EFFECT OF EARLY BLIGHT ON POTATO YIELDS IN MANITOBA AND EPIDEMIOLOGY OF THE DISEASE

by

CAROLINE JOYCE KENNEDY

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ABSTRACT

Kennedy, Caroline Joyce. M.Sc., Effect of early blight on potato yields in Manitoba and epidemiology of the disease. Major professor: Dr. Roger Rimmer.

Field trials with two potato (Solanum tuberosum L.) cultivars Norland and Russet Burbank were conducted in 1983 and 1984 to evaluate the effect of early blight, caused by fungal pathogen Alternaria solani Sorauer, on yield under Manitoba conditions. To generate different disease epidemics various schedules of fungicide (mancozeb) application were used.

In 1983 disease did not become epidemic; maximum early blight severities were under 2%. In 1984 a single mid-July fungal inoculation applied to only half of the plots increased disease severity of both cultivars. Average severity with respect to spray schedule ranged from 0% for the initial ratings of both cultivars to 11.2% and 60.6% for the final ratings of plots receiving zero fungicide applications (cultivars Russet Burbank and Norland, respectively). Trends toward reduced yield as early blight intensity increased were apparent, although significant only for cultivar Norland in 1984, where marketable tuber weight was increased as much as 19.3% in plots sprayed weekly compared to unsprayed plots.

Disease assessment data and yield data were subjected to regression analysis in order to define models for estimating yield. Multiple point models using early blight severity or defoliation assessments as the independent variables provided the best yield prediction models for cultivar Norland, explaining over 60% of the variation in yield; for cultivar Russet Burbank multiple point models using defoliation assessments as the independent variables explained almost 50% of the variation in yield.

Environmental conditions within the potato plant canopy (cultivar Russet Burbank) were monitored at two locations in Manitoba during 1982, 1983, and 1984 in order to compare early blight disease progression, through disease assessments and spore trapping, with ambient air temperature, relative humidity, duration of leaf wetness, and rainfall. Disease severity was more severe at Graysville in 1983 and 1984 than at Portage la Prairie; this was explained in part by drought stress (1983) and longer periods of leaf wetness (1984) at Graysville. Spore counts were similar at both locations in all three years; numbers of spores trapped increased near the end of July each year, at which time only a few initial lesions were visible on the crop.

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Chapter I

INTRODUCTION

Early blight has long been recognized as a disease of solanaceous crops and appears nearly everywhere these crops are grown (Hooker, 1981; Rich, 1983). The causal agent of potato early blight is *Alternaria solani* Sorauer. First described as a *Macrosporium* blight by Ellis and Martin, it was later differentiated from late blight and renamed *A. solani* by Jones and Grout in 1896 (Rands, 1917). Also in the same year, but slightly in advance of Jones and Grout, Sorauer named the fungus *Alternaria solani* (Rands, 1917). This fungus is also currently classified as *Alternaria dauci* f. sp. *solani* and *A. porri* f. sp. *solani*. However, *A. solani* is the most widely accepted classification (Rich, 1983).

Symptoms characteristic of early blight infection are circular or angular necrotic lesions consisting of several dark concentric rings which give the spots a target board appearance (Agrios, 1978; Hooker, 1983; Rich, 1983). Lesions are generally restricted by leaf venation, although chlorosis may be associated with the entire leaf. Typically the infection appears first on older lower leaves and later appears as indefinite flecks on young upper leaves. When severe, the infection can also occur on stems and leaf petioles. *Alternaria solani* can also infect the tubers. Lesions developing on the tubers are generally dark, slightly sunken leathery patches beneath which the tissue is often water-soaked.

As a member of the Deuteromycetes, this fungus has a relatively simple lifecycle, with no known sexual reproductive cycle. Overwintered mycelium on plant debris or overwintered asexually produced conidia initiate the primary infections of an epidemic. Penetration occurs directly through the plant tissue or via stomates or wounds. Then haustoria are produced. The mycelium is haploid and crosswalled. Portions of the mycelium differentiate into short erect conidiophores upon which are borne single conidia. The conidia are blown away or washed away and cause repeated generations of secondary infections.

Potato early blight has been recognized to affect yield, although the losses in yield described by various sources are not consistent. This disease is currently controlled by protective fungicide applications, as there are no systemic fungicides available for treatment. Throughout the years different spray regimes have been recommended for controlling this disease; however, these recommendations were also inconsistent. Furthermore, fungicide labels directing the use of the product are often written for control of more than one disease where early blight is not necessarily the primary target.

There were approximately 40,000 acres of potatoes grown in Manitoba in 1983, of which 78.6% were grown for processing, 13.2% for tablestock, and 8.2% for seed (Lee, 1983). Major yield losses have been attributed to weed infestation, drought, and disease. Potato early blight is prevalent in most of the potato production areas of Manitoba and is often the primary spray target. Growers have been known to spray their crops as often as seven times during a season to protect against early blight (personal communication: John Murta, 1983). Cost of one fungicide application ranged from approximately 6-16 dollars per acre in Ontario in 1983, depending on the chemicals used (Campbell, 1983).

The objectives of this study were threefold:

1. To evaluate the relationship between early blight disease and potato yield under Manitoba conditions.
2. To evaluate the environmental conditions most influencing the development of early blight, as detected by spore counts and disease assessments.
3. From the previous relationships, to determine factors which could help time initial and subsequent fungicide applications.

The two potato cultivars examined in this project were Russet Burbank and Norland, two of the ten leading cultivars in North America (Thornton and Sieczka, 1980). The Russet Burbank cultivar, released in 1876, is a good quality, late-maturing cultivar used for processing and tablestock. The Norland cultivar, released much later in 1957, is an early cultivar generally used for fresh market.

Chapter II

LITERATURE REVIEW

2.1 ALTERNARIA SOLANI

The causal agent of early blight of potatoes has the following taxonomy (Alexopoulos and Mims, 1979):

Subdivision	Deuteromycotina
Class	Deuteromycetes
Subclass	Hyphomycetidae
Order	Moniliaceae
Family	Dematiaceae
Genus	*Alternaria*
Species	*A. solani*

As a member of the Deuteromycetes, this fungus has no known sexual cycle. Primary infections are produced by overwintered asexual spores or mycelia on debris (Agrios, 1978; Rands, 1917; Rich, 1983). After successful germination, penetration, and colonization of host tissue, upright, septate conidiophores, 5-90 µm x 8-9 µm (Rich, 1983), are produced and upon these are borne dark-coloured single conidia. The conidia are blown or washed away, providing inoculum for secondary infection (Waggoner and Horsfall, 1969). The conidia are smooth, rigid spores with few longitudinal and 9-11 transverse crosswalls and with a tapered apex ending in a long filament or beak (Hooker, 1981; Joly, 1967). The average length of spore without the beak section is 70-90 µm with a width averaging 15-20 µm (Joly, 1967). In 1917 Rands recorded the average total size as 200x17 µm. The spore has characteristics similar to some other Alternaria dauci forms (Joly, 1967).

Cultures of A. solani can be identified by a typical discolouration of the growing medium (Easton et al 1975; Rands, 1917; Venette and Harrison, 1973). On potato-dextrose agar (PDA) a clear yellow pigmentation spreads in advance of the mycelium and beneath the mycelium the colour is typically deep purple (Easton et al, 1975; Rands, 1917). However, after several generations in pure culture, the colour may disappear (Rands, 1917). The colony can also be identified by inoculating susceptible foliage to produce the typical early blight disease symptoms (Easton et al, 1975).

Sporulation is usually absent on PDA (Easton et al, 1975); however, various techniques to induce abundant sporulation of A. solani have been developed (Douglas and Pavek, 1971; Lukens, 1960; Shahin and Shepard, 1979). Lukens (1960, 1963) reported that light stimulated conidiophore production but inhibited spore production. Later Lukens (1966) found spore production could occur in light at temperatures below 23°C . More recently, methods of inducing sporulation involved slashing or blending young active cultures grown on a primary medium. The mycelial blocks or liquid were then transferred to fresh media (Douglas and Pavek, 1971), special sporulation media (Shahin and Shepard, 1979), or filter paper (Lukens, 1960). Then the treated cultures were incubated for various time periods in darkness (Lukens, 1960; Shahin and Shepard, 1979) or in light but at cool temperatures (Douglas and Pavek, 1971; Lukens, 1966).

A variety of methods have also been used to obtain infection on host plants. Many researchers relied at least partly on natural inoculum for infection (Abdel-Rahman, 1977; Douglas and Groskopp, 1974; Easton *et al* 1975; Easton and Nagle, 1985; Feddersen, 1962; Franc *et al*, 1983 Harrison *et al*, 1965a,b,c; Harrison and Venette, 1970; Lahman *et al*, 1981; Rands, 1917; Rotem and Reichert, 1964; Soltanpour and Harrison, 1974; Teng and Bissonnette, 1985a; Venette and Harrison, 1973). Others sprayed the experimental rows with an *A. solani* spore suspension where the spores were produced *in vitro* (Barclay *et al*, 1973; Douglas and Pavek, 1972; Lahman *et al*, 1981; MacKenzie, 1981b; Venette and Harrison, 1973). Some inoculated 'spreader rows' to create artificially high spore loads (Barclay *et al*, 1973; Douglas and Groskopp, 1974). Manzer and Merriam (1974) found that previously infected debris provided an excellent source of inoculum. Dhiman *et al* (1981) produced inoculum by blending water with seven-day old *A. solani* cultures grown on PDA and filtering the puree through glass wool. They found the mycelial fragments made very effective infective units.

2.2 EFFECT OF ENVIRONMENTAL FACTORS ON DISEASE PHENOLOGY

In the literature concerning early blight there are discrepancies about the nature of the climatic conditions responsible for early blight epidemics. Rands (1917) cited the work of three early researchers: L.R. Jones, who named the disease 'early blight', found both warm dry weather followed by a moister period or cool dry weather favoured the disease; Rolfs described the disease on tomatoes as being more prevalent in moist warm seasons; however, after 20 years of observations, Lutman felt early blight was a "disease of the drier seasons". Rands (1917), himself, suggested that in combination with a host in a weakened condition, the necessary weather conditions for optimum progression of the epidemic were relatively high temperatures with moist periods of high relative humidity and dew or rain. Whetzel (1923) observed a severe epidemic in Bermuda in which the warm weather and overly abundant rainfall, initially providing for excellent crop growth, promoted the epidemic. Moore (1942) observed "appreciable" leafspot incidence with as little as four hours of humidity "sufficient to cause accumulation of dew" on tomato foliage. Harrison et al (1965a) felt their results supported research finding the disease to be "favoured by warmer, more moist conditions" because these conditions were conducive to heavier spore production. But they also observed that disease severity was as great in a cool dry year as in a warm moist one.

After reading the available literature and performing small experiments, Waggoner and Horsfall (1969) published a computer simulation program called EPIDEM. When fed appropriate data, the program simulated the progress curve of an early blight epidemic on tomatoes. In developing this program, they explored some of the apparent discrepancies about the weather conditions which promoted early blight epidemics. They considered the life cycle of the fungus as component subprocesses and found that each subprocess had different optimum conditions. For instance, germination and infection were promoted by warm wet weather, while lesion enlargement was promoted by cool wet weather. Light and warm wet conditions promoted conidiophore production, but darkness and cool wet conditions promoted conidia production. Dissemination of the spores occurred most readily under windy, dry conditions or in periods of heavy rainfall.

2.2.1 Conidiophore production

Lukens (1960, 1963) observed conidiophore formation occurred in the light, although continuous light inhibited conidia production. The number of conidiophores produced increased with the number of exposures to light regardless of temperature (Waggoner and Horsfall, 1969); the optimum temperature for differentiation of conidiophores was 22°C (Horsfall and Lukens, 1971), 4-6°C below the optimum temperature for normal hyphal growth. No conidiophores were produced at temperatures greater than 32°C (Waggoner and Horsfall, 1969). Moisture was found to promote conidiophore formation, but a dry environment did not prevent it (Waggoner and Horsfall, 1969).

2.2.2 Spore Initiation

Johnson and Halpin (1952) found that light intensities greater than 200 foot candles inhibited spore production in *A. solani*. Lukens (1965) found that it was actually wavelengths in the blue range that inhibited spore initiation, but that the inhibition could be reversed by exposure to red light. He later (1966) reported that at temperatures less than 23°C light did not inhibit spore production; the optimum temperature in light was 15°C . Lukens and Horsfall (1969) found that after 16 hours at 23°C all conidiophores had initiated spores and when previously initiated spores were exposed to light they continued to mature. Rands' (1917) data showed sporulation occurred during moist periods. Waggoner and Horsfall (1969), however, found that it could also occur during dry periods, although the amount of sporulation was reduced. Bashi and Rotem (1975) found sporulation of *A. solani* was increased by a regime of short interrupted wet periods, like those found during diurnal conditions, as compared to a long continuous wet period.

2.2.3 Spore Dispersal

Harrison et al (1965a) found the period of maximum spore release, between 9:00 am - 3:00 pm, coincided with the end of dew periods and with increasing wind velocities. Relatively few spores were released at night. Rotem (1964) also observed this diurnal dispersal pattern. Again, maximum spore dispersal coincided with increasing wind velocities and drying of dew. Sixty percent of spores were released between 10:00 am and 2:00 pm. Peak dispersal occurred around 11:00 am, preceding the driest, hottest, and windiest part of the day by 2-4 hours. Spores were not dispersed by wind from wet leaves (Rotem, 1964); however, spores could be dispersed by rainfall (Waggoner and Horsfall, 1969). Nutter (1978) found that heavy rainfall 'washed out' A. solani spores from the air. Occasionally spores were also dispersed by chewing insects (Greider et al, 1978). A. solani spores were found to be extremely resistant to both heat and drought; relative humidities between 14% and 38% were optimal for survival (Rotem, 1968).

The number of spores trapped increased dramatically in a period from near the middle to the end of the growing season (Harrison et al, 1965a). This time period coincided with an increase of disease. Harrison et al (1965a) postulated that this increase in spore numbers indicated the beginning of the period of secondary spread of the organism. Rotem (1964) found the highest rate of spore dispersal occurred in the final stage of disease and was dependent on physiological age of the crop and weather conditions.

2.2.4 Dissemination

To become airborne, spores must escape the boundary layer that surrounds foliage surfaces (Legg and Bainbridge, 1978). The thickness of this laminar boundary layer is dependent on turbulence; movement of air in plant canopies is almost always turbulent (Monteith, 1973). Thus, it is the wind speed within the crop that determines the thickness of this boundary layer. Generally mean wind speed within a crop is about 1/10 that 1 meter above the crop (Legg and Bainbridge, 1978).

Studies show that once spores are airborne, spore dispersal is greatest in the direction of air movement (Hirst and Stedman, 1960b; Waggoner, 1952). However, concentration of the spores in the atmosphere drops rapidly with distance, accounting for the occurrence of primary infection foci (Waggoner, 1962). Also, after there is one active lesion in a field, the danger of infection from within the field is generally greater than the danger of infection from foreign inoculum (Waggoner, 1962). Zadoks and Schein (1979) and Legg and Bainbridge (1978) provide in depth discussion on disease gradients from various inoculum sources and on deposition of spores on various surfaces.

2.2.5 Spore germination

Waggoner and Parlange (1974a,b) developed a mathematical model for spore germination where a wetted spore progressed through stages until germination was complete. Temperature affected the rate of progress and the number of stages required for completion. Germination progressed differently in two temperature ranges. Below 30°C the rate of germination occurred linearly, increasing with temperature, and from 30-40°C the rate decreased as temperature increased (Waggoner and Parlange, 1975). Every temperature change between the two ranges was detrimental and slowed the final rate. After a two hour exposure to wetness, 96%-98% of A. solani spores tested germinated at 20°C (Bashi and Rotem, 1974).

Rands (1917) found that varying the temperature altered the number of germ tubes produced by a single A. solani spore. At cool temperatures (1-3°C) only two to three germ tubes appeared after 46 hours, while at the optimum temperature (26-28°C), five to ten germ tubes were produced after only 35-45 minutes. Germ tubes formed at temperatures greater that 37°C were irregular and the spores died after six hours.

Germ tube development was better when the spore was provided with a continuous wet period, rather than interrupted wet periods (Bashi and Rotem, 1974). With interrupted wet periods, temperature during the dry periods determined the amount of germ tube elongation. Spores subjected to interrupted wet periods remained infective, but infections were less severe than those resulting from spores exposed to a continuously moist environment. Conidia germinated equally well in either darkness or continuous light (Goth et al, 1969).

Munnecke et al (1959) reported that the minimum relative humidity for germination of A. solani was 87%. Spores germinating in high relative humidity were able to withstand subsequent drying; however, spores germinating in free water died upon drying (Waggoner and Horsfall, 1969). In contrast, Rotem and Reichert (1964) reported that below 96% relative humidity the rate of germination was extremely low; they indicated free water was essential for foliage infection. In dew-like conditions they reported the minimum time necessary for infection was 12 hours at 10°C or 8 hours at 15°C.

2.2.6 Penetration

Germinating A. solani spores penetrate the host foliage directly through the cuticle, through wounds, or through stomates (Agrios, 1978; Rands, 1917). On tubers, wounds are the primary site of penetration with direct entry or entry through the lenticels occurring to a lesser extent (Venette and Harrison, 1973). The temperature optima for penetration vary according to host tissue. For tomato foliage it is 20°C (Horsfall and Lukens, 1971) and for potato tuber tissue it is 15°C (Gratz and Bonde, 1926). Potato foliage was infected in as short a period as 8 hours at 15°C and 4 hours at 25°C under continuous moisture (Bashi and Rotem, 1974).

2.2.7 Lesion Enlargement

In a greenhouse experiment Waggoner and Horsfall (1969) found lesions did not enlarge on dry leaves; however, rapid enlargement was evident under moist conditions. Barksdale (1969) found lesions which developed under moist periods were twice as large as lesions receiving moisture for only one 24-hour incubation period. Horsfall and Lukens (1971) indicated lesion expansion was favoured by temperatures not optimal for host growth. For example, the optimum temperature for lesion expansion in tomato foliage was 16°C, whereas the favourable temperatures for tomato growth were much higher than that. In potatoes, the optimum temperature for lesion expansion in tuber tissue was 25°C, whereas the favourable temperatures for potato growth were lower than 25°C. Goth et al (1969) found lesion expansion was inhibited by continuous illumination; the lesions were, on average, seven times smaller than those incubated in darkness and the characteristic chlorotic zone surrounding the lesion was absent.

2.2.8 Overwintering

Primary inoculum comes from overwintered spores and mycelium on debris. Viability of the spores increases as depth in the soil increases from 5 to 20 cm (Rands, 1917). Various factors such as frost action and temperature-water relations account for lessened viability. After 10 years of storage at 5°C and 38% relative humidity, both mycelium and spores grew vigorously (Rotem, 1968). Rotem (1968) found mycelium and spores were extremely heat resistant: mycelium tolerated temperatures as high as 88°C ; spores tolerated a lower maxmium temperature, 58°C ; and relative humidities of 14%-38% were optimal for survival at most temperatures.

2.2.9 Host plant

Meteorological conditions also influence the host-plant. Certain factors result in an increased susceptibility which may 'predispose' the plant to disease (Colhoun, 1978; Schoeneweiss, 1975). These factors include water stresses: water deficit, drought, and excess water, temperature stresses: chilling stress, freezing stress, and high temperature stress, defoliation stress, nutrient stress, and light stress. Modification of the environment through irrigation also influences the host-plant susceptibility. Higher soil moisture levels could leave host plants more susceptible to early blight earlier by increasing the yield/foliage ratio (Barratt and Richards, 1944; Horsfall and Heuberger, 1942b; Pound, 1951; Rotem and Palti, 1969). Rotem and Palti (1969) also reported that high turgidity in leaves was favourable for *A. solani* development.

2.2.10 Summary

Thus, the most important environmental factors influencing early blight development are temperature and moisture. In many plant pathogen-host relationships disease development occurs most rapidly when temperature is optimum for pathogen development but is above or below the optimum for host development (Agrios, 1978). Horsfall and Lukens (1971) summarized the optimum temperatures for the various phases of the Alternaria solani life cycle. For hyphal growth, germination, and germ tube production the optimum temperature was 28°C, while for production of appressoria, conidiophores, and conidia the optimum was only 22°C . The optimum temperature for penetration into tomato foliage was 20°C and into potato tuber tissue was 15°C; for lesion enlargement the optima were 16°C in tomato and 25°C in potato, where tomato and potato are generally a warm season and cool season crop, respectively.

Moisture, occurring as rain, irrigation, dew, relative humidity, or water of guttation, plays an important role in development of many plant diseases (Wallin, 1963) and most fungal spores require a period of free moisture during the infection processes of germination and penetration. Generally duration of the moisture is of more importance than amount or rate of deposition (Burrage, 1972). Although rain occurs irregularly in many parts of the world, enough moisture for disease development is often available from dew, even when air relative humidity is below the saturation point (Burrage, 1972; Rotem and Reichert, 1964). Dew is essentially the condensation that forms as heat is radiated away from a surface and water vapour suspended in the air through evaporation or evapotranspiration contacts the surface (Burrage, 1972; Crowe et al, 1978). As previously mentioned, the minimum relative humidity for A. solani spore germination was found to be 87% (Munnecke, 1959), although others considered free water was necessary for an early blight epidemic to occur (Moore, 1942; Rotem and Reichert, 1964).

2.3 MICROCLIMATE

Monitoring the microclimate is important for understanding weather and plant disease relationships. As epidemiologists, Zadoks and Schein (1979) defined the microenvironment as "the space in which the epidemiologic processes at cell and organ level occur" or the phyllosphere. The mesoenvironment was defined as the environment formed by the crop and the macroenvironment was that existing between crop and troposphere. They noted the meteorological definitions differed, where microclimate included physical phenomena at both leaf and crop level. Rotem (1978) defined microclimate simply as climate within the plant canopy. Waggoner (1965) referred to micrometeorology as the "meteorology of small places" and indicated that the microclimate of a spore would differ when on a leaf or when in the air. Coakely (1983) defined micrometeorology as the study of meteorology "in the boundary layer of the atmosphere where temperature and humidity can change strikingly in a short distance and where plants modify their environment." Hirst and Stedman (1960a) referred to 'weather' as the general term for meteorological conditions prevailing at any height and to 'ecoclimate' as the weather within the crop and to 'climate' as the weather at standard height. Wallin (1967) simply referred to ground level or plant level climate to denote the area in question. Generally 'microclimatic' observations were made within the plant canopy, where the available technology permitted.

When using results of weather monitoring for forecasting late blight outbreaks, Hirst and Stedman (1956) found monitoring within the crop was much more reliable than monitoring above the crop. Wallin and Waggoner (1950) found significant differences in both temperature and relative humidity between one-foot and five-foot levels of a tomato and potato crop. Waggoner and Shaw (1952) examined temperature of tomato and potato leaves and found little difference between the two species. Various environmental factors, however, affected leaf temperature; these included changes in radiation due to time of day, sky cover, angle of incidence, and shading, and changes in wind and stand density. Shaded leaves on all plant parts had similar temperatures and were 7-12°C cooler than leaves exposed to insolation. Lower exposed leaves were warmer than upper exposed leaves. Plant temperature and instrument shelter temperature differences were small during cloudy days or at night. During clear days upper exposed leaves were about 3-8°C warmer than temperatures in instrument shelters. When windy, temperature differences were generally smaller. An exposed leaf perpendicular to insolation was about 3°C warmer than a leaf parallel to insolation. In general instrument shelter temperatures were most similar to temperature of shaded lower leaves. During the day leaves of diseased plants or plants under drought stress could be as much as 14°C warmer than the air (Waggoner, 1965).

2.3.1 Microclimate-monitoring equipment

Various authors (Burrage, 1978; Pennypacker, 1978; Sutton, Gillespie, and Hildebrand, 1984) described equipment generally used to monitor microclimate for epidemiological studies. Temperature has been measured with thermistors, thermocouples, thermometers, and hygrothermographs. Relative humidity has been measured with hygrothermographs, ventilated psychrometers, and conductive sensors. Wallin (1963,1967) found relative humidity was useful in estimating dew periods: the period where relative humidity was greater than

90% was generally an hour less than the period of dew; a strong correlation existed between the two periods (Crowe et al, 1978). Dew was initially measured with dew balances or devices like the Taylor dew meter (Melching et al, 1970; Taylor, 1956; Wallin, 1963); although, more recently duration of the dew period has been measured with string-type sensors (MacHardy and Sondej, 1981) in which a string contracts when wet and connects an electrical circuit, or by electrical-resistance sensors (Gillespie and Kidd, 1978; Small, 1978; Weiss and Hagen, 1983). Tipping-bucket rain gauges have had considerable use for measuring both intensity and amount of rainfall. Other factors sometimes monitored included wind speed, wind direction, and irradiation, measured by cup or thermal anemometers, wind vanes, and thermopile pyranometers, respectively.

The electrical sensors, gradually replacing the mechanical sensors, have improved accuracy and when incorporated with data loggers, have also improved efficiency of monitoring. Sutton et al (1984) emphasized that the acquisition of valid data started with proper cleaning and regular calibration of equipment, protection of temperature and relative humidity equipment from the elements, and understanding the limitations of the equipment. For example, a hygrothermograph regularly serviced would record within 2%-5% of actual relative humidity, but accuracy would quickly deteriorate if the equipment were not properly maintained (Burrage, 1978). Also, as little as a 5°C error in a temperature measurement could cause as much as a 10-14 day shift in computer-simulated disease progress curves (Pennypacker, 1978). Careful choice of equipment site within the canopy was also emphasized because of the microclimatic variations possible (Burrage, 1978). For example, duration of leaf surface wetness varies with the position, angle, and specific location of an individual leaf (Sutton et al, 1984).

2.4 SPORE TRAPPING

Spore trapping has been important in epidemiological studies because it permits close monitoring of spore discharge, dispersal, and inoculum levels. Weather vane spore traps (Harrison et al, 1965a,b,c; Livingston et al, 1963) use a glass slide or plexiglass plate coated with vaseline to trap spores by impaction. More accurate are volumetric spore traps (Gadoury and MacHardy, 1983; Kramer and Pady, 1966; Sutton and Jones, 1976) which pull a prescribed volume of air past a revolving trapping surface. With a wind speed as low as 2 mph some traps were considered 100% efficient; however, efficiency decreased as wind speed increased (Kramer and Pady, 1966). Sutton and Jones (1976) found volumetric samplers trapped spores more frequently and in larger numbers than wind vane traps.

2.5 SUSCEPTIBLITY TO EARLY BLIGHT

Early blight has often been considered a disease of senescence (Hooker, 1981). Early in the 1900's the occurrence of this disease was associated with plant maturity. Rands (1917) noted that the disease was "not able to gain a foothold until the vines have surpassed their period of greatest vigor and are directing their energy to tuber formation." He also found that the younger leaves were infected as often as older leaves, but lesion enlargement in younger leaves progressed more slowly than in older leaves. In potato growing areas of both Maine and Florida, Gratz (1930) also observed that the "trouble does not appear until plants are approaching maturity." Horsfall and Heuberger (1942b) stated that the disease seldom attacked tomato plants before onset of fruiting.

Horsfall and Heuberger (1942b) observed that the age of tomato tissue and tomato fruit load were both directly related to defoliation. Similarly Pound (1951) and Barratt and Richards (1944) discovered that the rate of defoliation of tomatoes due to _A_. _solani_ infection was related to both physiological maturity of the host and to fruit load; the early maturing cultivars defoliated early because their periods of yield were early. As previously observed, Pound (1951) also noted that early blight was most severe on the oldest leaves. Moore and Thomas (1943) found that on tomato seedlings stress increased the amount of _A_. _solani_ infection.

For several reasons Harrison _et al_ (1965a) supported a theory of temporary juvenile resistance to explain the lack of early blight infection in certain cases. Although primary lesions were visible at the same time in plots of both early and late-maturing cultivars of potato, the early-maturing cultivar was more rapidly attacked by secondary infection. Also, during the period of secondary spread of the disease more spores were trapped in plots of the early-maturing cultivar than in the late-maturing cultivars. Although infection occurred early in the growing season, symptom development was delayed by at least one month. As the plants matured, however, symptom development was not retarded to this extent. Finally, the first lesions were noted on senescent lower leaves, although leaf isolations showed the middle and top leaves were infected as early.

Studies also showed early blight was related to plant nutrition. Jones and Darling (1953) suggested that potatoes had three phases of different susceptibility to early blight: pre-blossom was the least susceptible stage, followed by blossom, and post-blossom. They showed amounts of nitrogen and magnesium in leaf tissue decreased with age of the tissue; lowest leaves on plants at any growth stage had lowest nitrogen levels; and potassium levels decreased from the pre-blossom stage to the blossom stage. Compared to diseased plants, healthy plants contained higher levels of nitrogen, potassium, and magnesium. Plants grown under low levels of nutrition had considerably more early blight than plants receiving balanced nutrition; high levels of nutrients, particularly nitrogen, reduced intensity of early blight (Barclay _et_ _al_, 1973; Horsfall and Heuberger, 1942b; Jones and Darling, 1953; Soltanpour and Harrison, 1974; Thomas, 1948). Plants treated with high levels of nitrogen also contained significantly higher levels of total sugars than other treatments. This supported the classification of early blight as a 'low sugar' disease (Barclay _et_ _al_, 1973).

Barclay _et_ _al_ (1973) found that the amount of early blight on the Kennebec potato cultivar was significantly reduced by fertility treatments consisting of high levels of nitrogen and low levels of phosphorus. Tisdale and Nelson (1975) reported high nitrogen levels delayed plant maturity and high phosphorus levels hastened plant maturity. Stavely and Slana (1971) observed that _Alternaria_ _alternata_ penetrated tobacco leaves of all ages; however, immature leaves with potential for meristematic activity walled off the fungus, effectively stopped further penetration, and left only small flecks visible. Older mature leaves unable to wall off the fungus developed typical symptoms as the infection process continued. Cunningham (1928) noted that in a typical early blight lesion no cicatrice formation was present. Barclay _et_ _al_ postulated that the fertility regime they used delayed the onset of early blight by delaying plant maturity and extending the period of time possible for meristematic activity.

Soltanpour and Harrison (1974) found a positive relationship between fungicide control of early blight and fertility. Both treatments alone reduced early blight and increased yield; however, the yield response to fungicide application was greatest when fertility levels were adequate. They suggested along with increasing plant size, adequate fertility levels delayed plant senescence.

Douglas and Pavek (1972) found the relationship between plant maturity and susceptibility to be "relatively consistent", as early-maturing cultivars were very susceptible to the disease, while late-maturing ones were more resistant. Abdel-Rahman (1979) also indicated early-maturing cultivars were more susceptible. The difference between early cultivars and late cultivars was the tendency for early cultivars to form tubers earlier under long-day conditions or to produce maximal effective foliage earlier and maintain more rapid growth of tubers (Burton, 1966). Accompanying rapid foliage growth, however, was rapid foliage senescence.

2.6 POTATO GROWTH

Commercial production of the potato is primarily carried out with vegetative propagation, where lateral buds on tubers serve as the main reproductive units (Hooker, 1981). The number of emerged shoots is generally greater than the number of buds planted (Moorby, 1978). These young shoots depend on mother tuber reserves until they have established a leaf area of 200-400 cm^2 (Milthorpe, 1963). Generally the first few leaves grow to a larger size, but when shaded, leaves have a reduced capacity for photosynthesis (Milthorpe, 1963). After a leaf reaches its maximum size the rate of photosynthesis decreases with age and thus, the export of carbohydrate from the leaf also decreases with age (Milthorpe 1963). The leaf area index (LAI) is described by a hyperbolic curve (Dawes et al,1983 Lynch and Rowberry, 1977; Necas, 1965; Sale, 1973).

Tuber initiation begins with the accumulation of starch deposits and generally occurs during a two week period (Moorby, 1978). Tubers may also begin development later in the season; however, usually only tubers formed during the initial period reach marketable size; the others remain small or are reabsorbed (Milthorpe and Moorby, 1979). Therefore, this period is critical in determining final yield. Ninety percent of the dry matter of tubers is accumulated after initiation and only ten percent before initiation (Moorby, 1978). Expansion of the tuber occurs first by cell division and then by cell enlargement. Increase in weight of Russet Burbank and Kennebec tubers past 30-40 grams was attributed primarily to cell enlargement (Moorby, 1978). Once tuber growth is initiated the growth of all other organs is retarded, thus there is an inverse relationship between haulm and tuber growth (Moorby 1978). Tuber initiation is promoted by short days, shortage of nutrients, low temperatures, and high radiation (Milthorpe and Moorby, 1979). Tuber growth typically follows a sigmoidal curve with a long linear phase (linear bulking) (Moorby, 1978).

Tuber bulking rate is generally independent of current weather and remains constant over a long time period for any given treatment (Milthorpe, 1963). A leaf area index greater than one maintains the constant bulking rate (Milthorpe, 1963) and tuber growth decreases when the LAI falls below one (Milthorpe and Moorby, 1979). Tuber growth ceases only when all the foliage is dead (Milthorpe and Moorby, 1979). Moorby (1970) postulates that the dominant factor responsible for the rate of photosynthesis is the rate of tuber growth; the sink-source relationship helps maintain a constant rate (Milthorpe and Moorby, 1979).

2.7 DISEASE MEASUREMENT

Zadoks and Schein (1979) described the various levels of yield and classes of crop losses, where crop loss was defined as the difference between attainable yield (yield from crops grown using available modern technology to the fullest extent) and actual yield (yield obtained using current crop husbandry practices). Crop loss was also defined as a measureable reduction in quantity and quality of yield (James, 1974). Zadoks and Schein (1979) described two threshold levels: damage threshold was the amount of injury which justified artificial control measures, that is the amount of control which produced yield (profit) exceeding cost of the control measures; action threshold was the time at which control was necessary to reduce the rate of infection so that disease would not reach the damage threshold. However, only if the losses were estimated accurately could prevention of damage at threshold levels take place.

Large (1966) felt tactics for disease measurement would vary according to the particular disease, but suggested the following general strategy for disease measurement:

1. "A close descriptive study of the gross morphology and course of development of the healthy crop plant from sowing to harvest, or from season to season.
2. A similar close study of the course of the disease on plants in the field, over the whole range of attack.
3. The drawing up ...of a standard diagram or research key for the assessment of the disease, and later of a simplified field key, suitable for use by all observers.

4. The conduct of a series of field trials, over a number of years, in which progress curves for the disease are plotted by the field key, and yields are recorded, for plots on which the disease is allowed to run its course according to the conditions of the season, and an equal number of check plots kept as nearly as possible free from the disease by frequent spraying or other means.
5. The choice...of the particular disease assessments that will best serve to define severity of attack when employed in survey work, and the calibration of these assessments in terms of reduction of yield."

James (1974) and James and Teng (1979) supported this strategy for disease-loss appraisal; however, for clarity James and Teng (1979) suggested the term "disase measurement" include all methods of disease quantification. "Disease assessment" was any method where an estimate of disease was made in conjunction with a prepared standard. Other methods for measuring disease included remote sensing, counting of lesions, and chemical analysis. Disease intensity was disease incidence or disease severity. Disease incidence (%I) was defined as the number of plant units infected, expressed as a proportion of the total number assessed and disease severity (%S) was defined as the area of affected tissue, expressed as a proportion of the total area (James and Shih, 1973).

Two important criteria for any disease assessment method were its ability to be reproduced accurately and its rapidity and ease of use. Some advantages of using descriptive keys and standard area diagrams with percentage scales included fixed upper and lower limits, flexibility, divisibility and easy interpolation, and universality (James, 1971,1974).

Initial early blight researchers partially fulfilled requirements for the first two phases of Large's (1966) strategy for disease appraisal by distinguishing the disease from other diseases and then by initiating studies on the morphology and physiology of the fungus and on the lifecycle of the disease on its hosts (Rands, 1917). Environmental conditions permitted study on a wide range of attack (Rands, 1917; Whetzel, 1923). Plant growth was divided into three growth stages during which susceptibility to early blight differed: pre-bloom, bloom, and post-bloom (Jones and Darling, 1953). In describing stages at which late blight assessments should be made, James (1971) suggested assessing at regular intervals (such as one week) after the epidemic has started. For potatoes multiple assessments were necessary because yield accumulated over half the growing season and could be affected by blight at any point during bulking (James et al, 1972 James and Teng, 1979).

The third phase of Large's (1966) strategy first consisted of visual estimates (Whetzel,1923). Later, Horsfall and Heuberger (1942a) found counting the number of early blight lesions on tomato plants was objective and accurate, but also quite slow; as well the statistical error was large because sample size was generally small. They, therefore, used McKinney's (1923) method where the plants were ranked into one of five groups on the basis of the leaf area affected. In 1947 the British Mycological Society published a descriptive key for assessing damage caused by late blight of potatoes (Anon., 1947). Because the key was based on percentage leaf area destroyed, it served as a tool for assessing damage from other causes, for example, early blight. Fry (1977) modified the key by adding a description of damage at 0.01% and 0.1% disease levels. In 1954 Granovsky and Peterson published standard area diagrams of potato leaves with various degrees of damage according to percent leaf area affected by early blight. Basu (1974) measured early blight on tomato foliage by counting the number of leaves killed, that is leaves with 75-100% necrosis; he found that method to be less time consuming and more objective than using standard area diagrams. Rotem et al (1983a,b) found assessment of healthy haulm area was superior to assessment of disease severity because it reflected all factors affecting the crop; however, the time involved for this measurement was quite extensive.

James (1974) discussed five important factors regarding the field trials to be conducted in phase four. He felt identical experiments should be conducted in all important geographical areas over a period of at least three years. It was also important to use standard experimental designs with multiple levels of treatment where disease intensity was used as the covariable instead of the treatment level. Numerous early blight researchers thus far have had some input into this phase of Large's (1966) strategy, although experimental designs, goals, methods, and cultivars differed (Douglas and Groskopp, 1974; Easton and Nagle, 1985; Feddersen, 1962; Harrison et al, 1965b,c; Harrison and Venette, 1970; Haware, 1971; MacKenzie, 1981b; Soltanpour and Harrison, 1974, Teng and Bissonnette, 1984,1985a,b,c).

2.8 YIELD LOSSES ASSOCIATED WITH EARLY BLIGHT

Early blight is generally considered a foliage disease where primary losses are caused by premature death of the foliage resulting in decreased yield (Feddersen, 1962; Harrison and Venette, 1970; Lahman et al, 1981; Rands, 1917; Venette and Harrison, 1973). Losses also occur from the reduced quality of the potato. The highest percentage of defects such as growth cracks and knobs were found in diseased plots (Douglas and Groskopp, 1974) and the number and yield of US No. 1 potatoes was found to be significantly reduced in diseased plots (Douglas and Groskopp, 1974; Harrison and Venette, 1970). Damage to the tubers as a result of A. solani tuber infection is generally of minor importance, although during some years it remains a potential problem in certain areas (Douglas and Groskopp, 1974; Feddersen, 1962; Guthrie, 1958; Lahman et al 1981; Venette and Harrison, 1973).

Early estimates of yield losses attributed to early blight ranged from 10-25% in the United States and yield benefits greater than 50% were reported when good control of the disease was achieved in South Africa (Rands, 1917). Whetzel (1923) estimated losses from a devastating epidemic in Bermuda to be as high as 30-50%. Guthrie (1958) saw fields where defoliation attributed to early blight ranged from 0-50% during one year and up to 100% during the next year, but made no comment on amount of yield lost.

In southern Australia Feddersen (1962) compared the yield from unsprayed plots to the yield from plots protected from early blight by fungicide applications made at 14-day intervals and calculated an average yield increase of 30-44% in the sprayed plots. However, in 1965 a study in Colorado showed no yield increases as a result of spraying, although excellent control of early blight was achieved (Harrison et al, 1965b,c). Haware (1971) sprayed plots to obtain a range of disease intensities of early blight and found yield decreased as disease intensity increased. Compared to the yield of healthy plots, loss in yield ranged from 6% in plots where disease intensity was 25% at maturity to 40% in plots where disease intensity was 100% at maturity.

Harrison and Venette (1970) conducted an experiment in Colorado where spraying with a variety of chemicals was initiated in response to spore trapping results and continued in 14-day intervals until harvest. They found that the chemicals tested significantly reduced early blight and also resulted in statistically significant yield increases of US No. 1 potatoes, as compared to unsprayed plots, although total yield differences were statistically insignificant. Average increase in yield of US No. 1 potatoes was 20-35%.

Researchers in Idaho found similar results (Douglas and Groskopp, 1974). Significant yield differences in both total yield and yield of US No. 1 potatoes were evident in most of the spray schedules encompassing the period of secondary infection as compared to unsprayed plots. However, in Washington researchers felt early blight had little effect on potato yield because symptoms were generally "mild" until plants reached maturity (Easton et al, 1975). Early blight was controlled by fungicide application through central pivot irrigation systems. Increase in yield was not evident in one study (Easton and Nagle, 1985), but was significant in another (Franc et al, 1983).

Other researchers showed yield response to fungicide application for early blight control was even greater with adequate fertility levels (Soltanpour and Harrison, 1974).

Teng and Bisonnette (1984) showed two potato cultivars had different yield losses with a terminal blight severity of nearly 60%. The Norland cultivar, an early-maturing potato cultivar, suffered a maximum of 58.4% yield loss, whereas the Russet Burbank cultivar, a later-maturing cultivar, had a maximum yield loss of only 34.4%

Teng and Bissonnette (1985a) conducted another study on Russet Burbank and Norland potato cultivars, where plots received no fungicide sprays or fungicide sprays on a regular seven to ten-day basis, but where spraying was initiated according to the following disease stages: before onset, at 0.01% disease severity, when early blight was detected above the lower 1/3 of the plant canopy, and at 25% disease severity. Significant differences were observed for both total yield and yield of US#1 potatoes. Where spraying was initiated before disease onset, yields were usually significantly greater than other treatments, except where spraying was initiated at 0.01% severity. Compared to yield of unsprayed plots, yield of US#1 potatoes was increased as much as 35.3%. Where spraying was initiated at 0.01%, yield of US#1 potatoes was significantly greater than unsprayed plots by 24.5%.

Basu (1974) found tomato plants tolerated greater than 60% defoliation from natural infection of early blight without having a significantly reduced yield. He calculated a yield reduction of 10%-34% only in early epidemics and quality loss due to the number of visibly infected fruits was minimal for processing tomatoes, that is it was less than 10% on plants with up to 60% defoliation.

2.8.1 Disease-Loss Relationships

James _et al_ (1971a,b, 1972), working with potato late blight, examined four methods of relating yield loss to disease. Neither the critical point method where loss was related to disease at a particular growth stage, nor a critical level of disease severity, as suggested by Large (1952), were adequate for describing the relationship, because there were few distinct morphological changes and the tuber bulking period encompassed more than half the growing season. Nor was the area under the disease progress curve adequate for describing this relationship, as it did not distinguish between early-occuring light infections and late-occurring severe infections. The fourth method, an equation derived with multiple regression analysis based on disease increments, had a close association between real and predicted loss values. To determine yield loss they assumed that yield of plots treated throughout the season with fungicide was potentially 100% yield.

Teng and Bissonnette (1985b) also found the single predictor models, the models using one level of disease severity or severity at a particular time, were generally poor predictors of yield loss. This was contrary to Haware (1971), who implied a single final disease assessment was an adequate predictor. The coefficient of determination (r^2) generally increased when yield of US#1 potatoes was used as the dependent variable instead of the total yield (Teng and Bissonnette, 1985b). Using multiple regression analysis these researchers found several prediction equations which explained more than 70% of the variation in yields. They chose the two best three-variable equations which described yield loss occurring in early and late cultivars (Teng and Bissonnette, 1985b,c).

1. %Yield loss = 0.8183 + 0.6441*V10 + 0.6102*V11 + 1.3480*V12

   For the early cultivar (1) the variables used were disease increments from 56 to 66 days (V10), 66 to 76 days (V11), and 76 to 86 days (V12) after crop emergence. This equation explained 75% of the variation in loss with a standard error of estimate of 7%.

2. %Yield loss = 2.1846 - 4.7734*V2 + 0.7440*V4 + 0.5676*V6

For the late cultivar (2) the variables used were V2, V4, V6, actual disease severity on days 56, 76, 96, respectively, after crop emergence. Here the variation in yield explained by the equation was 70% with a standard error of estimate of 6%.

2.8.2 Quality loss

Tuber infection by *A. solani* was first described in 1925, but was generally not considered a serious problem (Venette and Harrison, 1973). As late as 1958 no confirmed cases of tuber blight were observed in Idaho, although as much as 100% defoliation attributed to early blight had been recorded (Guthrie, 1958). No studies on early blight of tubers were reported until 1973; however, the use of sprinkler irrigation, mechanical bulk harvesting, and higher storage temperatures for processing potatoes have contributed to the increase of tuber infection (Venette and Harrison, 1973). Gratz and Bonde (1926) found the rate of development of tuber infection in storage was fastest at approximately 15°C and much slower at temperatures below 5-7°C .

Wounds were found to be the primary avenue for infection and also provided moisture necessary for spore germination (Venette and Harrison, 1973). Even abrasive wounds as small as those caused by sandy soil were thought to promote infection. Maturation of the tubers before harvest reduced infection. Lahman (1981) found preharvest burning of foliage at temperatures of 250-300°F also effectively reduced tuber infections.

2.9 CONTROL RECOMMENDATIONS

In the early 1900's when resistance to early blight was first examined as a possible control measure, over 150 cultivars were tested, but not one of the most resistant was a commercially important North American cultivar (Rands, 1917). Later, other researchers studied the inheritance of this resistance; however, no cultivars with incorporated resistance were able to replace successful susceptible cultivars (Douglas and Pavek, 1972) and no cultivars were immune (Hooker, 1981).

Cultural practices recommended for controlling early blight included sanitation and crop rotation to reduce debris and, therefore, initial inoculum levels. Controlling alternate-host weeds, particularly those of the nightshade family, and insects which carry spores and cause wounds, especially flea beetles and Colorado potato beetles, were also suggested as control measures (Greider _et al_, 1978). Fumigation was also found to benefit yield; however, a decrease in early blight was attributed to increased vigor, because early blight is primarily spread by airborne inoculum (McCarter _et al_, 1976). Decrease in early blight was also attributed to the reduction of _Verticillium_ wilt, which, itself, can reduce plant vigor and cause premature senescence and death (Harrison, 1974). Good fertility levels were also promoted to aid the control of early blight; however, Barclay _et al_, (1983) warned that fertility levels required for early blight control exceeded levels required for optimum yield. MacKenzie (1981b) also warned that the extra nitrogen used to help control early blight would badly affect chip colour and reduce specific gravity of the tubers. Fungicide application is the most effective control when inoculum is present and environment is favourable for disease development; fungicide reduces the infection rate (Madden _et al_, 1978).

Recommendations for fungicide application to control early blight varied considerably. Early recommendations cited by Rands (1917) included 3-4 applications of Bordeaux mixture for effective control in Vermont, three applications for control in Connecticut, and not less than four applications where spraying started in mid-August in Wisconsin. Rands, himself, issued a recommendation for Wisconsin of 4-6 weekly sprays of standard Bordeaux mixture starting when the crop was 6-8 inches high. For the late crop he felt the 3-4 applications used to protect against late blight would suffice for early blight control.

Later, the importance of timing the initial fungicide application was recognized. The total number of sprays could be reduced while still maintaining effective disease control. Recommendations included starting fungicide application when initial symptoms of early blight were present (Ohms and Fenwick, 1961), spraying before any signs of the disease were evident, usually just after flowering (Feddersen, 1962), or spraying as soon as flowering began (Henderson, 1962). Other researchers found effective control was possible when spraying was initiated when high levels of _Alternaria solani_ spores were detected by spore trapping (Harrison _et al_, 1965b,c). Harrison _et al_ found three applications made at 14-day intervals, initiated according to spore trap results, controlled early blight as well as five sprays also made at 14-day intervals, but timed to begin at plant emergence. They postulated that the beginning of the period of secondary sporulation of _A. solani_ was detected by the high levels of _A. solani_ spores trapped and that initial symptom development was insignificant in determining when to initiate control practices. Research conducted by Teng and Bissonnette (1985a) supported recommendations (provided for non-irrigated farming conditions in Minnesota) to delay spraying for early blight until the disease was at a detectable level, from 0.01% severity to when the disease was visible above the lower 1/3 of the plant canopy.

Currently, recommendations still vary. Most support has been given to the initiation of spraying when first symptoms become visible (Hodgson _et al_, 1973; Lana _et al_, 1976; Nutter, 1978; Nutter and MacHardy, 1979; Ohms and Fenwick, 1961; Teng and Bissonnette, 1985a) or when spore trap results indicate secondary sporulation is occurring (Nutter, 1978; Nutter and MacHardy, 1979). Emphasis has also been placed on the use of weather monitoring to determine periods favourable and unfavourable for disease proliferation (Madden _et al_, 1978, 1980; Nutter, 1978; Pennypacker _et al_, 1983). A system which uses weather data to generate spray recommendations was developed for controlling early blight of tomatoes (Madden _et al_, 1978).

Manitoba potato production recommendations did not distinguish between control of early blight and late blight and referred the producer to the fungicide product labels (Manitoba Agriculture, 1985). The Dithane M-45 label recommended using a reduced rate for initial applications where applications started when the crop was six to eight inches tall and sprays at a higher rate continued on a regular seven to ten day basis. This recommendation was for controlling both late blight and early blight, where early blight was not necessarily the primary target.

Four sprays were the average number of fungicide applications made in Manitoba (personal communication: Blair Giesel, KVGA), although not uncommonly up to seven or more sprays were applied to the crops to protect against early blight (personal communication: John Murta, grower).

2.10 PLANT DISEASE FORECASTING IN RELATION TO EARLY BLIGHT

Forecasting plant disease is not a new idea; several reviews which discuss predictive systems, models, and simulators are available (Bourke, 1970; Miller and O'Brien, 1952,1957). Jones (1983) defines disease prediction as "the science of monitoring the physical conditions of the environment and declaring after 'disease weather,' but before symptoms are visible, that infection has occurred." Disease forecasting is distinguished from disease prediction, as it is based on future weather rather than past weather. In this sense predictions would be more accurate than forecasting. Krause and Massie (1975) feel that disease prediction is the forecast of symptom expression after infection has occurred; however, infection prediction is the forecast of infection before infection occurs. Others (Bourke, 1970; Miller and O'Brien, 1952,1957) do not make a distinction between terms.

Jones (1983) felt four factors were important when developing any disease prediction system: identification of criteria for predicting stages of life cycle susceptible to control measures, availability of a control measure, ability to disseminate predictions shortly after receiving data, and knowledge of the economic benefits and risks involved in the system.

Krause and Massie (1975) classified predictive systems into empirical systems, which were developed by studying historical records of weather and disease, and fundamental systems, which often had empirical origins but were developed from data obtained experimentally. Empirical prediction systems often resulted in the formation of "rules" of specific meteorological conditions, while fundamental systems were generally formed by fitting regression lines to a specific relationship. Thus, the systems could be quite simple or quite complex. An epidemiological model was described as a mathematical expression describing structures, patterns and interrelationships objectively and quantitatively (Kranz and Royle, 1978).

Kranz and Royle (1978) described three types of epidemiologic models: descriptive models, for example growth curves, predictive models, composed of variables picked by how well they predict the epidemic, and conceptual models which attempt to represent natural systems. With respect to early blight these models would include epidemic progress curves, regression equations, and simulators, where a simulator is the linkage of several models representing various aspects of a disease cycle (Krause and Massie, 1975). One of the first plant disease simulators was EPIDEM (Waggoner and Horsfall, 1969), which simulated an early blight epidemic on tomatoes.

In developing EPIDEM, Waggoner and Horsfall (1969) utilized both historical and experimental data. They considered the lifecycle of the fungus as component subprocesses and determined which environmental conditons affected each subprocess. Then they converted the logical sequence of events into Fortran language to create the program. When supplied with the proper environmental parameters including leaf wetness, relative humidity, temperature, sunshine, and wind speed, the program simulated disease progress curves previously obtained from actual field assessments of early blight epidemics. This simulation model, however, allowed for no recommendation for application of control measures to contain the epidemic.

The forecasting system FAST (Madden, Pennypacker, MacNab, 1978) forecast early blight of tomatoes by identifying periods of environmental conditions favourable for A. solani spore formation and infection of tomato and by providing for a fungicide application schedule. Using a matrix consisting of values of hours of leaf wetness and mean temperature during the leaf wetness periods, severity values were predicted. As well, rating values were predicted from mean temperature, hours of relative humidity greater than 90%, and rainfall data. As cumulative severity and rating values reached preset limits, fungicide applications were recommended. The effectiveness of FAST-generated spray schedules in relation to other spray schedules was evaluated by comparing disease ratings and apparent infection rates (Madden, Penneypacker, and MacNab, 1978; Pennypacker, Madden and MacNab, 1983). The FAST-generated spray schedules recommended a reduced number of sprays, but were as effective in reducing early blight as commercial spray schedules. The individual grower had to identify and compare economic benefits and risks of this system.

Two important aspects of forecasting have been verification and validation of the forecasting system. Verification, or model debugging, was described as the process which ensures that the translational phase into the mathematical model is accurate (Teng, 1981; Teng and Zadoks, 1980), while validation was described as the "continual process of bringing to an acceptable level the user's confidence that any inference from the model is correct" (Teng, 1981). Verification would use the same data used to create the program, while validation would always use new data. Verification of the FAST program for use on tomatoes in Pennsylvania was carried out during 1976 (Madden et al, 1978). Effectiveness of the program was determined by comparing final disease severities and apparent infection rates of various spray schedules including the FAST-generated schedules. Validation was carried out (Madden et al, 1980; Pennypacker et al, 1983) with effectiveness of the program determined in the same manner. The spray schedules produced by the forecasting system provided efficient and effective control of early blight in each case.

Nutter (1978) compared spray schedules generated by FAST under New Hampshire conditions with _A_. _solani_ spore trap data and early blight disease progress curves on potatoes and felt the spray schedule recommended was adequate. The first spray was recommended at the end of July when less than one lesion per ten plants was noted and spore numbers were increasing. Subsequent recommendations preceded the increase of disease.

In literature dealing with plant disease prediction, authors are quick to stress several factors: Predictive systems only advise; it is the grower who takes responsibility for the decision 'to spray or not to spray' (Jones, 1983; MacHardy, 1979; Nutter, 1980). Reducing the number of fungicide sprays is possible but may increase the risk for losses to the individual grower by increasing inoculum (risking tuber infection), reducing yield (if sprays are not timed properly, the epidemic may proceed), and increasing effects of other diseases usually controlled by the spray program (Jones, 1983; MacKenzie, 1981a). That is, growers are often more willing to apply extra sprays than to risk losing investments worth more than their potential savings. Finally, fungicide sprays are quite often protective rather than therapeutic; thus, information from 'late warning' systems must be disseminated quickly (Krause _et al_, 1975; MacHardy, 1979). In these cases, although less accurate, systems predicting infection rather than disease would be more desirable (Krause _et al_, 1975; Krause and Massie, 1975; Jones, 1983).

Chapter III

EFFECT OF EARLY BLIGHT ON POTATO YIELDS IN MANITOBA

3.1 INTRODUCTION

Early blight is a foliage disease of the potato (Solanum tuberosum L.) and other solanaceous crops and occurs nearly everywhere these crops are grown (Hooker, 1981; Rich, 1983). Primary losses are caused by premature death of the foliage resulting in decreased yield (Feddersen, 1962; Harrison and Venette, 1970; Lahman et al, 1981; Rands, 1917; Venette and Harrison, 1973). Losses also occur from reduced quality of the tubers; the highest percentage of growth defects were found in diseased plots (Douglas and Groskopp, 1974). Damage to the tubers as a result of A. solani tuber infection is generally of minor importance, although during some years it remains a potential problem in certain areas (Douglas and Groskopp, 1974; Feddersen, 1962; Guthrie, 1958; Lahman et al, 1981; Venette and Harrison, 1973).

Field trials were conducted by various researchers to determine the reduction in yield caused by this disease; however, results were not always consistent. Fungicide application encompassing the period of secondary spread of the pathogen often resulted in significant control of the disease, but yield response was not always significant (Harrison et al, 1965b,c; Easton and Nagle, 1985). When the yield response was significant, losses ranging from 6%-58% were reported (Douglas and Groskopp, 1974; Feddersen, 1962, Franc et al, 1983; Harrison and Venette, 1974; Teng and Bissonnette, 1984, 1985a). Often experimentnal designs, goals, methods, and cultivars differed.

Field trials with two potato cultivars, Norland and Russet Burbank, were conducted in 1983 and 1984 to evaluate the effect of early blight on potato yield under Manitoba conditions. Varying the fungicide application schedules was used to generate different disease severities. The yield trials were conducted at the University of Manitoba field substation at Portage la Prairie, Manitoba.

3.2 MATERIALS AND METHODS

3.2.1 Experimental design

In 1983 the design of the experiment was a replicated latin square in which the treatments were four different fungicide (Dithane M-45) application schedules. In 1984 a split-plot design was used where main treatments consisted of uninoculated plots or *Alternaria solani*-inoculated plots and subplot treatments consisted of the same fungicide application schedules as used in 1983. In both years individual plots consisted of six 30-foot long rows of which only the centre two rows were harvested.

The 1983 early blight disease assessments consisted of severity ratings and incidence ratings taken on a per plant basis within the plots. In 1984 disease severity and defoliation were assessed on a whole plot basis and incidence on a per plant basis within the plots.

3.2.2 Fungicide treatments

Fungicide treatments consisted of four spray schedules each year. During the season zero, two, four, or weekly sprays of Dithane M-45 (mancozeb) were applied to the plots. Weekly spraying started in mid-July and continued until harvest. The other spray treatments were also applied during this period. A three-point hitch sprayer, which delivered 560 l/ha of chemical solution, was used to apply the fungicide at a rate of 2.25 kg/ha. Mechanical damage on harvested rows was kept to a minimum by driving between guard rows only.

3.2.3 Inoculation

In 1984 the inoculation treatments which were superimposed on the fungicide treatments consisted of a control (water applied only) or a single inoculation with a water suspension of Alternaria solani. With a backpack sprayer 1 litre of inoculum or water was applied to the centre two rows of each plot. The inoculation treatments took place on the evening of July 23, 1984.

3.2.4 Inoculum preparation

Field isolates of Alternaria solani were collected and used to prepare inoculum. Cultures were induced to sporulate using a method described by Shahin and Shepard (1979). Cultures were grown on potato dextrose agar for 14 days at room temperature. Aerial mycelia were scraped off with a scalpel and rectangular sections of the medium containing the growing mycelium were cut into strips approximately 3cm x 1cm, and were placed on a sporulation medium composed of calcium carbonate, sucrose, and agar. Two ml of water were then added to each plate. The plates were incubated in darkness at 18°C for 5 days. Individual spores were then placed on PDA and cultures were grown for 14 days. Inoculum was prepared from these plates using a method described by Dhiman <u>et al</u> (1981). Seventy cultures were pureed with enough distilled water to make 3.5 litres. The puree was strained two times with a single, then a double layer of cheesecloth.

Concentration of mycelial fragments was checked using a haemocytometer and was found to be 4.0×10^6 per ml. The inoculum was kept on ice until the evening when it was diluted 10x and applied to the centre two rows of each inoculated plot, using 1 litre per plot. Final concentration of applied inoculum was 4.0×10^5 mycelial fragments per ml.

3.2.5 Ratings

The early blight disease level in each plot was monitored with the aid of a disease assessment key (Anon, 1947; Fry, 1977) (Appendix A) and standard area disease diagrams (Granousky and Peterson, 1954) (Appendix B). Percent severity was extrapolated when necessary.

In 1983 a total of four and five ratings were taken for the cultivars Norland and Russet Burbank, respectively. Rating was started in mid-July and continued in 2-weekly intervals until harvest. Disease severity and incidence were rated on a per plant basis within each plot: the average of ten randomly selected plants per plot gave the final plot ratings.

In 1984 a total of nine ratings were taken on both cultivars; disease was assessed weekly from mid-July until harvest. Ratings were taken on incidence, severity, and defoliation. As in 1983, incidence was assessed on ten randomly selected plants per plot and averaged to give percent incidence per plot. Disease severity was assessed on a whole plot basis. Defoliation was measured by comparing number of leaves in experimental plots with number of leaves in destructively sampled plots. Defoliation was the difference of the average number of leaves taken as a proportion of the number of leaves in the destructively sampled plots.

3.2.6 General cultural practices

In 1983 all plots were treated with a preplant incorporation of Sencor 500 (550 ml/ha) and Eptam 8E (5.0 l/ha) to control weeds. In 1984 Sencor 500 (600 ml/ha) was applied as a post-emergent spray. Fertilizer was applied with the seed; in 1983 340 kg/ha of 19-19-19 was applied, and in 1984 110 kg/ha of 0-19-19 was applied according to soil test results from Manitoba Department of Agriculture Soil Testing Services. Insecticide (Decis 2.5EC at 300 ml/ha) was applied each year as necessary. Hoeing, hilling, and cultivation were carried out as necessary. In row spacing of seed pieces differed per cultivar; Norland potatoes were spaced 32.8 cm apart and Russet Burbank potatoes were spaced 42.2 cm apart. Rows were spaced one meter apart.

3.2.7 Grading and weighing

All plots were harvested in September (Sept. 21 and 22, 1983 and Sept. 16 and 20, 1984) and the potatoes were graded according to size. Russet Burbank potatoes were graded on a 5 cm chain and Norland potatoes were graded on a 5.7 cm chain. The frequency of knobs, mechanical damage, and oversized potatoes was low; hence they were not culled out. For the purpose of this study, potatoes larger than the chain diameter specified per cultivar were called marketable potatoes. For example, Russet Burbank potatoes not fitting through a 5.7 cm diameter chain were considered marketable; those fitting through the chain were considered undersized.

3.2.8 Experimental analysis

An analysis of variance conducted at the 5% level of significance was performed on ratings and yield data. Multiple pairwise comparisons were made using the Least Significant Difference (LSD) Test.

Data were then subjected to regression analysis to evaluate the relationship of early blight disease and yield in these trials. Dependent variables marketable weight and number of marketable tubers were regressed with disease incidence, disease severity, severity increments, and defoliation. Variables having an unduely disproportionate net effect on yield were deleted from the regression (James et al, 1972; Teng and Bissonnette, 1985b). Equations resulting from maximization of r^2 (coefficient of determination) and from forward selection and stepwise selection procedures, where levels of entry into the equations were F-values where the probability of a greater F-value was less than 0.5 and 0.15, respectively, were compared. These comparisons resulted in three or four-variable equations which described the early blight-yield relationship.

3.2.9 Phenological development

Four extra plots of each cultivar were planted for destructive sampling in 1984. The same cultural operations were carried out on these plots as in the main yield trial. These plots were also sprayed with fungicide on a weekly basis. Inner rows of the plots were divided into sectors, so that meter quadrats could be selected in such a fashion that each was completely surrounded with guard plants. Two sectors of each cultivar were then picked randomly each week for analysis. Sampling was started in mid-July and continued until harvest of the yield trial.

Number of leaves, leaf area, and fresh weight of tubers were recorded. Healthy leaves and those leaves with less than 25% senescence were counted individually. Fully developed, unexpanded leaves at the apex of branches and stems were grouped together and counted as one leaf. Leaf area was measured in square centimeters using a Li-Cor Lamda leaf area meter, Model LI-3000. Leaf area is reported as leaf area index (LAI).

All three variables were regressed with time to find a close-fitting description of the growth relationship. This description could then be related to percentage disease severity and defoliation. Also amount of yield loss could be estimated if growth were terminated at any point.

3.3 RESULTS

3.3.1 Yield

In both 1983 and 1984 the fungicide spray schedule had no significant effects at the 5% level on weight or number of marketable tubers for the cultivar Russet Burbank (Table 1).

For the cultivar Norland, 1983 results were similar: no significant differences were apparent at the 5% level for either number or weight of marketable potatoes. In 1984, however, fungicide spray schedule had a signifi-

TABLE 1. Effects of fungicide spray schedule on production (number (1,000) per ha) and yield (1,000 kg per ha) of marketable tubers: Portage la Prairie, 1983 and 1984.

SPRAY SCHEDULE[1]	RUSSET BURBANK				NORLAND			
	1983		1984		1983		1984	
	Number	Yield	Number	Yield	Number	Yield	Number	Yield
W	97.3 a[2]	22.8 a	106.3 a	27.4 a	137.8 a	27.5 a	153.8 a	31.6 a
4	97.6 a	22.7 a	106.4 a	26.5 a	129.6 a	24.6 a	134.6 b	29.1 ab
2	101.1 a	22.9 a	100.5 a	25.6 a	137.4 a	26.3 a	141.8 ab	28.2 b
0	102.1 a	22.9 a	100.8 a	26.4 a	134.1 a	26.7 a	129.2 b	25.5 b

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Means in a column followed by the same letter do not differ at the 5% level of significance.

cant effect on both number and yield. Weekly-sprayed plots produced significantly more marketable tubers than either unsprayed plots or plots sprayed only four times. Weekly-sprayed plots also significantly outyielded unsprayed plots (Table 1). The weekly-sprayed plots produced 16.0% more marketable tubers than unsprayed plots and marketable weight was increased by 19.3%.

In 1984 one inoculation treatment was superimposed over half of the plots. The number of marketable potatoes was significantly decreased in those plots of both cultivars that had been inoculated, compared to uninoculated plots (Table 2). Inoculation similarly affected the yield of both cultivars, but only in the cultivar Norland were the differences significant. With respect to the interaction between inoculation and spray schedule, neither the differences in number nor the differences in weight of marketable tubers were significant at the 5% level for either cultivar.

TABLE 2. Effect of inoculation and fungicide spray schedule on production (number (1,000) per ha) and yield (1,000 kg per ha) of marketable tubers: Portage la Prairie, 1984.

INOCULATION[1]	RUSSET BURBANK		NORLAND	
	NUMBER	YIELD	NUMBER	YIELD
0	106.9 a[2]	27.8 a	157.7 a	32.6 a
1	97.5 b	25.2 a	122.0 b	24.6 b

INOCULATION x SPRAY SCHEDULE[3]		RUSSET BURBANK		NORLAND	
		NUMBER	YIELD	NUMBER	YIELD
0	W	107.8 a	26.4 a	166.4 a	34.0 a
0	4	107.2 a	28.6 a	151.9 a	34.0 a
0	2	104.1 a	26.8 a	157.8 a	32.6 a
0	0	108.6 a	29.5 a	154.3 a	29.6 a
1	W	104.9 a	28.5 a	141.3 a	29.1 a
1	4	94.9 a	24.5 a	117.0 a	21.3 a
1	2	97.0 a	24.5 a	125.9 a	23.7 a
1	0	93.1 a	23.3 a	103.9 a	24.1 a

[1] Inoculation treatment: 0=no inoculation, 1=one inoculation with *Alternaria solani* July 23,1984. with concentration of 4 x 10^5 I.U./ml.

[2] Means in a column followed by the same letter do not differ at the 5% level of significance.

[3] Fungicide spray schedule throughout the season: W=weekly applications, 4, 2, 0=four, two, zero applications, respectively.

3.3.2 Disease

3.3.2.1 Incidence

Percent incidence was rated as the average incidence of early blight on ten randomly selected plants per plot. In both 1983 and 1984 disease incidence in both cultivars increased gradually with time. In weekly-sprayed plots there was a general trend towards a lower percent incidence than in other plots, although this trend was often not significant (Tables 3,4).

In 1983 at the time of the first rating, the eighth week after planting, roughly half of the plants rated were infected with at least one early blight lesion. Disease incidence reached 100% in both cultivars by the 14th week after planting. In 1984 ratings taken seven weeks after planting showed incidence to be less than 10%. By the 11th and 12th weeks after planting incidence had reached 100% in cultivars Norland and Russet Burbank, respectively. All inoculated plots reached 100% incidence by week 10, within two weeks after inoculation (Table 5).

3.3.2.2 Severity

Disease severity increased with time during both growing seasons (Table 6,7). The range of average disease severity per spray schedule in 1983 was 0.01%, all spray schedules (cultivar Russet Burbank) at the time of the first rating, to 1.6%, unsprayed plots (cultivar Norland) at the time of the last rating. Most plots had reached a level of 0.1% severity by the tenth week after planting and a level of 1.0% by the fourteenth week.

The range of average disease severity with respect to spray schedule in 1984 was from 0.0%, in all plots at the time of the first rating, to 11.2%,

TABLE 3. Progression of disease incidence (%) for different fungicide spray schedules: Portage la Prairie, 1983.

SPRAY SCHEDULE[1]	RUSSET BURBANK				
	WEEK OF RATING[2]				
	8	10	12	14	16
W	52.5 a[3]	71.2 a	80.0 a	100.0 a	100.0 a
4	45.0 a	86.2 b	92.5 b	100.0 a	100.0 a
2	53.8 a	92.5 bc	97.5 b	100.0 a	100.0 a
0	52.5 a	98.9 c	98.5 b	100.0 a	100.0 a

SPRAY SCHEDULE[1]	NORLAND			
	WEEK OF RATING[2]			
	8	10	12	14
W	50.0 a	77.5 a	90.0 a	100.0 a
4	53.8 a	81.2 a	97.5 a	100.0 a
2	68.8 b	88.8 a	97.5 a	100.0 a
0	71.2 b	80.0 a	97.5 a	100.0 a

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.
[2] Number of weeks after planting.
[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 4. Progression of disease incidence (%) for different fungicide spray schedules: Portage la Prairie, 1984.

SPRAY SCHEDULE[1]	RUSSET BURBANK					
	WEEK OF RATING[2]					
	7	8	9	10	11	12
W	3.7 a[3]	5.0 a	21.2 a	71.2 a	95.0 a	100.0 a
4	3.7 a	6.2 a	22.5 a	90.0 b	100.0 a	100.0 a
2	1.2 a	13.8 a	40.0 a	88.8 b	98.8 a	100.0 a
0	4.4 a	16.2 a	30.0 a	92.5 b	100.0 a	100.0 a

SPRAY SCHEDULE	NORLAND					
	WEEK OF RATING					
	7	8	9	10	11	12
W	0.0 a	6.2 a	7.5 a	81.2 a	100.0 a	100.0 a
4	0.6 a	6.2 a	12.5 a	91.2 b	100.0 a	100.0 a
2	0.0 a	5.0 a	16.2 a	93.7 b	100.0 a	100.0 a
0	2.0 a	7.5 a	21.2 a	93.7 b	100.0 a	100.0 a

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Number of weeks from planting.

[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 5. Progression of disease incidence (%) with respect to inoculation: Portage la Prairie, 1984.

INOCULATION[1]	RUSSET BURBANK					
	WEEK OF RATING[2]					
	7	8	9	10	11	12
0	3.5 a[3]	7.5 a	26.5 a	71.2 a	96.9 a	100.0 a
1	3.1 a	13.1 a	31.2 a	100.0 b	100.0 b	100.0 a

INOCULATION	NORLAND					
	WEEK OF RATING					
	7	8	9	10	11	12
0	0.9 a	8.1 a	12.5 a	80.0 a	100.0 a	100.0 a
1	0.6 a	4.4 a	16.2 a	100.0 a	100.0 a	100.0 a

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[1] Inoculation treatment: 0=no inoculation, 1=one inoculation with *Alternaria solani* at week 8, July 23, 1984.
[2] Number of weeks from planting.
[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 6. Progression of disease severity (%) for different fungicide spray schedules: Portage la Prairie, 1983.

SPRAY SCHEDULE[1]	RUSSET BURBANK				
	WEEK OF RATING[2]				
	8	10	12	14	16
W	0.01 a[3]	0.06a	0.3 a	0.6 a	0.7 a
4	0.01 a	0.1 a	0.5 a	0.8 a	0.8 ab
2	0.01 a	0.8 b	1.0 b	1.3 ab	1.2 bc
0	0.01 a	0.5 b	0.8 b	1.4 b	1.4 c

SPRAY SCHEDULE	NORLAND			
	WEEK OF RATING			
SPRAY SCHEDULE	8	10	12	14
W	0.02 a	0.2 a	0.4 a	0.9 a
4	0.02 a	0.2 a	0.5 a	1.0 a
2	0.04 b	0.2 a	0.6 a	1.2 ab
0	0.05 b	0.2 a	0.5 a	1.6 b

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.
[2] Number of weeks from planting.
[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 7. Progression of disease severity (%) for different fungicide spray schedules: Portage la Prairie, 1984.

SPRAY SCHEDULE[1]	RUSSET BURBANK								
	WEEK OF RATING[2]								
	7	8	9	10	11	12	13	14	15
W	0.0 a[3]	0.0 a	0.01 a	1.3 a	2.9 a	4.0 a	5.3 a	5.8 a	6.2 a
4	0.0 a	0.01a	0.01 a	2.3 ab	4.0 ab	5.4 b	6.1 a	5.9 a	7.5 a
2	0.0 a	0.01a	0.01 a	2.9 b	5.0 b	5.4 b	6.6 a	7.5 ab	8.1 a
0	0.0 a	0.0 a	0.01 a	4.3 c	5.1 b	5.6 b	7.4 a	8.2 b	11.2 b

SPRAY SCHEDULE	NORLAND								
	WEEK OF RATING								
	7	8	9	10	11	12	13	14	15
W	0.0 a	0.0 a	0.0 a	3.8 a	12.1 a	16.0 a	28.8 a	38.8 a	38.8 a
4	0.0 a	0.0 a	0.01a	10.7 ab	22.9 b	24.8 b	30.0 a	46.2 ab	46.2 ab
2	0.0 a	0.0 a	0.01a	14.3 bc	24.5 b	31.9 bc	35.0 a	51.2 bc	53.8 bc
0	0.0 a	0.0 a	0.01a	19.1 c	23.6 b	31.9 c	40.0 a	58.1 c	60.6 c

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[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Number of weeks from planting.

[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

in unsprayed plots of cultivar Russet Burbank and to 60.6%, in unsprayed plots of cultivar Norland, at the time of the final rating. In 1984 most plots of both cultivars had reached 0.01% severity by week nine, 1.0% by week ten, and 10% severity by week eleven for the cultivar Norland and by harvest for the cultivar Russet Burbank.

In 1984 plants were inoculated eight weeks after planting and infection became evident within two weeks (Table 8). By the tenth week after planting the average disease severity in inoculated plots increased by a factor of more than ten times that of uninoculated plots of cultivar Russet Burbank and increased more than 40 times that of uninoculated plots of cultivar Norland. Significant interaction effects between spray schedule and inoculation with respect to disease severity were also evident by week ten (Table 9). After this week interactions between the two treatments were no longer significant for cultivar Russet Burbank; however, differences in disease severity of cultivar Norland continued to be significant. By the time of the final rating four distinct groups of severity arose: the uninoculated plots, the inoculated weekly-sprayed plots, the inoculated plots sprayed four times, and the inoculated plots which were sprayed twice or remained unsprayed. The range of severity throughout the season with respect to the interaction of treatments was from 0.0% to 13.8%, cultivar Russet Burbank, and from 0.0% to 90.0%, cultivar Norland.

3.3.2.3 Defoliation

Defoliation was rated in 1984 only. Differences in percent defoliation with respect to spray schedule became significant by weeks 10 and 12 for cultivars Russet Burbank and Norland, respectively (Table 10). Final rat-

TABLE 8. Progression of disease severity (%) with respect to inoculation: Portage la Prairie, 1984.

INOCULATION[1]	RUSSET BURBANK								
	WEEK OF RATING[2]								
	7	8	9	10	11	12	13	14	15
0	0.0 a[3]	0.0 a	0.01 a	0.4 a	1.2 a	1.9 a	3.9 a	4.9 a	6.8 a
1	0.0 a	0.01a	0.01 a	5.0 b	7.3 b	8.3 b	9.1 b	8.8 b	9.6 a

INOCULATION	NORLAND								
	WEEK OF RATING								
	7	8	9	10	11	12	13	14	15
0	0.0 a	0.0 a	0.01a	0.5 a	3.4 a	6.9 a	13.8 a	23.4 a	23.4 a
1	0.0 a	0.0 a	0.0 a	23.4 b	38.1 b	45.3 b	53.1 b	73.8 b	76.2 b

[1] Inoculation treatment: 0=no inoculation, 1=one inoculation with Alternaria solani at week 8, July 23, 1984.

[2] Number of weeks from planting.

[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 9. Progression of disease severity (%) with respect to interaction of different fungicide spray schedules and inoculation: Portage la Prairie, 1984.

RUSSET BURBANK

SPRAY SCHEDULE[1] x INOCULATION[2]		WEEK OF RATING[3] 7	8	9	10	11	12	13	14	15
W	0	0.0 a[4]	0.0 a	0.0 a	0.01a	0.6 a	1.0 a	3.0 a	4.0 a	5.0 a
4	0	0.0 a	0.0 a	0.01a	0.6 a	1.5 a	2.0 a	3.5 a	3.0 a	6.2 a
2	0	0.0 a	0.0 a	0.01a	0.6 a	1.3 a	2.0 a	4.5 a	6.2 a	7.5 a
0	0	0.0 a	0.0 a	0.0 a	0.3 a	1.5 a	2.5 a	4.8 a	6.5 a	8.8 a
W	1	0.0 a	0.0 a	0.01a	2.5 b	5.2 a	7.0 a	8.8 a	7.5 a	7.5 a
4	1	0.0 a	0.01a	0.01a	4.0 bc	8.8 a	8.8 a	8.8 a	8.8 a	8.8 a
2	1	0.0 a	0.01a	0.01a	5.2 c	8.8 a	8.8 a	8.8 a	8.8 a	8.8 a
0	1	0.0 a	0.0 a	0.01a	8.2 d	6.5 a	8.8 a	10.0 a	10.0 a	13.8 a

NORLAND

SPRAY SCHEDULE x INOCULATION		WEEK OF RATING 7	8	9	10	11	12	13	14	15
W	0	0.0 a	0.0 a	0.0 a	0.08a	3.0 a	7.0 a	13.8 a	27.5 a	27.5 a
4	0	0.0 a	0.0 a	0.01a	0.09a	2.0 a	5.8 a	10.0 a	17.5 a	17.5 a
2	0	0.0 a	0.0 a	0.01a	1.0 a	5.2 a	7.5 a	13.8 a	17.5 a	17.5 a
0	0	0.0 a	0.0 a	0.0 a	0.8 a	3.5 a	7.5 a	17.5 a	31.2 a	31.2 a
W	1	0.0 a	0.0 a	0.0 a	7.5 a	21.2 b	25.0 a	43.8 a	50.0 b	50.0 b
4	1	0.0 a	0.0 a	0.01a	21.2 b	43.8 c	43.8 a	50.0 a	75.0 c	75.0 c
2	1	0.0 a	0.0 a	0.0 a	27.5 b	43.8 c	56.2 a	56.2 a	85.0 c	90.0 d
0	1	0.0 a	0.0 a	0.01a	37.5 b	43.8 c	56.2 a	62.5 a	85.0 c	90.0 d

---

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Inoculation treatment: 0=no inoculation, 1=inoculation with Alternaria solani at week 8, July 23,1984.

[3] Number of weeks from planting.

[4] Means in a column followed by the same letter do not differ at the 5% level of significance.

ings for the cultivar Russet Burbank were not significantly different; however, for the cultivar Norland there were two distinct groups: unsprayed plots and plots sprayed only twice during the season had significantly more defoliation than the plots sprayed weekly and four times during the season.

The effect of inoculation on defoliation became apparent by the tenth and eleventh weeks after planting, cultivars Russet Burbank and Norland, respectively (Table 11). In the inoculated plots defoliation was significantly greater than in the uninoculated plots, but by the final rating this difference was no longer significant for the cultivar Russet Burbank. The cultivar Norland on the other hand, remained significantly affected. For the cultivar Russet Burbank the interaction of spray schedule and inoculation was significant for only the rating during week eleven (Table 12). For the cultivar Norland the interaction was significant for the 12th and 14th weeks after planting (Table 12).

TABLE 10. Progression of defoliation (%) for different fungicide spray schedules: Portage la Prairie, 1984.

SPRAY SCHEDULE[1]	RUSSET BURBANK								
	WEEK OF RATING[2]								
	7	8	9	10	11	12	13	14	15
W	0.0 a[3]	1.0 a	1.2 a	5.5 a	6.2 a	7.5 a	10.0 a	11.2 a	12.5 a
4	0.0 a	1.0 a	1.8 a	6.2 a	11.2 b	8.7 a	14.4 b	15.6 a	18.1 a
2	0.0 a	1.0 a	1.0 a	8.2 b	12.0 b	9.3 a	13.1 ab	13.1 a	16.2 a
0	0.0 a	1.0 a	1.8 a	6.6 ab	13.1 b	9.3 a	14.4 b	13.7 a	14.4 a

SPRAY SCHEDULE	NORLAND								
	WEEK OF RATING								
	7	8	9	10	11	12	13	14	15
W	0.0 a	1.0 a	1.2 a	7.5 a	16.9 a	18.1 a	30.0 a	38.8 a	56.2 a
4	0.0 a	1.0 a	1.2 a	7.5 a	21.2 a	26.2 b	31.9 a	46.2 ab	61.2 a
2	0.0 a	1.0 a	1.2 a	11.3 a	21.9 a	31.2 b	36.9 ab	53.8 bc	72.5 b
0	0.0 a	1.0 a	2.0 a	10.0 a	21.2 a	29.4 b	43.1 b	60.6 c	76.2 b

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Number of weeks from planting.

[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 11. Progression of defoliation (%) with respect to inoculation: Portage la Prairie, 1984.

INOCULATION[1]	RUSSET BURBANK								
	WEEK OF RATING[2]								
	7	8	9	10	11	12	13	14	15
0	0.0 a[3]	1.0 a	1.2 a	4.8 a	6.3 a	6.6 a	8.4 a	11.2 a	11.9 a
1	0.0 a	1.0 a	1.6 a	8.4 b	15.0 b	10.9 a	17.5 b	15.6 a	15.0 a

INOCULATION	NORLAND								
	WEEK OF RATING								
	7	8	9	10	11	12	13	14	15
0	0.0 a	1.0 a	1.6 a	6.2 a	10.0 a	9.7 a	13.8 a	23.4 a	46.9 a
1	0.0 a	1.0 a	1.2 a	11.9 a	30.6 b	42.8 b	57.2 b	76.2 b	86.2 b

[1] Inoculation treatment: 0=no inoculation, 1=inoculation with Alternaria solani at week 8, July 23,1984.
[2] Number of weeks from planting.
[3] Means in a column followed by the same letter do not differ at the 5% level of significance.

TABLE 12. Progression of defoliation (%) with respect to interaction of different fungicide spray schedules and inoculation: Portage la Prairie, 1984.

RUSSET BURBANK

SPRAY SCHEDULE[1] x INOCULATION[2]		WEEK OF RATING[3]								
		7	8	9	10	11	12	13	14	15
W	0	0.0 a[4]	1.0 a	1.5 a	3.5 a	5.0 a	6.2 a	7.5 a	10.0 a	10.0 a
4	0	0.0 a	1.0 a	1.0 a	5.0 a	7.5 a	7.5 a	8.8 a	12.5 a	12.5 a
2	0	0.0 a	1.0 a	1.0 a	6.2 a	5.2 a	6.2 a	8.8 a	12.5 a	15.0 a
0	0	0.0 a	1.0 a	1.5 a	4.5 a	7.5 a	6.2 a	8.8 a	10.0 a	10.0 a
W	1	0.0 a	1.0 a	1.0 a	7.5 a	7.5 a	8.8 a	12.5 a	12.5 a	15.0 a
4	1	0.0 a	1.0 a	2.5 a	7.5 a	15.0 b	10.0 a	20.0 a	18.8 a	23.8 a
2	1	0.0 a	1.0 a	1.0 a	10.0 a	18.8 b	12.5 a	17.5 a	13.8 a	17.5 a
0	1	0.0 a	1.0 a	2.0 a	8.8 a	18.8 b	12.5 a	20.0 a	17.5 a	18.8 a

NORLAND

SPRAY SCHEDULE x INOCULATION		WEEK OF RATING								
		7	8	9	10	11	12	13	14	15
W	0	0.0 a	1.0 a	1.5 a	5.0 a	10.0 a	8.8 a	13.8 a	27.5 a	37.5 a
4	0	0.0 a	1.0 a	1.5 a	5.0 a	10.0 a	10.0 a	10.0 a	17.5 a	37.5 a
2	0	0.0 a	1.0 a	1.5 a	8.8 a	10.0 a	10.0 a	13.8 a	17.5 a	50.0 a
0	0	0.0 a	1.0 a	2.0 a	6.2 a	10.0 a	10.0 a	17.5 a	31.2 a	62.5 a
W	1	0.0 a	1.0 a	1.0 a	10.0 a	23.8 a	27.5 b	46.2 a	50.0 b	75.0 a
4	1	0.0 a	1.0 a	1.0 a	10.0 a	32.5 a	42.5 c	53.8 a	75.0 c	85.0 a
2	1	0.0 a	1.0 a	1.0 a	13.8 a	33.8 a	52.5 c	60.0 a	90.0 d	95.0 a
0	1	0.0 a	1.0 a	2.0 a	13.8 a	32.5 a	48.8 c	68.8 a	90.0 d	90.0 a

---

[1] Fungicide spray schedule throughout the season: W=weekly applications, 4,2,0=four,two, and zero applications, respectively.

[2] Inoculation treatment: 0=no inoculation, 1=inoculation with <u>Alternaria solani</u> at week 8, July 23,1984.

[3] Number of weeks from planting.

[4] Means in a column followed by the same letter do not differ at the 5% level of significance.

3.3.3 Relationship of yield and disease

The stepwise selection procedure, with an entry level of 0.15 significance, admitted the fewest variables into the regression equations. The forward selection procedure and the maximum r^2 selection usually selected the same variables, although the forward selection procedure also admitted variables with a significance level for entry into the equation of 0.5. Occasionally the forward selection procedure admitted only one or two variables into the equation. Under these circumstances, the three-variable equation maximizing the r^2 value was chosen.

The two yield parameters analyzed with respect to disease were number of marketable tubers per plot and weight of marketable tubers, pounds per plot. In 1983 no significant relationships were obtained for regression of number or weight of either cultivar with disease incidence or severity.

In 1984, however, some significant relationships were apparent. The best single-predictor models using various disease parameters explained a maximum of 42% of the variation in number of marketable tubers cultivar Russet Burbank, 28% of the variation in weight of marketable tubers of the same cultivar, 56% of the variation in number of marketable tubers of cultivar Norland, and 62% of the variation in marketable weight of cultivar Norland. Multiple variable prediction equations explained more of the variation in yield. Forward selection procedures, using a level of significance for entry into the equation of 0.5, generally admitted three variables into the equations. The best three-variable regression equations, using assessments of incidence, assessments of severity, severity increments, and assessments of defoliation as the independent variables, are found in tables 13,14,15, and 16, respectively. These equations explained a maximum of close to 50% of the variation in both number and weight of marketable tubers of the cultivar Russet Burbank, and a maximum of over 60% of the variation in yield parameters for the cultivar Norland.

Multiple regression with incidence of early blight (Table 13) produced the least reliable prediction equations, often explaining a smaller percentage of the variation in yield than many single predictor variables. Multiple regression using assessments of disease severity as the independent variables explained approximately 30% of variation in yield for cultivar Russet Burbank and over 60% of the variation in yield for cultivar Norland (Table 14). Increments of disease severity throughout the season, calculated by subtraction of weekly severity assessment values, explained similar amounts of variation in yield as disease severity (Table 15). Multiple regression using weekly defoliation assessments as the independent variables generally produced predictive equations which explained more of the variation in yield than other regressions (Table 16).

TABLE 13. The best-fitting three-variable regression equations depicting the relationships between marketable yield and early blight disease incidence: Portage la Prairie, 1984.

VARIETY	YIELD VARIABLE	= WEEK OF RATING[1]	REGRESSION EQUATION[2]	ROOT MSE[3]	F VALUE	R SQUARE[4]
Russet Burbank	TNO[5]	= 7 8 10	$Y = 116.6 - 0.509X_7 - 0.337X_8 - 0.219X_{10}$	20.13	1.32	0.124
Russet Burbank	TWT[6]	= 7 8 9	$Y = 30.2 - 0.996X_7 - 0.238X_8 - 0.272X_9$	13.62	3.64*	0.281
Norland	TNO	= 8 9 10	$Y = 195.2 + 0.655X_8 - 1.05X_9 - 0.90X_{10}$	35.47	4.12*	0.306
Norland	TWT	= 7 9 10	$Y = 45.0 - 2.68X_7 - 0.540X_9 - 0.560X_{10}$	17.22	7.24**	0.437

[1] Plots were rated weekly for disease incidence in 1984, starting the seventh week after planting and continuing until the 15th week after planting ($X_7 \ldots X_{15}$).
[2] Regression equation is of the form $Y = Bo + B_1X_1 + B_2X_2 + \ldots + BnXn$.
[3] Square root of the mean sum of squares for error (standard deviation).
[4] Coefficient of determination.
[5] TNO represents the number of marketable tubers (1,000 per ha).
[6] TWT represents the weight of marketable tubers (1,000 kg per ha).
*,** Significant at the 5% and 1% levels, respectively.

TABLE 14. The best-fitting three-variable regression equations depicting the relationships between marketable yield and early blight disease severity: Portage la Prairie, 1984.

VARIETY	YIELD VARIABLE	= WEEK OF RATING[1]	REGRESSION EQUATION[2]	ROOT MSE[3]	F VALUE	R SQUARE[4]
Russet Burbank	TNO[5]	= 10 12 14	$Y = 104.0 - 4.27X_{10} + 0.56X_{12} + 0.804X_{14}$	17.77	3.90*	0.295
Russet Burbank	TWT[6]	= 10 13 14	$Y = 27.3 - 3.24X_{10} + 1.82X_{13} - 0.908X_{14}$	13.17	4.54*	0.327
Norland	TNO	= 10 14 15	$Y = 163.4 - 1.40X_{10} - 2.25X_{14} + 1.75X_{15}$	26.55	14.68***	0.611
Norland	TWT	= 13 14 15	$Y = 36.5 + 0.575X_{13} - 0.750X_{14} - 0.235X_{15}$	13.11	19.24***	0.673

[1] Plots were rated weekly for disease severity in 1984, starting the seventh week after planting and continuing until the 15th week after planting ($X_7 \ldots X_{15}$).

[2] Regression equation is of the form $Y = Bo + B_1X_1 + B_2X_2 + \ldots + BnXn$.

[3] Square root of the mean sum of squares for error (standard deviation).

[4] Coefficient of determination.

[5] TNO represents the number of marketable tubers (1,000 per ha).

[6] TWT represents the weight of marketable tubers (1,000 kg per ha).

*,*** Significant at the 5% and 0.1% levels, respectively.

TABLE 15. The best-fitting three variable regression equations depicting the relationships between marketable yield and severity increment: Portage la Prairie, 1984.

VARIETY	YIELD VARIABLE	= SEVERITY INCREMENT[1]	REGRESSION EQUATION[2]	ROOT MSE[3]	F VALUE	R SQUARE[4]
Russet Burbank	TNO[5]	$= X_3\ X_5\ X_7$	$Y = 105.2 - 2.82X_3 + 1.56X_5 + 1.36X_7$	18.02	3.96**	0.298
Russet Burbank	TWT[6]	$= X_3\ X_5\ X_7$	$Y = 27.9 - 2.46X_3 + 1.82X_5 - 0.906X_7$	13.13	4.63**	0.332
Norland	TNO	$= X_3\ X_7\ X_8$	$Y = 158.1 - 2.16X_3 - 0.517X_7 + 2.82X_8$	27.25	13.45***	0.590
Norland	TWT	$= X_3\ X_6\ X_7$	$Y = 35.3 - 0.569X_3 - 0.338X_6 - 1.02X_7$	13.64	17.09***	0.647

[1] Increments of early bilght severity were calculated by subtraction of severity values. X_1=week 8 - week 7; X_2=week 9 - week 8; X_3=week 10 - week 9; X_4= week 11 - week 10; X_5= week 12 - week 11; X_6=week 13 - week 12; X_7= week 14 - week 13; X_8= week 15 - week 14.

[2] Regression equation is of the form $Y = Bo + B_1X_1 + B_2X_2 + \ldots + BnXn$.

[3] Square root of the mean sum of squares for error (standard deviation).

[4] Coefficient of determination.

[5] TNO represents the number of marketable tubers (1,000 per ha).

[6] TWT represents the weight of marketable tubers (1,000 kg per ha).

,* Significant at the 1% and 0.1% levels, respectively.

TABLE 16. The best-fitting three-variable regression equations depicting the relationships between marketable yield and defoliation: Portage la Prairie, 1984.

VARIETY	YIELD VARIABLE	= WEEK OF RATING[1]	REGRESSION EQUATION[2]	ROOT MSE[3]	F VALUE	R SQUARE[4]
Russet Burbank	TNO[5]	= 12 14 15	$Y = 123.0 - 3.46X_{12} - 0.997X_{14} + 0.596X_{15}$	15.63	8.83***	0.472
Russet Burbank	TWT[6]	= 11 13 14	$Y = 31.3 - 1.85X_{11} + 1.44X_{13} - 1.22X_{14}$	12.08	7.18**	0.435
Norland	TNO	= 11 14 15	$Y = 181.2 - 0.96X_{11} - 0.32X_{14} - 0.49X_{15}$	26.94	13.98***	0.600
Norland	TWT	= 13 14 15	$Y = 38.3 + 0.418X_{13} - 0.700X_{14} - 0.234X_{15}$	13.30	18.55***	0.665

[1] Plots were rated weekly for defoliation in 1984, starting the seventh week after planting and continuing until the 15th week after planting ($X_7 \ldots X_{15}$).
[2] Regression equation is of the form $Y = Bo + B_1X_1 + B_2X_2 + \ldots + BnXn$.
[3] Square root of the mean sum of squares for error (standard deviation).
[4] Coefficient of determination.
[5] TNO represents the number of marketable tubers (1,000 per ha).
[6] TWT represents the weight of marketable tubers (1,000 kg per ha).
,* Significant at the 1% and 0.1% levels, respectively.

3.3.4 Phenological development

Development as recorded by growth stage was similar each year (Table 17), although not all growth stages were recorded for both cultivars in each year. Also, the individual stages were not necessarily completely distinct for either cultivar.

Leaf area index (LAI) of the cultivar Russet Burbank increased rapidly at the beginning of the season, reached a maximum about August 27, and then declined slightly (Figure 1). Number of leaves also reached a maximum level at this time (Figure 2). Both LAI and number of leaves of the cultivar Norland increased slightly, peaked the week of Aug. 13 and and decreased with maturity.

Regression equations relating LAI to time were highly significant for both cultivars (Table 18). The relationship between number of leaves of the cultivar Russet Burbank and time was also highly significant; however, a similar significant relationship for cultivar Norland was not found.

Tuber set began in the second and third weeks of July in the cultivar Russet Burbank, as the first sampling produced a few bud-like enlargements at the end of stolons. The cultivar Norland initiated tuber development sometime previous to this, because at the first sampling small tubers were present. Tuber weight of both cultivars increased each week until the final sampling in September and average weight of the cultivar Norland was always greater than that of the cultivar Russet Burbank (Figure 3). Quadratic regression of time and tuber weight gave close-fitting curves for both cultivars. A highly significant relationship was found between weight and LAI and weight and number of leaves for the cultivar Russet Burbank, but these relationships were not significant for the cultivar Norland (Table 18).

TABLE 17. Phenological development of potato cultivars Russet Burbank and Norland: Portage la Prairie, 1983,1984.

RUSSET BURBANK DATE 1983	RUSSET BURBANK DATE 1984	GROWTH STAGE[1]	NORLAND DATE 1983	NORLAND DATE 1984
25 MAY	29 MAY	PLANTING	26 MAY	30 MAY
12 JUNE	18 JUNE	50% EMERGENCE	19 JUNE	22 JUNE
19 JUNE	22 JUNE	100% EMERGENCE	23 JUNE	26 JUNE
27 JUNE	26 JUNE	ERECT (6-8" TALL)	27 JUNE	30 JUNE
18 JULY	----	FLOWER BUD	18 JULY	16 JULY
02 AUG	16 JULY	50% BLOOM	----	----
----	30 JULY	FULL BLOOM	02 AUG	23 JULY
16 AUG	07 AUG	PAST FULL BLOOM	----	30 JULY
23 AUG	20 AUG	FULL GROWN	09 AUG	07 AUG
30 AUG	27 AUG	MATURE	16 AUG	20 AUG
----	----	DIEBACK	30 AUG	03 SEPT

[1] Not all growth stages were visible for each variety each year, nor were all stages completely distinct from other stages.

Figure 1: Mean leaf area index and regression of leaf area index with time in weeks.
A) Cultivar Russet Burbank.
B) Cultivar Norland.

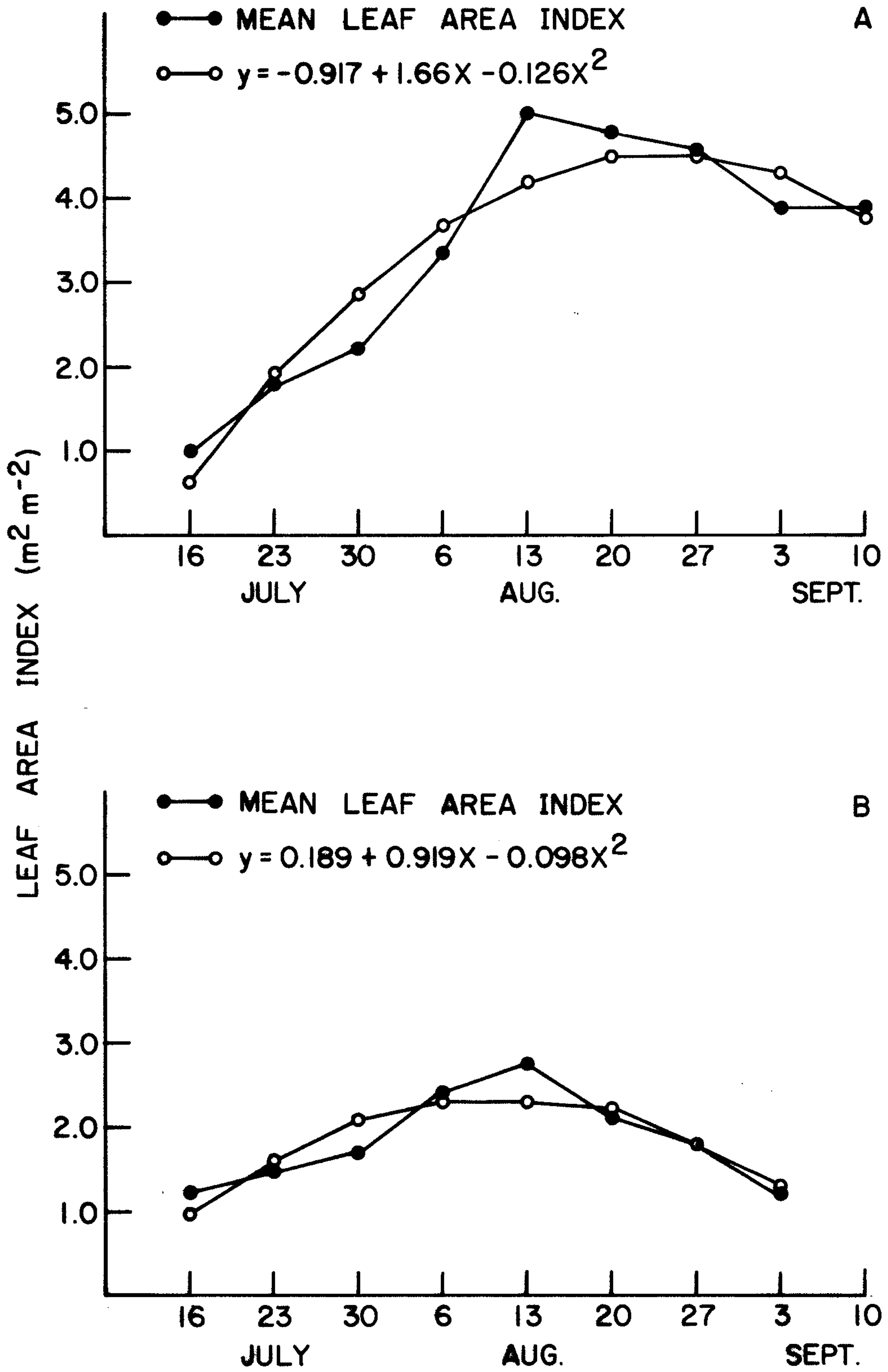

MEAN LEAF AREA INDEX
$y = -0.917 + 1.66X - 0.126X^2$
A
MEAN LEAF AREA INDEX
$y = 0.189 + 0.919X - 0.098X^2$
B
LEAF AREA INDEX ($m^2\ m^{-2}$)
1.0
2.0
3.0
4.0
5.0
16
23
30
6
13
20
27
3
10
JULY
AUG.
SEPT.

Figure 2: Mean number of leaves (per square meter) and regression of number of leaves with time in weeks.

A) Cultivar Russet Burbank.
B) Cultivar Norland.

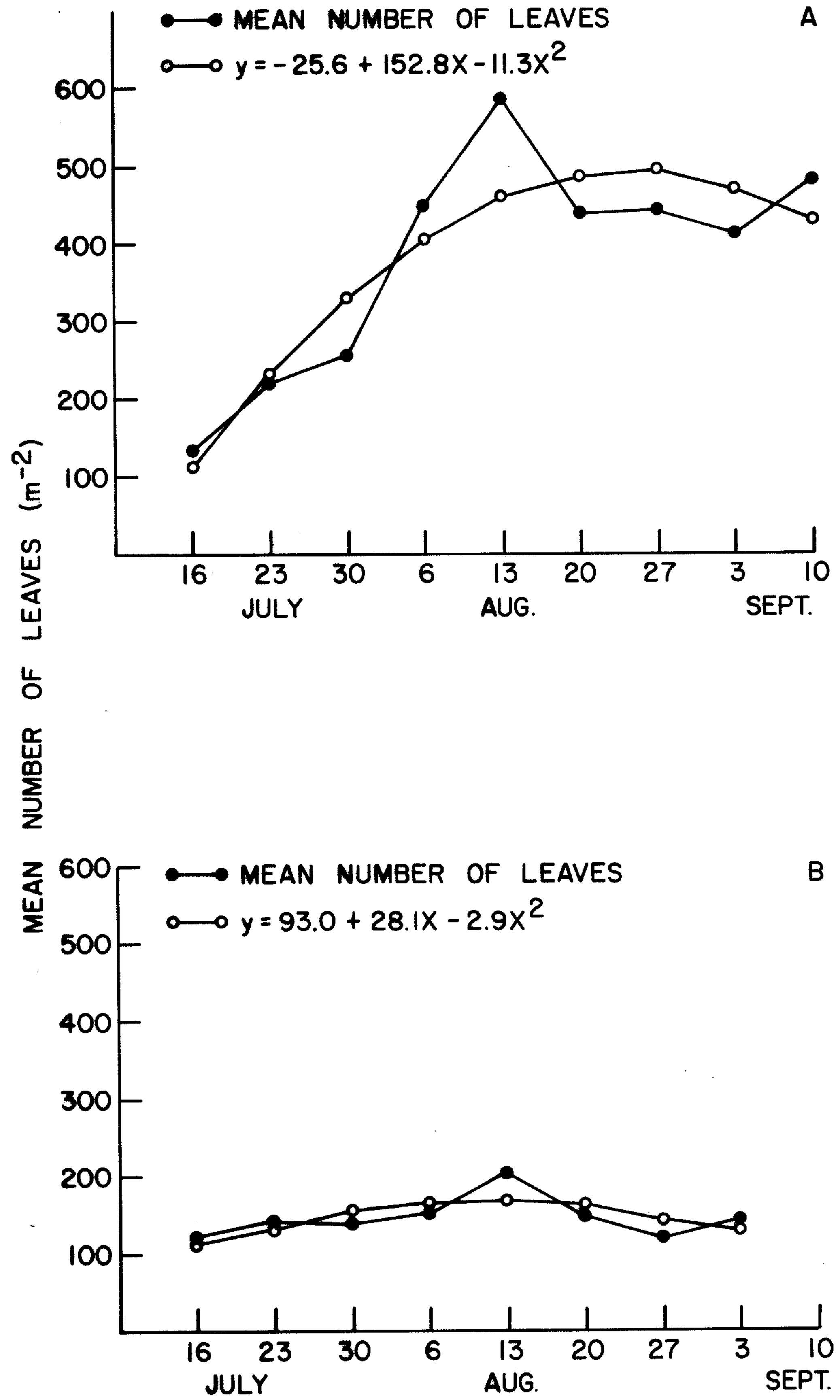

MEAN NUMBER OF LEAVES
$y = -25.6 + 152.8X - 11.3X^2$
A
600
500
400
300
200
100
16
23
30
6
13
20
27
3
10
JULY
AUG.
SEPT.
MEAN NUMBER OF LEAVES (m^{-2})
MEAN NUMBER OF LEAVES
$y = 93.0 + 28.1X - 2.9X^2$
B
600
500
400
300
200
100
16
23
30
6
13
20
27
3
10
JULY
AUG.
SEPT.

TABLE 18. Regression equations relating various phenological parameters to time and tuber weight: Portage la Prairie, 1984.

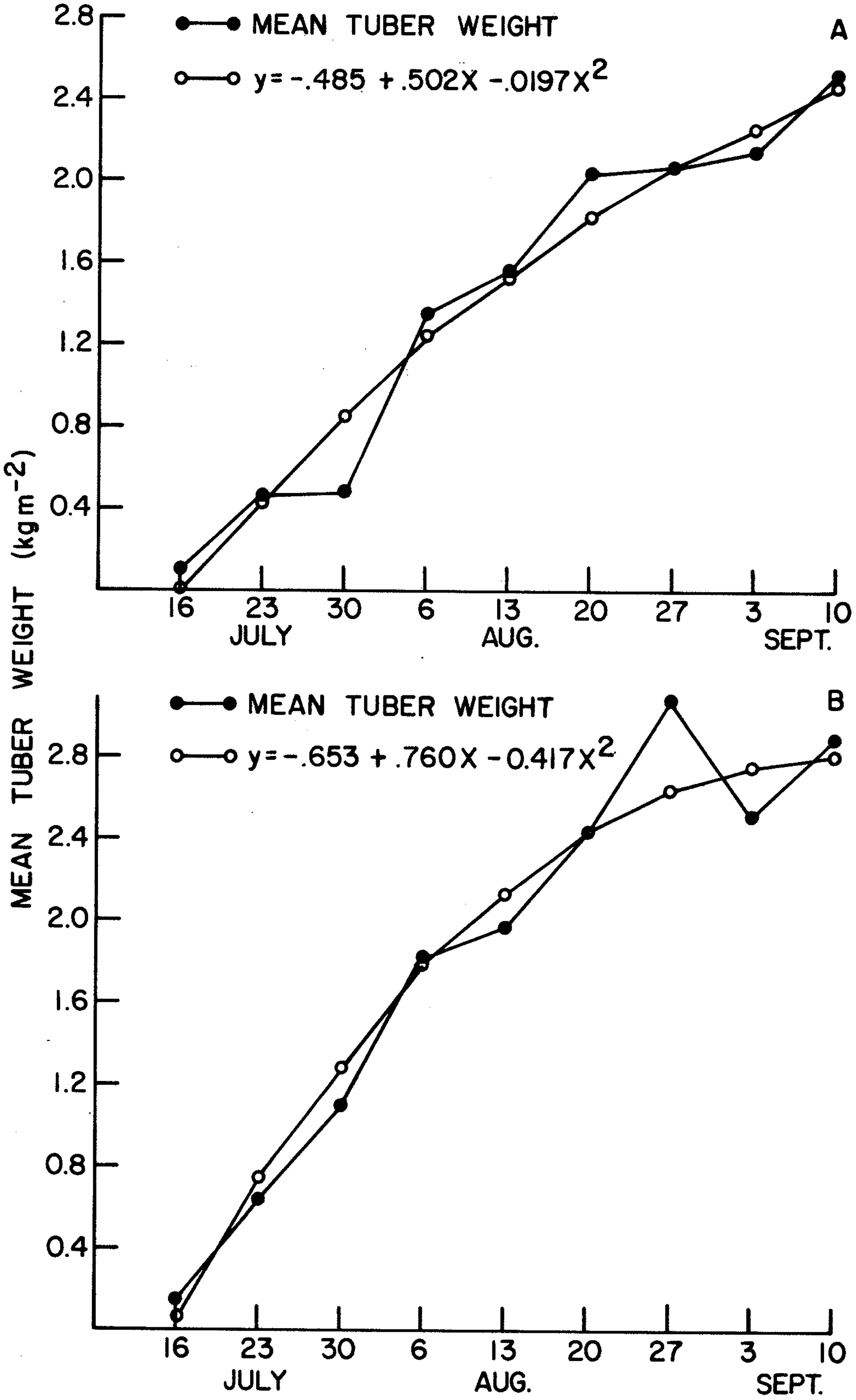
VARIETY	REGRESSION MODEL	REGRESSION EQUATION[1]	F VALUE	R SQUARE[2]	C.V.[3]
Russet Burbank	LAI[4] = TIME[5] + (TIME*TIME)	$Y = -0.917 + 1.66X - 0.126X^2$	49.64***	0.869	15.9
Norland	LAI = TIME + (TIME*TIME)	$Y = 0.189 + 0.919X - 0.0978X^2$	18.59***	0.741	16.4
Russet Burbank	# LEAVES[6] = TIME + (TIME*TIME)	$Y = -25.6 + 152.8X - 11.33X^2$	24.52***	0.766	19.4
Norland	# LEAVES = TIME + (TIME*TIME)	$Y = 93.0 + 28.1X - 2.91X^2$	0.91	0.123	28.6
Russet Burbank	WEIGHT[7] = TIME + (TIME*TIME)	$Y = -484.9 + 502.5X - 19.66X^2$	70.07***	0.959	14.4
Norland	WEIGHT = TIME + (TIME*TIME)	$Y = -652.7 + 760.1X - 41.72X^2$	96.0***	0.970	10.9
Russet Burbank	WEIGHT = LAI	$Y = -384.2 + 523.8X$	21.55**	0.755	32.6
Norland	WEIGHT = LAI	$Y = 454.0 + 681.9X$	0.97	0.139	57.6
Russet Burbank	WEIGHT = # LEAVES	$Y = -397.0 + 4.75X$	28.44***	0.640	37.4
Norland	WEIGHT = # LEAVES	$Y = 160.0 + 0.70X$	0.01	0.001	58.6

[1] Regression equation is of the form $Y = B_0 + B_1X_1 + B_2X_2 + ... + BnXn$.
[2] Coefficient of determination.
[3] Coefficient of variation.
[4] LAI represents the leaf area index.
[5] TIME represents the time in weeks.
[6] # LEAVES represents the number of leaves per meter^2.
[7] WEIGHT represents the tuber weight in grams.
*,**,*** Significant at the 5%, 1%, and 0.1% levels, respectively.

Figure 3: Mean tuber weight per square meter and regression of tuber weight with time in weeks.

A) Cultivar Russet Burbank.

B) Cultivar Norland.


A
MEAN TUBER WEIGHT
y=-.485 + .502X -.0197X2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
16
23
30
6
13
20
27
3
10
JULY
AUG.
SEPT.
MEAN TUBER WEIGHT (kg m-2)
B
MEAN TUBER WEIGHT
y=-.653 + .760X - 0.417X2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
16
23
30
6
13
20
27
3
10
JULY
AUG.
SEPT.

3.4 DISCUSSION

3.4.1 Yield

'Marketable' weight was the weight variable used in this trial because it was the variable most closely resembling weight values associated with commercial production, as suggested by James (1974). Total weight included too many small potatoes which would not have been picked up with commercial harvesters.

In 1983 there were no significant yield differences with respect to treatment for either cultivar. Disease intensity was extremely low and fertility levels were high, thus all treatments grew vigorously. Research performed by Basu (1974) and Harrison et al (1965a,b) also lacked significant yield losses when they relied on natural infection to increase disease levels on tomatoes and potatoes, respectively.

In 1984 trends toward reduced yield as early blight intensity increased were apparent although insignificant for the cultivar Russet Burbank. Other researchers also found spraying controlled disease, but gave no direct significant yield benefit (Easton and Nagle, 1985; Harrison et al, 1965b,c). Disease severities in 1984 were low, with the average per treatment always less than 15%. Leaf area index remained well above one for the whole period of bulking. Perhaps this led to a constant bulking rate in all treatments (Milthorpe, 1963; Milthorpe and Moorby, 1979) and was the reason disease had little effect on yield.

In 1984 the cultivar Norland had significant increases in both weight and number of tubers with weekly spraying. These results are in accordance with the results of Haware (1971), Harrison and Venette (1970), Douglas and Groskopp (1974), and Teng and Bissonnette (1985a). Higher disease severity affected yield: stressed plants set fewer tubers or reabsorbed previously set tubers (Milthorpe and Moorby, 1979) and also yielded less with respect to weight. Trends toward heavier yields when fungicide controlled disease were evident, but were significant only for the Norland cultivar in 1984 when infection became epidemic. This may suggest that a certain threshold level of disease (Zadoks and Schein, 1979) is permissible. Verification of this hypothesis and determining what levels are permissible would require analysis of results from many more yield trials.

In 1984 tuber set on the cultivar Russet Burbank began in the latter part of July, corresponding to the time period shortly before full bloom. Initiation of tuber set on the cultivar Norland occurred slightly earlier, also corresponding to the time period shortly before its full bloom stage. A stress-inducing fungal inoculation at this point could have had significant effects on yield because usually only tubers set during this initial period reach marketable size (Moorby, 1978). _A_. _solani_ inoculation took place during the third week of July.

In both years the average yield of the Norland cultivar surpassed that of the Russet Burbank cultivar, contrary to the findings of Teng and Bissonnette (1985a). However, the Norland cultivar was well into dieback by the end of August, while the other cultivar had just reached maturity. By the beginning of September the LAI of the Russet Burbank cultivar was still near its peak, at approximately 4.5, while the LAI of the Norland cultivar had fallen to approximately one, under which point the tuber growth decreases (Milthorpe and Moorby, 1979). Finally, the tuber growth of the Russet Burbank cultivar, as described by regression, was increasing, while that of the

Norland cultivar was reaching a limit. Lacroix (1984, personal communication) found that the Russet Burbank cultivar can have as much as a 50% increase in yield weight from the second week in September until the end of September in Manitoba. These data point to the Russet Burbank cultivar having a potentially higher yield than the Norland cultivar, in support of Teng and Bissonnette (1985a). In both years, however, both cultivars were harvested in mid-September.

3.4.2 Disease

Neither phytotoxic nor beneficial effects were observed as a result of spraying with Dithane M-45 (mancozeb). If there were such effects on these cultivars, the effects should have been apparent in 1983 when there was little disease pressure, but spraying was carried out regardless. Callbeck (1969a,b) found similar results.

Factors influencing amount of disease included inoculum levels, host susceptibility, and environmental conditions. Prior to 1983 potatoes had not been grown on the experimental site for at least five years. Each year the experiments were conducted on summer fallow; therefore, debris was minimal, possibly reducing initial inoculum loads. Airborne inoculum from nearby fields may have contributed particularly to initial disease symptoms in both years. In 1984 inoculation increased disease levels in plots receiving inoculations, but even in uninoculated plots disease levels were higher. This may be partly due to interplot interference (James et al, 1973). Although inoculum was applied on a virtually windless evening, once the inoculum dried, it may have been blown into uninoculated plots. Also, more lesions produced as a result of the inoculation would have produced more spores, increasing the secondary inoculum load. Waggoner (1962) found that after infection was present in a field, there was a higher chance of infection from within the field than from another field.

Host susceptibility may have been affected by fertility levels. All plots were planted on summer fallow and received fertilizer at planting. In 1983 a much higher level of fertilizer was applied and plants were particularly vigorous. Studies have shown early blight to be nutrition-related (Barclay et al, 1973; Horsfall and Heuberger, 1942b; Jones and Darling, 1953; Soltanpour and Harrison, 1974; Thomas, 1948). Increased fertility, particularly high nitrogen levels, may have delayed plant maturity (Tisdale and Nelson, 1975), thus allowing for an argument of juvenile resistance (Harrison et al, 1965b; Lana et al, 1976) and increased time for meristematic activity (Barclay et al, 1973; Stavely and Slana, 1971), or delayed senescence (Harrison et al, 1965b; Hooker, 1981; Lana et al, 1976; Soltanpour and Harrison, 1974) to explain the low disease intensities.

In 1984 the plants were less vigorous although according to soil test results adequate fertilizer was applied. Disease intensity was higher in both cultivars; however, the disease gradient in the cultivar Norland was much greater. The difference in susceptibility was possibly related to the earlier physiological maturity of the early cultivar Norland, as Horsfall and Heuberger (1942b), Pound (1951), and Barratt and Richards (1944) found for tomato. Perhaps with one inoculation the cultivar Russet Burbank would become as diseased as the cultivar Norland, if the inoculation were to take place when both cultivars were at a similiar stage of maturity. However, there is little flexibility for planting dates in Manitoba; in late-July the two cultivars will usually be at different maturity levels. Douglas and Pavek (1972) and Abdel-Rahman (1979) also indicated early-maturing potato cultivars were more susceptible to early blight than later-maturing cultivars.

Inoculation took place in late July, often when natural infection is first noted in fields in Manitoba. Within two weeks evidence of the inoculation was apparent on both cultivars. The leaf area indices of the two cultivars were similar at inoculation; however, during the incubation period of the disease, the LAI of the Russet Burbank cultivar increased to almost 3.5, while the LAI of the Norland cultivar increased to only 2.5. The peak LAI of both cultivars occurred during the third week after inoculation, when the LAI of the Russet Burbank cultivar reached a value above 5, while the LAI of the Norland cultivar remained below 3. Thus, the Russet Burbank cultivar may have had a better chance of 'outgrowing' the disease.

Environmental differences may also account for varying amounts of disease during the two years; however, environment will be discussed in the following paper.

3.4.2.1 Incidence

Weekly sprayed plots generally had a lower percent incidence longer than other plots. This was expected because Dithane M-45 has some residual activity, but is protective, not eradicant.

The relationship between yield and incidence was significant in 1984, but incidence was a poor indicator of yield. Incidence was easily rated and was very objective (Horsfall and Heuberger, 1942a); however, a level of 100% was reached well before the end of the season. Therefore, other factors could have contributed to yield loss after the time 100% incidence was reached.

3.4.2.2 Severity

In 1983 disease severity in all plots was less than 2%. In general plots sprayed four times and weekly throughout the season had significantly less disease than other plots. However, because the level of disease was very low the significance of the difference is of questionable value. The assessment key did not differentiate between size of plants and host size may differ between cultivar or stage of growth. For example, individual plants of the cultivar Russet Burbank were larger than those of the cultivar Norland and although planting density was higher in the cultivar Norland, the LAI of the cultivar Russet Burbank was greater; at peak levels of LAI, the ratio of size was approximately 2:1. Low severities were rated as number of lesions per plant; however, if 10 lesions on a small young plant constituted 1% disease, surely that number of lesions on larger, older plants did not also represent 1% disease. Ratio of leaf area indices could be as high as 5:1 for older Russet Burbank plants compared to younger plants.

In 1984 the wide range of disease severity was due partly to inoculation. Weekly sprayed plots generally had significantly less disease than unsprayed plots; this showed spraying had a positive effect. The relationship between disease severity and yield was also significant; for the cultivar Russet Burbank approximately 30% of the variation in yield was explained; for the cultivar Norland, which had a wide range of severity and suffered heavy yield losses, severity was a good predictor, explaining over 60% of the variation in yield. Increments of disease severity explained similar amounts of variation in yield for both cultivars. Teng and Bissonnette (1985b,c) found three-variable multiple regression equations using early blight severity or severity increments explained over 70% of the variation in weight of US# 1 potatoes of both cultivars.

Although multiple regression equations were statistically significant in many cases, for some disease variables when the values were changed just slightly, there was a large effect on yield. In natural situations a very small increase in disease is unlikely to alter yield significantly. Both James et al (1972), working with late blight, and Teng and Bissonnette (1985b), working with early blight, used subjective analysis along with statistical analysis to counteract this effect. The three criteria James et al used included a small residual mean square, no single disease increment had a net effect of increasing tuber yield, and no single disease increment had so large a net effect on estimated yield that a small change in the value would greatly alter predicted yield loss. Teng and Bissonnette performed a tolerance check on size and range of values for each variable to delete redundant material or variables with potentially large net effects. The positive effect of some variables on yield or the tremendous net effect of a single variable on yield probably stems from a variety of factors including a single heavy inoculation and significance of results from only one year.

3.4.2.3 Defoliation

Defoliation was a good yield predicting variable for the cultivar Russet Burbank; it significantly explained almost 50% of the variation in yield. Defoliation was as good a predictor as severity in determining yield loss for the cultivar Norland.

One stem or leaf petiole lesion may have more effect than one lesion on a leaf; this was unaccounted for in the severity rating. However, when a leaf dropped off due to any lesion, it was accounted for in the defoliation ratings. Other problems, in addition to early blight, may have also affected the level of defoliation.

3.4.3 Growth

Analysis of growth stage data revealed that the cultivar Norland was full grown two weeks earlier than the Russet Burbank cultivar. Both leaf area index data and leaf number data from 1984 also indicated that the cultivar Norland reached maturity two weeks earlier than the cultivar Russet Burbank. The latter methods were more useful, however, because the growth stage data were not completely distinct, and were somewhat subjective.

The fact that tuber weight was significantly related to the leaf area index of the cultivar Russet Burbank was expected because of the significant relationships of both LAI and time and weight and time. Moorby (1978) reported that linear relationships between leaf area duration and tuber yield were poor unless all LAI above three were presumed to be three. This same relationship was not significant for the cultivar Norland, whose leaf area index was always less than three during the season.

3.5 SUMMARY

No significant differences for weight or number of either cultivar were obtained in 1983, where disease levels were extremely low.

A field trial was conducted in 1983 and 1984 to evaluate the effects of early blight on yield of two potato cultivars, Russet Burbank and Norland. In 1984 after inoculum was applied to half the plots, disease levels increased in most plots of both cultivars, although to a much higher level in the early maturing cultivar, Norland. No significant differences in yield were obtained for the Russet Burbank cultivar; however, for the cultivar Norland, weekly sprayed plots significantly outyielded other plots. Inoculation affected disease severity of both cultivars significantly, but significant interaction effects between inoculation and fungicide treatment were evident only for the cultivar Norland. There were no significant interaction effects on yield for either cultivar. The effects of inoculation were visible within two weeks.

Regression of yield with defoliation explained close to 50% of the variation in yield of the cultivar Russet Burbank, while regression with disease severity or defoliation explained over 60% of the variation in yield of the cultivar Norland.

Leaf area index of both cultivars increased to a peak in mid-August and then declined with maturity. LAI of the Russet Burbank cultivar was generally higher than the LAI of the Norland cultivar. LAI of the Russet Burbank cultivar increased dramatically after inoculation, while the LAI of the cultivar Norland increased to a lesser extent.

Chapter IV

EPIDEMIOLOGY OF EARLY BLIGHT OF POTATOES IN MANITOBA

4.1 INTRODUCTION

Throughout the years a variety of weather conditions have been considered responsible for the promotion of early blight (Harrison et al, 1965a; Moore, 1942; Rands, 1917; Whetzel, 1923). Harrison et al (1965a) illustrated the variety of conditions when they observed the disease severity to be as great in a cool dry year as in a warm moist one.

The most important environmental factors affecting early blight are temperature and moisture. Each phase of the lifecycle has its own optimum conditions. For hyphal growth, germination, and germ tube development the optimum temperature was 28°C, while for production of appressoria, conidia, and conidiophores the optimum was only 22°C (Horsfall and Lukens, 1971). Potato foliage infection could occur within four hours at 25°C, eight hours at 15°C, or twelve hours at 10°C (Bashi and Rotem, 1974; Rotem and Reichert, 1964). Munnecke et al (1959) reported that the minimum relative humidity required for germination of *A. solani* spores was 87%. Rotem and Reichert (1964) reported, however, that below 96% relative humidity the rate of germination was extremely low; thus, they indicated free water was essential for foliage infection. Spore formation occurred in moist periods as well as in dry periods and was enhanced by the occurrence of short interrupted wet periods (Bashi and Rotem, 1975; Rands, 1917; Waggoner and Horsfall, 1969).

Spore dispersal was favoured by windy dry conditions or by periods of heavy rainfall (Nutter, 1978; Rotem, 1964; Waggoner and Horsfall, 1969).

Fungicide application is the most effective control measure when inoculum is present and environment is favourable for disease development (Madden *et al*, 1978). But because fungicide applications are expensive, from 6-16 dollars per acre (Campbell, 1983), researchers have searched for methods to reduce the number of applications required, while still maintaining effective control. A primary method is proper timing of the initial fungicide application. Recommendations include starting spraying when initial disease symptoms were present, before any signs of diseases were present usually just after flowering, as soon as flowering began, or when a high influx of spores was present (Feddersen, 1962; Harrison, 1965b,c; Henderson, 1962; Ohms and Fenwick, 1962). Another important method of reducing the number of fungicide applications is disease forecasting through disease and environmental monitoring. Madden *et al* (1978) published an early blight forecasting system which, when supplied with appropriate data, identified periods favourable for *A. solani* spore formation and infection of tomato. This program provided recommendations for initial and subsequent fungicide applications.

The purpose of this study was two-fold: to permit *Alternaria solani* to develop naturally on its potato host in order to gain further understanding in the relationship between host, pathogen, and environment, and from this relationship to determine factors suitable for running an efficient fungicide application schedule in Manitoba.

4.2 MATERIALS AND METHODS

Weekly ratings of early blight disease levels, twice-weekly ratings of Alternaria solani spore levels, and continuous monitoring of environmental conditions were performed at two locations in 1982,1983, and 1984. The early blight disease level was monitored with the aid of a disease assessment key (Anon., 1947; Fry, 1977) (Appendix A) and standard area disease diagrams (Granousky and Peterson, 1954) (Appendix B). Single plots of Russet Burbank potatoes were maintained in Graysville, Manitoba (Murta Farm) and in Portage la Prairie Manitoba (Vust Farm and University of Manitoba Field Substation at Portage la Prairie). At Murta Farm and Vust Farm plots were grown on land on which potatoes had been grown within the previous two years. At the University Station, however, no potatoes had been grown on the plots for at least five years. All cultural operations including planting, hilling, cultivations, and insecticide applications were carried out by the producers or in conjunction with the yield trial. No fungicide treatments were applied. These plots consisted of twelve twelve meter-long rows.

4.2.1 Spore trapping

A weather vane spore trap was placed in the plot at each location. The trapping surface consisted of two removable glass microscope slides covered with a thin coating of WD-40. Spores were trapped by impaction at a level of 152 cm above the ground. Slides were replaced two times per week and numbers of Alternaria solani spores on each slide were counted under a magnification of 100X. The number of spores was averaged for each location and was divided by the number of days the slides had been in the field to give an average daily spore count.

4.2.2 Environmental data

Environmental data recorded consisted of temperature, duration of leaf surface wetness, relative humidity, and rainfall. All environmental data were recorded on Bendix-Freeze hygrothermographs placed inside Stevenson screens at ground level within the plant canopy. The hygrothermographs were modified to accommodate a leaf wetness recorder and rainfall gauge (MacHardy and Sondej, 1981). The leaf wetness recorders were located separate from the Stevenson screens and were also placed within the plant canopy.

Two-hourly temperature readings were averaged over 24 hours to obtain average daily temperature values. These values were compared to the Environment Canada average daily temperatures derived from maximum and minimum values recorded at the standard height of approximately 1.2 meters. Environment Canada data were obtained from two nearby stations: Murta Farm at Graysville and the Canadian Forces Base at Portage la Prairie.

Time when leaves became wet through rainfall or dew and the duration of the leaf wetness were recorded and average temperature during the period of leaf wetness was determined. Two-hourly relative humidity (RH) readings were compared to similar readings recorded at standard height by Environment Canada at Portage la Prairie and regression analysis was performed to determine the relationship. Regression was also used to determine the relationship between the duration of leaf wetness and the hours of RH$\geq$90% and $\geq$85%.

4.2.3 'FAST' Program

An early blight forecasting system developed by Madden et al (1978) was examined for its potential use with potatoes under Manitoba growing conditions. Originally developed for use with tomatoes, the system was called FAST: Forecasting *Alternaria solani* on Tomatoes.

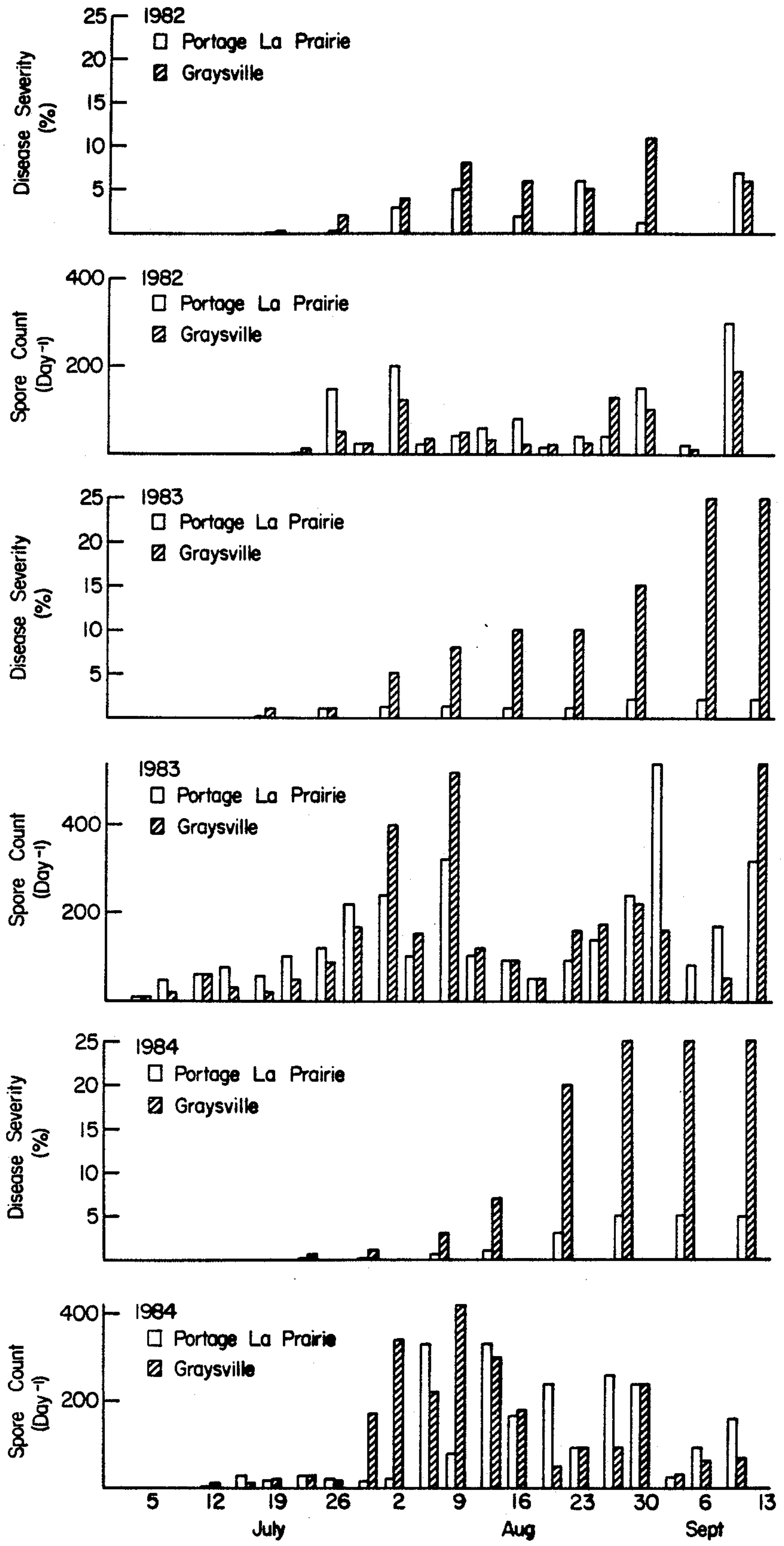
A computer program was fashioned after 'FAST' to evaluate environmental data recorded in the potato plant canopy. Severity values were created by comparing the periods of leaf wetness to average temperature during those periods, as determined by the matrix presented in Appendix C. Rating values were created by comparing temperature and rainfall with the number of hours of relative humidity ≥90% over five days (Appendix D). The value of relative humidity determining the rating value was also substituted with RH≥85% to test the importance of this variable. The necessity of a fungicide application was determined by severity values. Severity values were permitted to accumulate over the season until a level of 35 was reached, at which time the initial spray recommendation was given. At this point severity values were re-accumulated over seven days to create the cumulative severity value (CS value). Subsequent spray applications were recommended when the CS value reached a level of 14. Each time a spray recommendation was issued, the CS value was reset to zero.

The importance of the rating value was to determine whether five-day or seven-day spray schedules were necessary. Rating values were accumulated over five days to create the cumulative rating value (CR value). When a spray recommendation was issued on the basis of the CS value, a seven-day spray schedule was recommended if CR<9 and a five-day schedule was recommended if CR≥9.

4.3 RESULTS

Each year plots at Graysville were planted earlier than those at Portage la Prairie. Each year initial small influxes of spores appeared in mid-July at both locations (Figure 4). Increasing numbers of spores were trapped starting in late-July. Early blight became apparent around this point and increased gradually. Symptoms usually appeared sooner at Graysville and were more severe than at Portage la Prairie, although spore counts were similar. Lowest observable levels of disease were approximately 0.01%, as determined with the early blight assessment key. As the amount of disease increased, the percent severity was extrapolated from the assessment key and standard disease diagrams. Maximum severity observed in these plots was 25% disease. No major focal points of disease were identified; disease appeared uniformly throughout the plots.

Figure 4: Spore trapping results and progression of disease severity for Portage la Prairie and Graysville 1982, 1983, and 1984.


1982
□ Portage La Prairie
▨ Graysville
Disease Severity (%)
25
20
15
10
5
1982
□ Portage La Prairie
▨ Graysville
Spore Count (Day-1)
400
200
1983
□ Portage La Prairie
▨ Graysville
Disease Severity (%)
25
20
15
10
5
1983
□ Portage La Prairie
▨ Graysville
Spore Count (Day-1)
400
200
1984
□ Portage La Prairie
▨ Graysville
Disease Severity (%)
25
20
15
10
5
1984
□ Portage La Prairie
▨ Graysville
Spore Count (Day-1)
400
200
5
12
19
26
2
9
16
23
30
6
13
July
Aug
Sept

4.3.1 Environment

Eighty percent of the Environment Canada average daily temperature values were within ± 1.0 °C of the plant canopy average daily temperature values. Thus, when missing values were encountered in the plant canopy data, the Environment Canada values were substituted for both Portage la Prairie and Graysville.

Regression analysis was performed on the full range of values of relative humidity taken from the plant canopy data at Portage la Prairie with respect to their Environment Canada counterparts. A close-fitting relationship, on the basis of the coefficient of determination (R^2) and coefficient of variation (C.V.), was observed. However, the frequency of predicted values of RH≥85% was less than 60% of the frequency of observed values of RH≥85%. The upper ranges of relative humidity are the most important when considering Alternaria germination and infection. Therefore, plant canopy data from the upper ranges of relative humidity (RH≥75%) were regressed with their respective Environment Canada counterparts. Here the relationship fit well on the basis of coefficient of variation (Table 19). The frequency of RH≥85% and RH≥90% of the predicted values was 100% and 85%, respectively, of the original plant canopy data. When missing relative humidity values were encountered for the Portage la Prairie plant canopy data, new RH values, predicted from Environment Canada data using the 'RH≥75%' equation, were substituted.

Environment Canada relative humidity data were not available from the Graysville station. Regression equations, relating Graysville plant canopy data to Environment Canada data obtained from Portage la Prairie, were developed to predict relative humidity in Graysville (Table 19). However, be-

TABLE 19. Regression equations relating relative humidity in the plant canopy to relative humidity at standard height.[1]

SOURCE OF PLANT CANOPY DATA	REGRESSION EQUATION[2]	F VALUE	R SQUARE[3]	C.V.[4]	ROOT MSE[5]
Portage RH>75%	P = 61.32 + 0.315S	219.27***	0.337	6.6	5.72
Graysville	P = 32.02 + 0.733S	190.64***	0.501	14.9	12.87

[1] Relative humidity data recorded at standard height were recorded by Environment Canada, Portage la Prairie, 1982,1983, and 1984.

[2] Regression equations are of the form P = B0+ B1* S1 where the variable P is the plant canopy RH and S is the standard height RH.

[3] Coefficient of determination.

[4] Coefficient of variation.

[5] Square root of the mean of the sum of squares for error.

*** Significant at the 0.1% level.

cause the periods of missing data from Graysville were so frequent, missing values were not substituted with predicted values.

A significant relationship occurred in most cases between relative humidity variables, hours of $Rh \geq 90\%$ and hours of $Rh \geq 85\%$, and the duration of leaf surface wetness (Table 20). For most combinations of location-years, the fit was rather poor; the coefficients of determination (r^2) were quite low, less than 0.35, and the coefficients of variation were quite high, often greater than 60.

Environmental data are depicted in relation to disease severity in figures 5, 6, 7, 8, 9, 10. Leaf wetness data recorded in 1983 for both locations were inaccurate due to equipment malfunction and therefore, have been deleted.

The growing season in 1983 was much warmer than in either of the other years. For both locations, the number of "hot" days, where the average daily temperature was greater than 20°C, exceeded 50 days, while in 1982 and 1984 the number of days was less than 30 and 40, respectively. The number of "hot" days at Portage la Prairie in 1983 exceeded the number at Graysville by almost 20 days and there were almost 10 more days where average temperature was greater than 25°C at Portage la Prairie than at Graysville.

During each year at both locations there were several days with five or more hours where relative humidity was greater than or equal to 90%. There were relatively few days, however, with more than 20 hours of relative humidity greater than 90%. The location-year, Graysville-1984, had more of these days than other location-years.

TABLE 20. Regression equations depicting the relationship betweeen duration of leaf surface wetness and hours of high relative humidity (RH≥90% and RH≥85%).

RH VARIABLE	LOCATION[1]	REGRESSION EQUATION[2]	F VALUE	R SQUARE[3]	C.V.[4]	ROOT MSE[5]
RH≥90%	P82,G82,P84,G84	$Y = 7.70 + 0.311X$	25.71***	0.101	63.8	6.06
RH≥85%	P82,G82,P84,G84	$Y = 5.82 + 0.427X$	57.23***	0.204	60.0	5.73
RH≥90%	P82,P84	$Y = 6.97 + 0.172X$	2.79	0.024	84.2	6.53
RH≥85%	P82,P84	$Y = 5.08 + 0.337X$	14.97***	0.117	80.1	6.21
RH≥90%	G82,G84	$Y = 8.83 + 0.347X$	24.29***	0.177	46.1	5.18
RH≥85%	G82,G84	$Y = 6.98 + 0.464X$	48.52***	0.308	41.5	4.74

[1] Locations were Portage la Prairie 1982 (P82), Portage la Prairie 1984 (P84), Graysville 1982 (G82), and Graysville 1984 (G84).

[2] Regression equations are of the form $Y=B_0+B_1X_1$ where the variable Y is the predicted value for duration of leaf wetness and X is the RH variable.

[3] Coefficient of determination.

[4] Coefficient of variation.

[5] Square root of the mean sum of squares for error (standard deviation).

Figure 5: Progression of disease severity and various weather conditions with time: Graysville, 1982.

├─┤ refers to missing data.

A) Progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.
E) Hours of duration of leaf wetness per day.
F) Average ambient air temperature during the leaf wetness period.

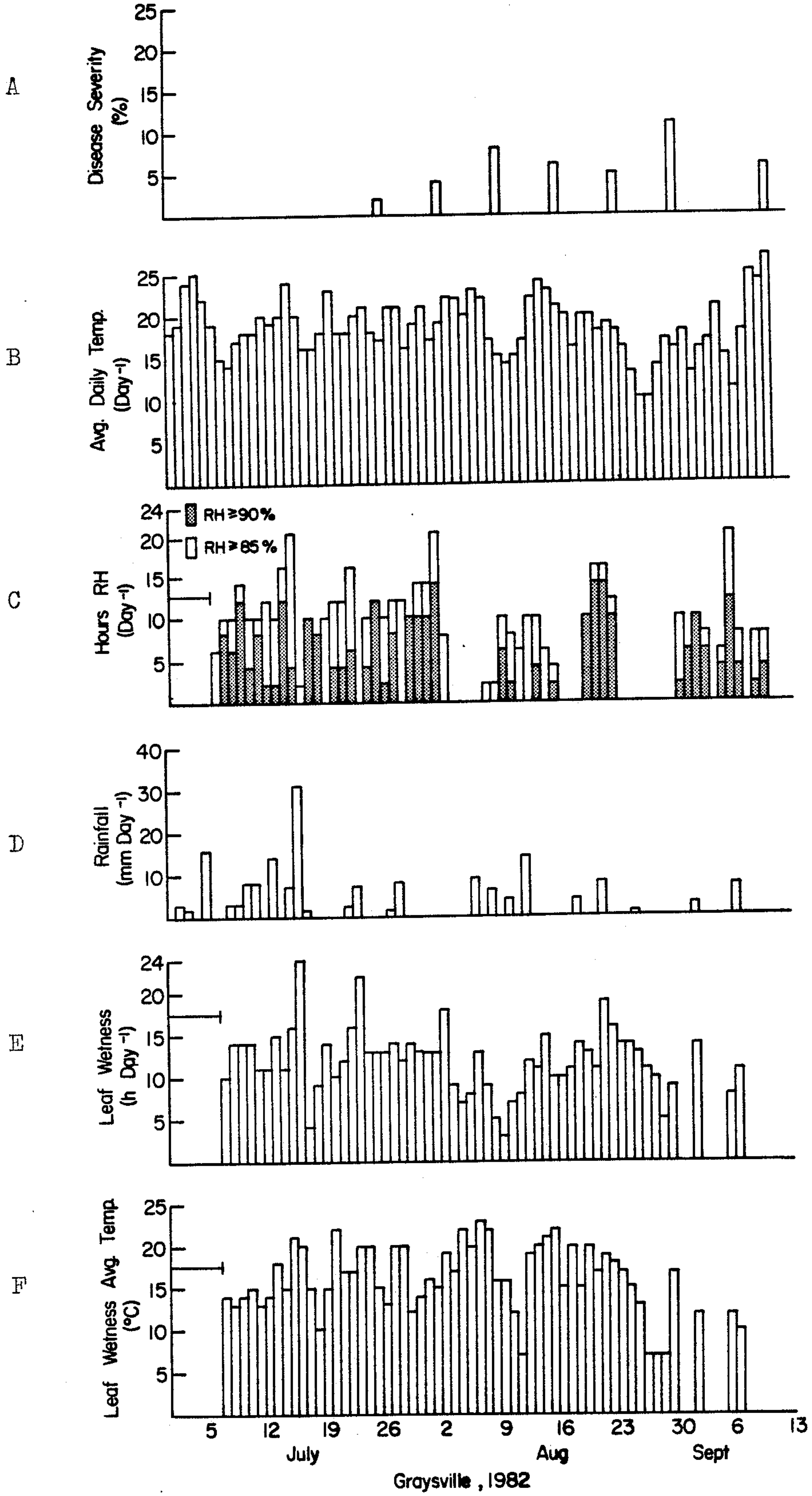

A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (Day-1)
24
20
15
10
5
RH≥90%
RH≥85%
D
Rainfall (mm Day-1)
40
30
20
10
E
Leaf Wetness (h Day-1)
24
20
15
10
5
F
Leaf Wetness Avg. Temp. (°C)
25
20
15
10
5
5
12
19
26
2
9
16
23
30
6
13
July
Aug
Sept
Graysville, 1982

Figure 6: Progression of disease severity and various weather conditions with time: Portage la Prairie, 1982.
├─┤ refers to missing data.
A) Progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.
E) Hours of duration of leaf wetness per day.
F) Average ambient air temperature during the leaf wetness period.

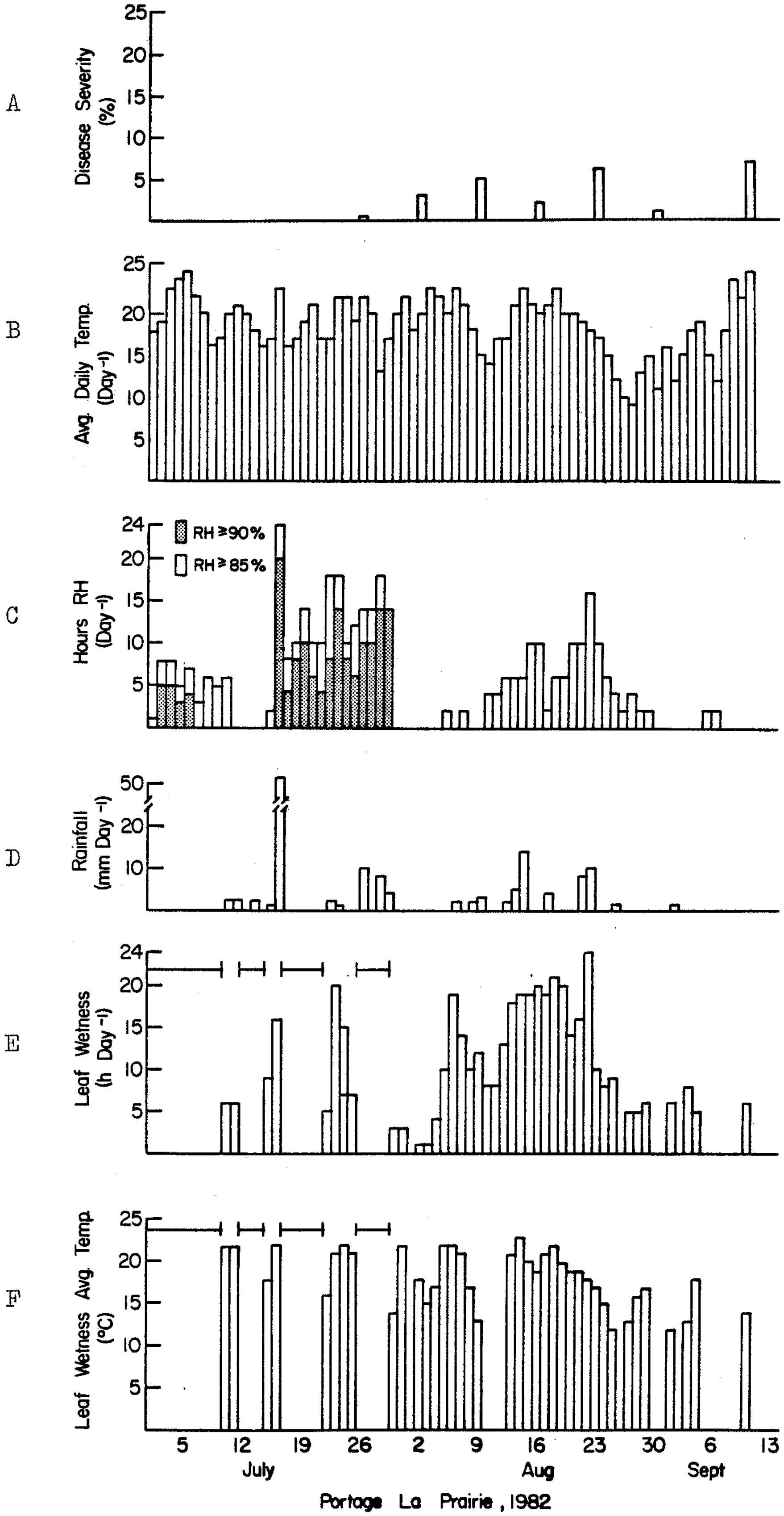

A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (Day-1)
24
20
15
10
5
RH ≥90%
RH ≥85%
D
Rainfall (mm Day-1)
50
20
10
E
Leaf Wetness (h Day-1)
24
20
15
10
5
F
Leaf Wetness Avg. Temp. (°C)
25
20
15
10
5
5
12
19
26
2
9
16
23
30
6
13
July
Aug
Sept
Portage La Prairie, 1982

Figure 7: Progression of disease severity and various weather conditions
with time: Graysville, 1983.
├─┤ refers to missing data.
A) Progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.

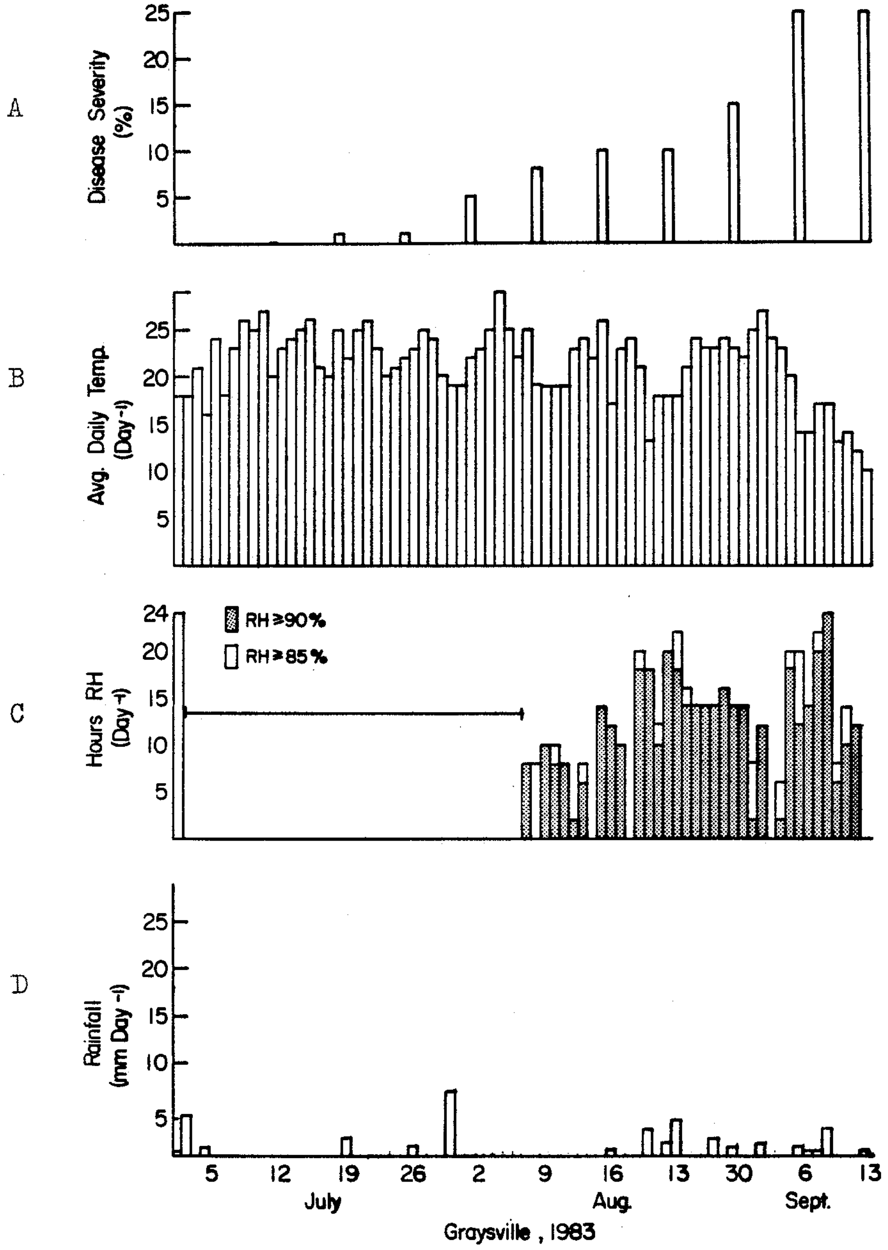

A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (Day-1)
24
20
15
10
5
RH ≥90%
RH ≥85%
D
Rainfall (mm Day-1)
25
20
15
10
5
5
12
19
26
2
9
16
13
30
6
13
July
Aug.
Sept.
Graysville, 1983

Figure 8: Progression of disease severity and various weather conditions with time: Portage la Prairie, 1983.

├─┤ refers to missing data.

A) Progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.

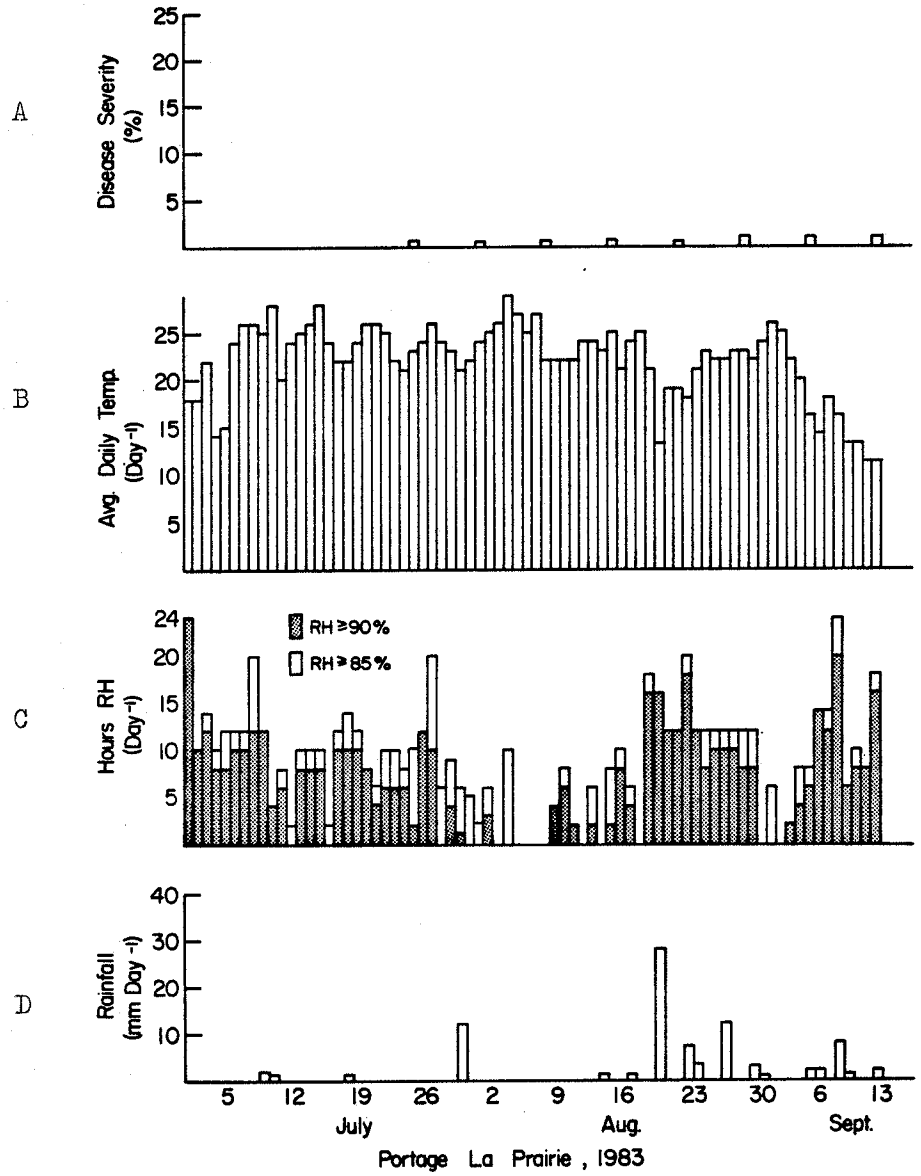

A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (Day-1)
24
20
15
10
5
▨ RH ≥90%
☐ RH ≥85%
D
Rainfall (mm Day -1)
40
30
20
10
5
12
19
26
2
9
16
23
30
6
13
July
Aug.
Sept.
Portage La Prairie, 1983

Figure 9: Progression of disease severity and various weather conditions with time: Graysville, 1984.
|—| refers to missing data.
A) progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.
E) Hours of duration of leaf wetness per day.
F) Average ambient air temperature during the leaf wetness period.

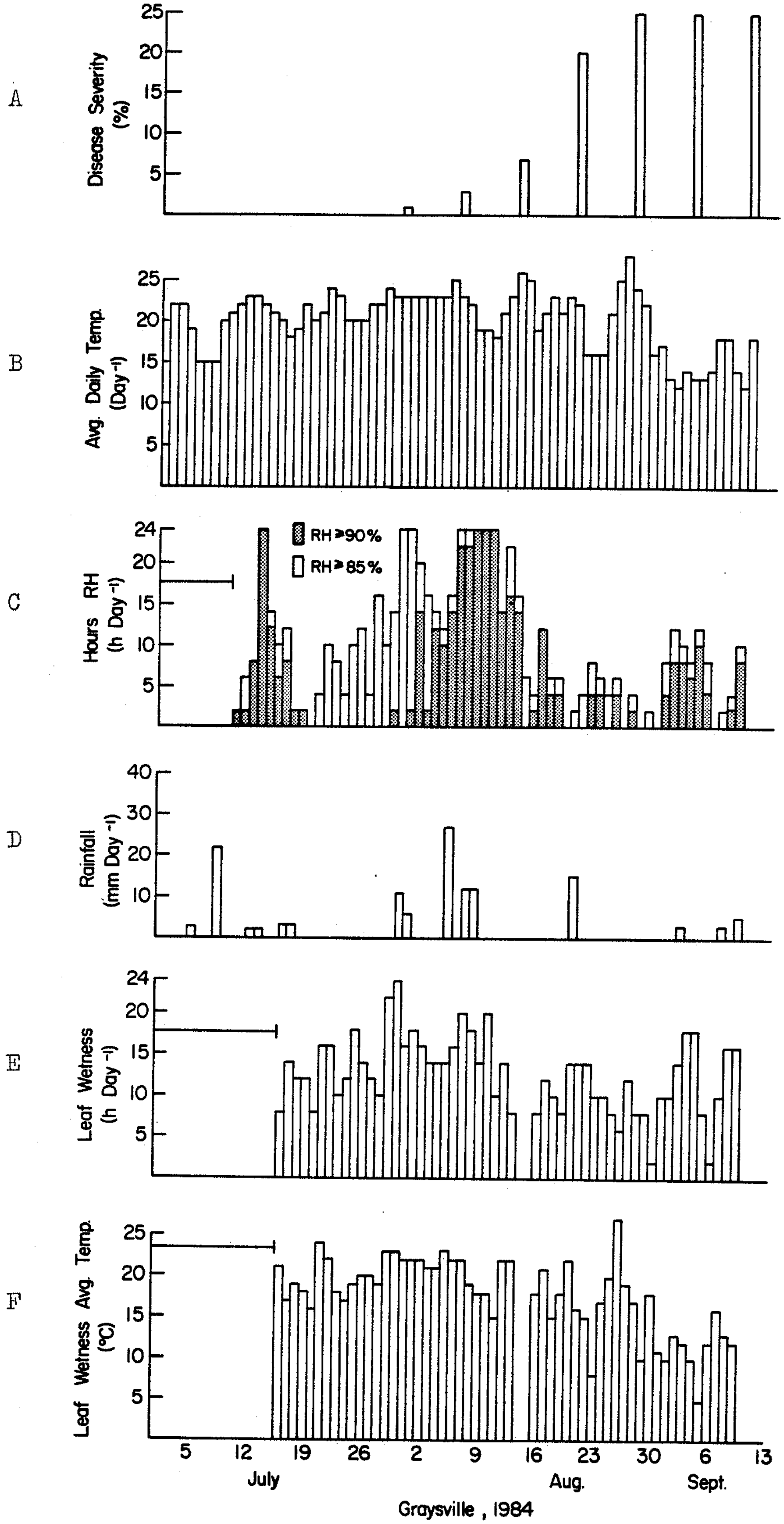
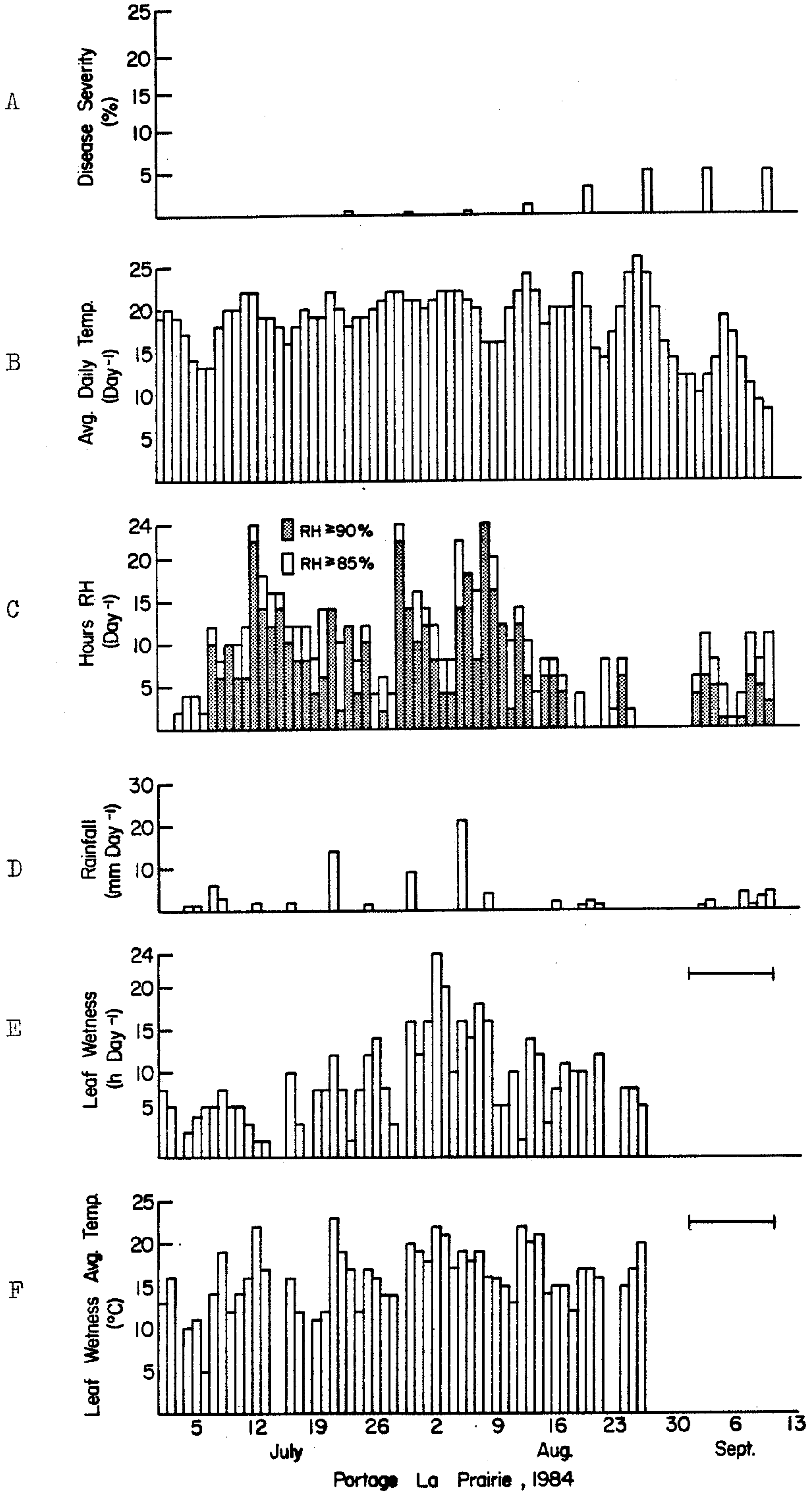

A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (h Day-1)
24
20
15
10
5
RH≥90%
RH≥85%
D
Rainfall (mm Day-1)
40
30
20
10
E
Leaf Wetness (h Day-1)
24
20
15
10
5
F
Leaf Wetness Avg. Temp. (°C)
25
20
15
10
5
5
12
19
26
2
9
16
23
30
6
13
July
Aug.
Sept.
Graysville, 1984

Figure 10: Progression of disease severity and various weather conditions with time: Portage la Prairie, 1984.
├─┤ refers to missing data
A) Progression of disease severity.
B) Average daily temperature.
C) Hours per day of relative humidity >85% and >90%.
D) Daily rainfall.
E) Hours of duration of leaf wetness per day.
F) Average ambient air temperatur during the leaf wetness period.


A
Disease Severity (%)
25
20
15
10
5
B
Avg. Daily Temp. (Day-1)
25
20
15
10
5
C
Hours RH (Day-1)
RH ≥90%
RH ≥85%
24
20
15
10
5
D
Rainfall (mm Day-1)
30
20
10
E
Leaf Wetness (h Day-1)
24
20
15
10
5
F
Leaf Wetness Avg. Temp. (°C)
25
20
15
10
5
5
12
19
26
2
9
16
23
30
6
13
July
Aug.
Sept.
Portage La Prairie, 1984

During each season 15-24 days of rainfall, usually much less than 10 mm each day, were recorded at each location.

At the Graysville plots in both the 1982 and 1984 seasons there were more than 30 days where a minimum of 10 hours of leaf wetness was recorded. At Portage la Prairie, however, there were only 16 or 17 days recorded with a minimum of 10 hours of leaf wetness. In all location-years there were at least 29 days where the average temperature during the leaf wetness periods was greater than 15°C.

4.3.2 'FAST' Results

Missing temperature and relative humidity data were substituted with Environment Canada data, as previously described. Data from 1983 are not presented due to the inaccuracies of the leaf wetness data which form the basis for the 'FAST' spray recommendations.

When the level of relative humidity determining the rating value was set at 90%, in all location-years only seven-day spray schedules were recommended on the basis of cumulative rating (CR) values. Accumulation of severity values was started in July of each year and at least one fungicide application was recommended for each location-year (Table 21).

When the level of relative humidity determining the rating value was changed from 90% RH to 85% RH, spray schedule at only one location-year was altered. On the basis of CR values, for Graysville, 1984, five-day spray schedules were recommended for two sprays. This altered the spray schedule, but the total number of recommended spray applications did not change. All other spray recommendations remained unaltered.

TABLE 21. 'FAST'-generated spray schedules for Portage la Prairie and Graysville, 1982 and 1984.

Week Starting	1982				1984			
	GRAYSVILLE		PORTAGE LA PRAIRIE		GRAYSVILLE		PORTAGE LA PRAIRIE	
	% Disease	Spray[1]	% Disease	Spray	%Disease	Spray	% Disease	Spray
9/07					0 %		0 %	
16/07	0.1%		0 %		0.01%		0 %	
23/07	2 %		1 %		0.05%	TS=37 CR=0	0.01%	
30/07	4 %	TS[2]=35 CR[3]=0	4 %		1 %	CS=22 CR=0	0.1%	
6/08	8 %		6 %	TS=36 CR=0	3 %	CS=18 CR=7	0.5%	TS=36 CR=1
13/08	6 %		3 %	CS=22 CR=0	7 %		1 %	
20/08	5 %	CS[4]=14 CR=1	7 %		20 %		3 %	
27/08	11 %		2 %		25 %		5 %	
3/09	--		--		25 %		5 %	
10/09	6 %		8 %		25 %		5 %	

[1] Spray recommendation was generated on the basis of total severity value (TS) and cumulative severity value (CS); cumulative rating value (CR) dictated whether a seven-day or five-day spray schedule was used.

[2] Critical level for total severity value-generated recommendation is TS>35.

[3] Critical level for 5-day spray schedule is CR>9; otherwise a 7-day schedule is used.

[4] Critical level for cumulative severity value-generated recommendation is CS>14.

The 'FAST' program recommended initial applications when disease severities ranged from less than one percent to about four percent and subsequent recommendations preceded assessed disease increases.

4.4 DISCUSSION

4.4.1 Spore Trapping

Variation in spore trapping results was due to several factors: wind speed, wind direction, other environmental factors, spores of other _Alternaria_ species, and varying production of _A. solani_ spores. Because weather vane spore traps relied on wind to carry the spores through the trap, the resultant impaction of spores could have been erratic and inaccurate. Volumetric spore traps, of the type described by Gadoury and MacHardy (1983) and Sutton and Jones (1976), which pull a prescribed amount of air past the trapping surface would have been more accurate. These traps would also have provided a picture of the total amount of spores per litre of air and variations of spore numbers throughout the day.

Similarities between various _Alternaria_ species may also account for variation in spore numbers. _Alternaria solani_ spores are quite similar in morphology to _A. brassicae_, _A. oleracea_, _A. linicola_, and several other _A. dauci_ forma speciales (Changsri and Weber, 1963; Joly, 1967), some of which may have been present in the area. Nearby fields of rapeseed and flax at both locations may have influenced the counts of _Alternaria_ spp. spores.

The arrival of spores in spore traps appeared to coincide loosely with the occurrence of moisture in the form of high relative humidity (RH>90) and leaf wetness. There was often a time lag ranging from half of a week to a full week before the numbers of spores increased. These data support Rands

(1917), Waggoner and Horsfall (1969), and Bashi and Rotem (1975) who found that spore production was enhanced by moisture.

Harrison et al (1965a) found most A. solani spores were liberated during daylight between the hours of 9:00 am and 3:00 pm. Environmental factors promoting liberation of spores were drying of leaves, heating of air creating updrafts, and wind (Rotem and Reichert, 1964; Waggoner and Horsfall, 1969). Spores were also liberated by rainfall; however, these spores would often be washed onto lower leaves or the ground and not into the air (Waggoner and Horsfall, 1969).

The fact that the number of spores increased dramatically near the end of July each year and that this increase remained apparent throughout the season supported Harrison's (1965a,b) hypothesis that the increase marked the start of the period of spread of secondary inoculum. He suggested that the spores trapped to this point were from sporulating lesions on debris left from the previous year. This also lent credence to Waggoner's (1979) hypothesis that spore production is based on a degree-day relationship, where temperature had additive effects on spore germination. These observations pointed to a recommendation that no fungicide sprays were necessary until this time (Harrison, 1965c). Before this time little inoculum would be available to infect the crop and a protective fungicide application with only limited residual activity would be useless, regardless of environmental conditions. A spray at this time, however, would protect the crop from the initial onslaught of secondary inoculum.

4.4.2 Disease

First visible disease symptoms were apparent on the crop close to the arrival of secondary inoculum. This information supported the view that no sprays were necessary until initial disease symptoms appeared (Hodgson *et al*, 1973; Lana *et al*, 1976; Nutter, 1978; Nutter and MacHardy, 1979; Ohms and Fenwick, 1961; Teng and Bissonnette, 1985a).

Amount of disease beyond this point was related more to other factors than spore levels. In 1983 the Portage la Prairie plot succumbed to only 2% disease when the Graysville plot had nearly 25% disease severity; spore numbers trapped, however, were similar.

No particular focal points starting the early blight infections were observed. Perhaps the wind borne *A. solani* spores landed evenly throughout the small plots. In the Graysville plots, even distribution of debris from previous years may also have accounted for the lack of a focal point of disease.

When using the assessment key, levels of disease under 1% severity were based on number of lesions per plant instead of percent area affected (Anon., 1947; Fry, 1977). Plant size was an important factor when considering accuracy at these low levels: on small plants the rating may have been too low and on large plants the rating may have been too high. Epidemiologically, the low levels were very important (Zadoks and Schein, 1979). Disease progression from 0.01% to 0.1% has undergone the same 10-fold increase as progression from 10% to 100%. When 50% disease is reached, the epidemic has reached the mid-time and the start of the terminal phase of the epidemic, during which time most of the damage is done to the crop and treatment is "next to useless" (Zadoks and Schein, 1979).

Throughout the entire three year study disease levels ranged from 0% to 25%. Disease control could have been achieved with fungicide application (Douglas and Groskopp, 1974; Harrison et al, 1965c; Harrison and Venette, 1970; Haware,' 1971; Teng and Bissonnette, 1985a), but profit from the increased yield due to the application must outweigh the costs of the chemical application to be of value (Jones, 1983; Zadoks and Schein, 1979).

4.4.3 Environment

An attempt was made to monitor environmental conditions within the plant canopy. When missing data were encountered data were acquired from other sources when possible, despite the fact that these new macroclimatic data would be less reliable (Hirst and Stedman, 1956; Wallin and Waggoner, 1950). A significant relationship was found where regression was used (and equations were tested for goodness-of-fit to reduce unreliability) to predict relative humidity values within the plant canopy. In contrast, Crowe et al (1978) found microclimatic relative humidity measurements were not significantly related to macroclimatic measurements.

Wallin (1963,1967) found that the hours of relative humidity >90% were closely related to the hours of dew duration; often the two periods were only one hour different. This close, simple relationship was not apparent in the current study for either relative humidity variable, hours of RH>90% or hours of RH>85% (Table 20), although when the relative humidity variables were correlated with the hours of leaf wetness, however, significant relationships were found in most cases. For most of the location-years, the relationships were not particularly close-fitting, as demonstrated by both the coefficients of determination and coefficients of variation. Perhaps calibration of the hygrothermographs and the leaf wetness sensors partially accounts for the poor fit. Crowe et al (1978) found the relationship of dew with RH>90% to have good correlation, although the results were only accurate locally. Rotem and Reichert (1964) found, however, that dew quite often occurred when the relative humidity at night was not high.

During 1982 both Portage la Prairie and Graysville sites fostered similar early blight severity levels (Figures 5 and 6). Of the environmental parameters monitored, the greatest differences lay with respect to moisture. Although rainfall levels were similar, the number of days with more than 5 hours of relative humidity greater than 90% and the number of days with more than 10 hours of leaf wetness recorded at Graysville were almost double the number recorded at Portage la Prairie. However, the fewer number of days with this type of moisture must have also been adequate for sporulation, germination, and infection of A. solani spores at the Portage site.

In 1983 disease severity was higher at Graysville than at Portage la Prairie (Figures 7 and 8). At the Graysville site, the generally hot year coupled with only light rainfall put crops under drought stress. There were 17 and 18 days where some rainfall was recorded at Portage la Prairie and Graysville, respectively. At Portage la Prairie, however, levels of rainfall were higher with three days where more than 10 mm of rain fell, while at the Graysville site there were no days with this much rain. Stress has been shown (Moore and Thomas, 1943) to be a factor contributing to early blight. Other moisture factors (leaf wetness) may also have had a role in altering disease levels.

In 1984 disease was once again more severe at Graysville than at Portage la Prairie (Figures 9 and 10). As in 1982, of the environmental parameters monitored, the greatest differences were with respect to moisture, particularly leaf wetness. At Graysville there were twice as many days with more than 10 hours of leaf wetness recorded than at Portage la Prairie. There were three times as many days where the temperature during the leaf wetness period was greater than 20°C. Perhaps this allowed more time for sporulation, uniform spore germination, and penetration.

Rotem and Reichert (1964) reported that infection could occur on foliage in free water within 12 hours at 10°C or 8 hours at 15°C . Conditions like these existed most days during July and August at Graysville in both 1982 and 1984. At Portage la Prairie, however, the above criteria were met only half of the time in 1982 and much less than half of the time in 1984. This could account for a lesser disease severity at the Portage la Prairie location, particularly in 1984.

4.4.4 Cultural Practices

Other factors may also have contributed to higher disease levels generally found at the Graysville sites. The crop at Graysville was planted approximately one week earlier each year and on lighter soil. Cultural practices including fertilization were carried out by the producers or in conjunction with the yield trial. Thus, factors such as nutrition (Barclay et al, 1973; Horsfall and Heuberger, 1942; Jones and Darling, 1953; Soltanpour and Harrison, 1974; Thomas, 1948), juvenile resistance (Douglas and Pavek, 1972; Harrison et al, 1965a; Lana et al, 1976), longer periods of meristematic activity (Barclay et al, 1973; Stavely and Slana, 1971), and senescence (Harrison et al, 1965a; Hooker, 1981; Lana et al, 1976) may have affected host susceptibility to early blight. The plots at Graysville were always adjacent to and part of a much larger potato field which was involved in a short rotation. At Portage la Prairie only in 1982 was the plot part of a larger field; at the University Station the plots were adjacent to no more than 4 acres of potatoes and were planted on summer fallow land which had not been planted to potatoes for at least five years. This may have affected both initial and secondary inoculum levels, undetected by the weather vane spore traps. This observation supports recommendations for long crop rotations.

4.4.5 FAST Forecasting System

The FAST program used total severity values and cumulative severity values for timing of initial and subsequent spray recommendations (Table 21). Cumulative rating values played no part in timing of the spray recommendations, while the relative humidity value used in creating the rating value was 90%. When the relative humidity value was lowered to 85%, in only one year did the spray schedule differ, although the same number of sprays were recommended. Thus, the periods of leaf wetness and temperature during these periods were the most important environmental parameters used in the FAST program. High cumulative severity values reflected conditions favourable for conidiophore and conidia formation. Shortly after spray applications were recommended on the basis of high cumulative severity values (within 7-10 days) disease severity usually increased. This period was similar to the incubation period, providing time for germination, infection, and lesion development. Thus, it appeared that the FAST program did identify periods favourable for early blight development. Evaluation of final disease severities and apparent infection rates resulting from commercial spray schedules and FAST-generated spray schedules would determine the effectiveness of the FAST system in controlling early blight under Manitoba conditions and would provide further validation of the system.

Presumably use of the FAST-generated spray schedules would maintain minimal disease severity. In previous validation of the program with tomatoes (Madden _et al_, 1978 Pennypacker _et al_, 1983), the FAST-generated spray schedules maintained disease at levels comparable the levels obtained from weekly spraying. Where early blight of tubers has not been a problem, the possibility exists such that the level of disease could be higher without reaching the economic damage threshold, that is the level of disease where artificial control is economically justifiable (Zadoks and Schein, 1979).

4.5 SUMMARY

Numbers of trapped _A. solani_ spores increased near the end of July each year. At this time disease intensity was quite low; only a few initial lesions were visible.

Environmental conditions, including temperature , leaf wetness, relative humidity, and rainfall, were monitored within the plant canopy. Using regression analysis data were compared to Environment Canada data recorded at Portage la Prairie and where missing values of temperature and relative humidity occurred, predicted values were substituted when possible. In 1982 both Portage la Prairie and Graysville sites succumbed to similar amounts of disease. Graysville generally had more moisture available for disease progression, although the moisture available at the Portage site was also adequate. Disease severity was more severe at Graysville in 1983. The growing season was generally hotter than in other years and the plot at Graysville appeared to be under drought stress. Graysville also claimed a higher disease severity in the 1984 season. In this year there were twice as many days at Graysville where more than 10 hours of leaf wetness were recorded.

On the basis of environmental data the FAST program (Madden _et al_, 1978), created to forecast early blight on tomatoes, recommended 1-3 sprays. Initial sprays were recommended at the same time as disease severity was assessed between 0%-5% and subsequent sprays were recommended shortly before higher disease severities were assessed.

Chapter V

GENERAL DISCUSSION

The mid-July inoculation was successful on the basis that disease symptoms were apparent throughout the inoculated plots within two weeks after inoculation. Environmental conditions during that time were often favourable for A. solani infection. Rotem and Reichert (1964) indicated free water was essential for A. solani infection and that infection was possible within 8 hours at 15°C or 12 hours at 10°C. Therefore, infection was possible on ten of the days within the two week period following inoculation and there was an average of more than 11 hours per day of leaf wetness. High relative humidity periods occurred often during these two weeks as well. Thus, lesion expansion would also have been favoured by the moist conditions.

Not all growth stages were distinguishable for both cultivars in both years; for example the full bloom period was not apparent for the cultivar Russet Burbank in 1983. This could present difficulties if growth stages were to be used for initiating disease monitoring or spraying (Feddersen, 1962; Henderson, 1962).

With the small range of disease found in 1983, little could be predicted. However, with the broader range of severities on both cultivars in 1984, regression can be used to analyze and predict yield losses. Generally several years' results and validation of regression models using new data are required for accurate yield loss prediction (James, 1974; James and Teng, 1979). From field trial results the damage threshold (Zadoks and Schein, 1979) may be determined. Once the producer knows the amount of yield at risk with a certain amount of disease, he can compare costs, including cost of labour and of spray application, with profits gained from the increased yield resulting from the spray application. Only when the profits outweigh the costs would it be advisable to spray.

In 1984 with a maximum of almost 15% disease, no significant yield differences with respect to treatment were obtained for the cultivar Russet Burbank. This would suggest that until disease levels passed this point no artificial control measures would be necessary, provided early blight of tubers was not a problem. If this is the case, the FAST program indicated an abundance of sprays in the following location-years: Portage la Prairie-1982,-1984, and Graysville-1982 (due to missing data in 1983, the FAST program was not used to recommend spray schedules at either location). Thus, the FAST program would require modification to reduce the number of spray recommendations. The modification could include altering the time of the initial spray by changing the recommended peak total severity level, by starting environmental monitoring later, or by monitoring disease level and using FAST-based scheduling only after a certain level of disease was reached. Disease monitoring carried out concurrently, would continually test the validity and accuracy of the FAST system.

The Norland cultivar succumbed to a broader range of disease in the 1984 yield trial and significant yield losses in the absence of fungicide treatments were observed. Weekly sprayed plots significantly outyielded unsprayed plots and plots sprayed only twice during the season, but not plots sprayed four times during the season. Thus, it was possible to reduce the number of sprays without significantly affecting yield. With proper timing, it may be possible to further reduce the number of sprays required to keep disease in check while maintaining yield. When comparing initial assessments of disease, it is apparent that the initial spray application was of little benefit.

Based on the 1984 results, the FAST program also has potential to ensure less disease in the Norland cultivar. One spray recommendation was generated by the FAST program for the Portage la Prairie site. When comparing timing of the recommended spray with disease severity of uninoculated plots, it is apparent that the recommended application would have taken place approximately 10 days before a 'jump' in severity to about 3%. A second large increase in percent severity occurred by week 13. A spray controlling this increase would also be beneficial. Altering the critical level of cumulative severity value (CS) to CS>9 would generate a second spray recommendation approximately 10 days before this increase in severity.

Thus, it appears that different cultivars have different requirements for an 'adequate' spray schedule. Before the FAST program could be used reliably with potatoes in Manitoba, the total severity value, the cumulative severity value, and the cumulative rating value would have to be evaluated. Validation of the system would require the conduct of field trials, where FAST-generated spray schedules were compared to other spray schedules by comparing early blight disease progression and yield. All cultivars where the FAST program had potential use would require individual testing.

Further testing with a broader range of disease levels would indicate at which level disease control prevents significant yield loss and at which level disease becomes uncontainable with any amount of control. Final disease intensities ranging from virtually disease-free to levels of 100% disease would improve yield prediction values.

Chapter VI

GENERAL CONCLUSIONS

The following conclusions were based on research of early blight on the cultivars Russet Burbank and Norland on unirrigated fields.

1. The disease ranges obtained in these trials were not broad enough to provide an accurate assessment of early blight-induced yield loss currently occurring in Manitoba; however, trends toward reduced yield as early blight intensity increased were apparent.
2. It was possible to control disease with a reduced number of fungicide applications as compared to weekly applications.
3. Spraying to control early blight was unnecessary before Alternaria solani spore loads increased, usually in late July.
4. Initial symptoms generally appeared just before or about the same time as the dramatic increase in spore loads was apparent.
5. Once substantial increases in spore loads were detected, subsequent spore monitoring consistently revealed high levels of spores throughout the season.
6. The cultivar Norland was more sensitive to early blight infection because of physiological age and earlier maturity, smaller maximum leaf area, or other factors.
7. The cultivar Norland was more susceptible to the mid-July inoculation, also for the above reasons.

8. Interplot interference possibly created higher spore loads, undetected by wind-vane spore traps, and contributed to higher disease severities of all plots.
9. The FAST program appeared to detect periods favourable for early blight development in Manitoba.
10. Leaf wetness data and temperature data were the environmental parameters having the most impact on FAST-generated spray schedules.
11. The FAST system has potential use in Manitoba for predicting spray schedules which provide efficient control of early blight; however, validation of the system should be carried out with any potato cultivars for which use of the program is intended.

Chapter VII

GENERAL RECOMMENDATIONS

1. Spore levels and disease severity should be monitored regularly to provide insight on timing of initial spray application.
2. Initial spraying of unirrigated potato fields should commence when a significant influx of _Alternaria solani_ spores is detected by spore trapping, usually mid- to late-July.
3. Alternatively, initial spraying should commence when initial symptoms are first visible, usually mid- to late-July.
4. Once substantial increases in _A. solani_ spore loads are detected, further spore monitoring is unnecessary.
5. Further research is recommended in the area of spray predictions on the basis of environmental conditions. Validation of the FAST program for use with potatoes in Manitoba is recommended.
6. When irrigation is used, fields should be monitored individually.*
7. Permissible levels of disease--threshold levels--should be determined from future yield trials.
8. If a forecasting system is adopted, monitoring disease is important to ensure system is working accurately. In event of a system failure and the epidemic does progress, a spray program of regular frequent fungicide applications should be reinstated.*
9. The inherent risks associated with any 'late warning' program should be understood before a program of this nature is used.*

* Recommendation was not derived from this research.

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Appendix A

EARLY BLIGHT ASSESSMENT KEY

Blight (%)	Description of Infection[1]
0.0	No disease symptoms.
0.01	5 infected leaflets per 10 plants; 2 lightly infected leaves per 10 plants.
0.1	5 infected leaflets per plant; 2 lightly infected leaves per plant.
1.0	Up to 10 spots per plant, or general light spotting.
5	About 50 spots per plant or up to 1 leaflet in ten attacked.
25	Nearly every leaflet with lesions, plants still retaining normal form: field may smell of blight, but looks green although every plant affected.
50	Every plant affected and about 50% of leaf area destroyed; field looks green flecked with brown.
75	About 75% of leaf area destroyed: field looks neither predominantly brown nor green
95	Only a few leaves left green, but stems green.
100	All leaves dead, stems dead or dying.

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[1] Adopted from Anon. (1947) and Fry (1977).

Appendix B

STANDARD AREA DIAGRAM OF POTATO LEAVES SHOWING EARLY BLIGHT INJURY (%)[1]

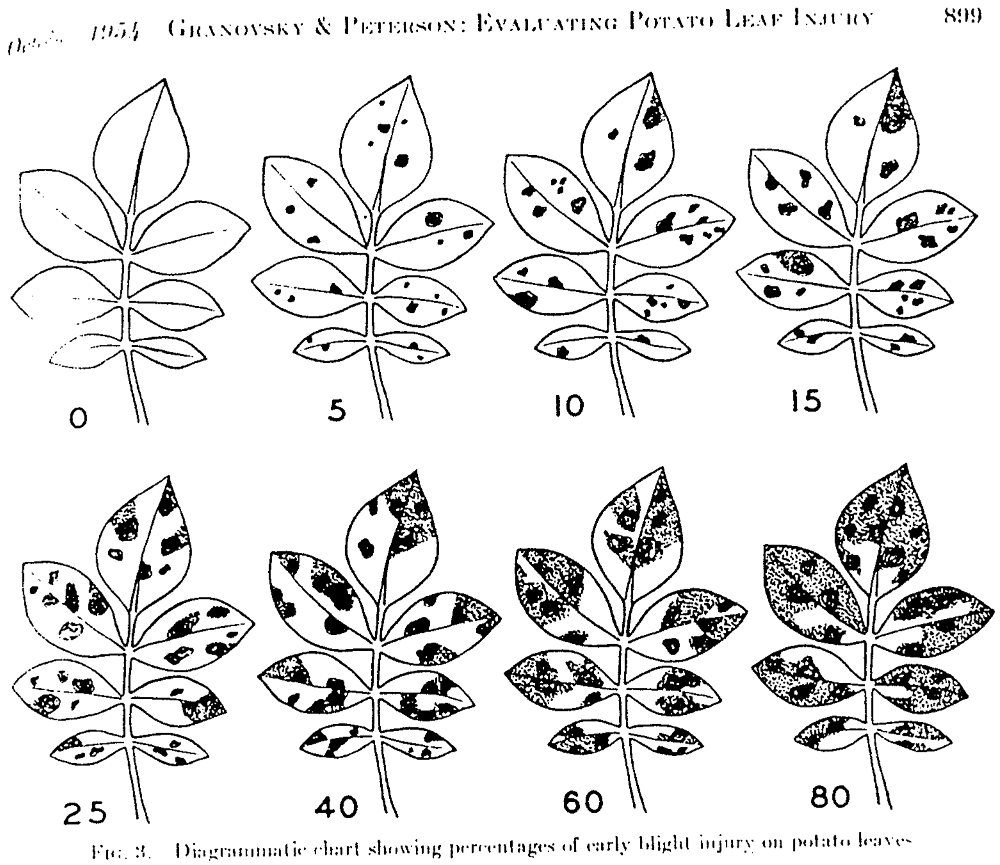
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FIG. 3. Diagrammatic chart showing percentages of early blight injury on potato leaves

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[1] Granovsky and Peterson (1954).

Appendix C

SEVERITY VALUES AS DETERMINED BY "FAST"

Early blight of tomato disease severity values as a function of leaf wetness period and average ambient air temperature during the wetness period.[1]

Mean Temperature (C)	Leaf-wetting time (hr) required to produce daily severity values[2] of:				
	0	1	2	3	4
13-17	0-6	7-15	16-20	21+	--
18-20	0-3	4-8	9-15	16-22	23-24
21-25	0-2	3-5	6-12	13-20	21-24
26-29	0-3	4-8	9-15	16-22	23-24

[1] From Madden, Pennypacker, and MacNab (1978).

[2] The scale of S-values range from 0 (environmental conditions favourable for <u>Alternaria solani</u> spore formation) to 4 (highly favorable conditions.)

Appendix D

RATING VALUES AS DETERMINED BY "FAST"

Early blight of tomato disease severity rating values as a function of average ambient air temperature, hours of relative humidity greater than 90%, and total rainfall.[1]

Temperature[2] (C)	Hours RH>90%[3]	Total Rain[4]	R[5]
<22	<60	<2.5	0
>22	<60	<2.5	0
<22	>60	<2.5	1
<22	<60	>2.5	1
<22	>60	>2.5	1
>22	>60	<2.5	2
>22	<60	>2.5	2
>22	>60	>2.5	3

---

[1] Madden, Pennypacker, and MacNab (1978).
[2] Average Temperature for past five days.
[3] Hours RH>90% for past five days.
[4] Total rainfall for past seven days (cm).
[5] Disease severity rating scale: 0 indicates environmental conditions unfavorable for Alternaria solani spore formation and infection of tomato; 3 indicates that conditions are highly favorable.