting 0.25, 0.50, 0.75 and 1 % leaf area blighting, developed and used in the maize trials at Cedara.



Appendix 3.3 SC627 leaf area diagrams depicting 0.25, 0.50, 0.75 and 1 % leaf area blighting, developed and used in the maize trials at Cedara.

Appendix 4.1 Treatment 1 - a predicted spray application based on the Plant-*Plus* model, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
19/10/00	1	Dithane	3 kg
24/10/00	2	Acrobat	2 kg
31/10/00	3	Acrobat	2 kg
07/11/00	4	Bravo	2 l
		Bond	100 ml
09/11/00	5	Bravo	2.5 l
		Bond	100 ml
17/11/00	6	Dithane	2.5 kg
		Bond	100 ml
24/11/00	7	Bravo	2.0 l
29/11/00	8	Bravo	2.5 l
		Bond	100 ml
10/12/00	9	Bravo	2.5 l
		Bond	100 ml
18/12/00	10	Tanos	500 g
		Dithane	3 kg
		BP oil	500 ml
22/12/00	11	Bravo	2.5 l
		Bond	100 ml
01/01/01	12	Bravo	2.5 l
		Bond	100 ml
12/01/01	13	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml

Appendix 4.2 Treatment 2 - a predicted spray based on the Winstel late blight model, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
28/10	1	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
09/11/00	2	Bravo	2 l
		Bond	100 ml
17/11/00	3	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
29/11/01	4	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
10/12/00	5	Acrobat	2 kg
22/12/00	6	Dithane	2.5 kg
01/01/01	7	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml

Appendix 4.3 Treatment 3 - commercial calendar-based treatment and field scouting, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
24/10/00	1	Dithane	2.5 kg
28/10/00	2	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
03/11/00	3	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
08/11/00	4	Dithane	3 kg
17/11/00	5	Dithane	2.5 kg
		Bond	100 ml
24/11/00	6	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
01/12/00	7	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
10/12/00	8	Dithane	2.5 kg
		Bond	100 ml
18/12/00	9	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
22/12/00	10	Dithane	2.5 kg
01/01/01	11	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml
08/01/01	12	Tanos	500 g
		Dithane	2.5 kg
		BP oil	500 ml

Appendix 4.4 Treatment 4 - commercial calendar-based treatment and field scouting, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
24/10/00	1	Dithane	2.5 kg
28/10/00	2	Acrobat	2.0 kg
03/11/00	3	Bravo	2.0 l
		Bond	100 ml
09/11/00	4	Bravo	2.5 l
		Bond	100 ml
17/11/00	5	Amistar	300 ml
24/11/00	6	Bravo	2.0 l
01/12/00	7	Amistar	300 ml
10/12/00	8	Bravo	2.5 l
		Bond	100 ml
18/12/00	9	Amistar	300 ml
22/12/00	10	Bravo	2.5 l
		Bond	100 ml
01/01/01	11	Amistar	300 ml
08/01/01	12	Bravo	2.5 l
		Bond	100 ml

Appendix 4.5 Treatment 5 - treatment to show the effects of spraying a contact (preventative) fungicide after flowering, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
09/11/00	1	Dithane	2.5 kg
		Bond	100 ml
24/11/00	2	Dithane	2.5 kg
10/12/00	3	Dithane	2.5 kg
22/12/00	4	Dithane	2.5 kg
08/01/01	5	Dithane	2.5 kg

Appendix 4.6 Treatment 6 - preventative, weekly contact fungicide treatment, 2000/01 season

Date of application	Number of sprays	Product applied	Product application rate ha^{-1}
24/10/00	1	Dithane	2.5 kg
31/10/00	2	Dithane	2.5 kg
		Bond	100 ml
07/11/00	3	Bravo	2.0 l
		Bond	100 ml
09/11/00	4	Dithane	2.5 kg
		Bond	100 ml
17/11/00	5	Dithane	2.5 kg
		Bond	100 ml
24/11/00	6	Dithane	2.5 kg
01/12/00	7	Dithane	2.5 kg
10/12/00	8	Dithane	2.5 kg
18/12/00	9	Dithane	2.5 kg
22/12/00	10	Dithane	2.5 kg
01/01/01	11	Dithane	2.5 kg
08/01/01	12	Dithane	2.5 kg

Appendix 4.7 Treatment 1 - a predicted spray application based on the late blight Plant-*Plus* model, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
02/11	1	Dithane	2.5 kg
		Bond	100 ml
09/11	2	Dithane	2.5 kg
		Bond	100 ml
16/11	3	Dithane	2.5 kg
		Bond	100 ml
22/11	4	Dithane	2.5 kg
		Bond	100 ml
29/11	5	Dithane	2.5 kg
		Bond	100 ml
05/12	6	Dithane	2.5 kg
		Bond	100 ml
07/12	7	Dithane	2.5 kg
		Bond	100 ml
11/12	8	Dithane	2.5 kg
		Bond	100 ml
18/12	9	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml
24/12	10	Dithane	2.5 kg
		Bond	100 ml
31/12	11	Dithane	2.5 kg
		Bond	100 ml
07/01	12	Dithane	2.5 kg
		Bond	100 ml
11/01	13	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml

Appendix 4.8 Treatment 2 - a predicted spray based on the Winstel late blight model, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
02/11	1	Dithane	2.5 kg
		Bond	100 ml
09/11	2	Dithane	2.5 kg
		Bond	100 ml
16/11	3	Dithane	2.5 kg
		Bond	100 ml
22/11	4	Dithane	2.5 kg
		Bond	100 ml
30/11	5	Dithane	2.5 kg
		Bond	100 ml
18/12	6	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml
27/12	7	Dithane	2.5 kg
		Bond	100 ml
07/01	8	Dithane	2.5 kg
		Bond	100 ml
11/01	9	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml

Appendix 4.9 Treatment 3 - commercial calendar-based treatment and field scouting, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
02/11	1	Dithane	2.5 kg
		Bond	100 ml
09/11	2	Dithane	2.5 kg
		Bond	100 ml
16/11	3	Dithane	2.5 kg
		Bond	100 ml
22/11	4	Dithane	2.5 kg
		Bond	100 ml
29/11	5	Dithane	2.5 kg
		Bond	100 ml
13/12	6	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml
21/12	7	Dithane	2.5 kg
		Bond	100 ml
27/12	8	Dithane	2.5 kg
		Bond	100 ml
03/01	9	Dithane	2.5 kg
		Bond	100 ml
11/01	10	Tanos	500 g
		Dithane	2.5 kg
		Oil	500 ml

Appendix 4.10 Treatment 4 - commercial calendar-based treatment and field scouting, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
2/11	1	Bravo	2 l
09/11	2	Bravo	2 l
16/11	3	Bravo	2 l
22/11	4	Bravo	2 l
29/11	5	Bravo	2 l
07/12	6	Amistar	300 ml
13/12	7	Bravo	2 l
21/12	8	Amistar	300 ml
27/12	9	Bravo	2 l
03/01	10	Amistar	300 ml
11/01	11	Bravo	2 l

Appendix 4.11 Treatment 5 - treatment to show the effects of spraying a contact (preventative) fungicide after flowering, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
07/12/01	1	Dithane	2.5 kg
		Bond	100 ml
21/12/01	2	Dithane	2.5 kg
		Bond	100 ml
03/01/02	3	Dithane	2.5 kg
		Bond	100 ml

Appendix 4.12 Treatment 6 - preventative, weekly contact fungicide treatment, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
2/11/01	1	Dithane	2.5 kg
		Bond	100 ml
09/11/01	2	Dithane	2.5 kg
		Bond	100 ml
16/11/01	3	Dithane	2.5 kg
		Bond	100 ml
22/11/01	4	Dithane	2.5 kg
		Bond	100 ml
29/11/01	5	Dithane	2.5 kg
		Bond	100 ml
07/12/01	6	Dithane	2.5 kg
		Bond	100 ml
13/12/01	6	Dithane	2.5 kg
		Bond	100 ml
21/12/01	7	Dithane	2.5 kg
		Bond	100 ml
27/12/01	8	Dithane	2.5 kg
		Bond	100 ml
03/01/01	9	Dithane	2.5 kg
		Bond	100 ml
11/01/02	10	Dithane	2.5 kg
		Bond	100 ml

Appendix 4.13 Treatment 7 - unsprayed control, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
	Unsprayed control	Unsprayed control	Unsprayed control

Appendix 4.14 Treatment 8 - a predicted treatment based on the early blight Plant-*Plus* model, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
09/11/01	1	Phosguard	1 % solution
16/11/01	2	Dithane	2.5 kg
		Bond	100 ml
		Phosguard	1 % solution
22/11/01	3	Dithane	2.5 kg
		Bond	100 ml
		Previcur N	3 l/m2 (drench)
29/11/01	4	Phosguard	1 % solution
30/11/01	5	Dithane	2.5 kg
		Bond	100 ml
07/12/01	6	Dithane	2.5 kg
		Bond	100 ml
		Phosguard	1 % solution
		Previcur N	2 l
11/12/01	7	Dithane	2.5 kg
		Bond	100 ml
13/12/01		Phosguard	1 % solution
		Previcur N	2 l
18/12/01	8	Dithane	2.5 kg
		Bond	100 ml
		Phosguard	1 % solution
		Previcur N	2 l
21/12/01	9	Phosguard	1 % solution
		Previcur N	2 l
24/12/01	10	Dithane	2.5 kg
		Bond	100 ml
27/12/01	11	Phosguard	1 % solution
		Previcur N	2 l
31/12/01	12	Dithane	2.5 kg
		Bond	100 ml
03/01/02	13	Phosguard	1 % solution
		Previcur N	2 l
07/01/02	14	Dithane	2.5 kg
		Bond	100 ml
11/01/02	15	Phosguard	1 % solution
		Previcur N	2 l

Appendix 4.15 Treatment 9 - Early blight uncontrolled and late blight controlled, 2001/02 season

Date of Application	Number of Sprays	Product applied	Product application rate ha^{-1}
09/11/01	1	Phosguard	1 % solution
16/11/01	2	Phosguard	1 % solution
22/11/01	3	Previcur N	3 l/m2 (drench)
29/11/01	4	Phosguard	1 % solution
07/12/01	5	Phosguard	1 % solution
		Previcur N	2 l
13/12/01	6	Phosguard	1 % solution
		Previcur N	2 l
18/12/01	7	Phosguard	1 % solution
		Previcur N	2 l
21/12/01	8	Phosguard	1 % solution
		Previcur N	2 l
27/12/01	9	Phosguard	1 % solution
		Previcur N	2 l
03/01/02	10	Phosguard	1 % solution
		Previcur N	2 l
11/01/02	11	Phosguard	1 % solution
		Previcur N	2 l