FACTORS INFLUENCING A PETAL-BASED FORECASTING SYSTEM FOR SCLEROTINIA STEM ROT OF CANOLA

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ABSTRACT

Studies from 1987 to 1990 investigated the influence of the following factors on the relationship between the percentage of canola petals infested with Sclerotinia sclerotiorum and the incidence of sclerotinia stem rot: canopy density; diurnal and other weather-mediated fluctuations in petal infestation; and long-term changes in infestation during flowering. Disease incidence was significantly related to canopy density, as indicated by percentage light penetration through the canopy, and increased as light penetration decreased. Higher disease incidence in the denser canopies was attributed to more favorable microenvironmental conditions.

A general pattern of increasing petal infestation from morning to afternoon was observed in 1987 and 1988. Infestation was found to be significantly higher during the afternoon than the morning in 4 of 7 crops. Increases from morning to afternoon ranged from 0.3 to 46%; reductions ranging from 0.5 to 14% were also observed on a few days. The pattern in petal infestation probably resulted from periodicity in ascospore discharge related to several environmental factors.

Long-term fluctuations of up to 94% petal infestation were observed during flowering. These changes were mostly increases; however, in 1989, infestation generally decreased during flowering. These changes were related to variation in rainfall which influenced inoculum production. In general, disease incidence was significantly related to petal infestation at flowering stages when the presence of inoculum coincided with favorable host and environmental conditions. Multiple regression analyses with infestation at early, full and late bloom, light penetration, leaf area index and crop height as independent variables accounted for 55-98% of the variation in disease incidence.

For practical on-farm disease forecasting, long-term changes in petal infestation may be more important than diurnal fluctuations for determining disease risk and incidence. However, as a precaution against underestimating infestation, petals should be sampled in

the afternoon and not after substantial rainfall or dew. Sampling petals more than once during flowering will be essential to account for long-term variations in infestation. The influences of the host and environment are also important; however, assessing their effect may be difficult, especially for on-farm disease forecasting.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
DI	Disease incidence
DLWD	Daily leaf wetness duration
GS	Growth stage
LAI	Leaf area index
MDI	Mean disease incidence
MHT	Mean crop height
MLAI	Mean leaf area index
MNPS	Mean number of plants per m^2
MPLP	Mean percentage light penetration
MPPI	Mean percentage petal infestation
MPPIEB	Mean percentage petal infestation at early bloom
MPPIFB	Mean percentage petal infestation at full bloom
MPPILB	Mean percentage petal infestation at late bloom
MST	Mean stem thickness
PPI	Percentage infestation of canola petals with S. sclerotiorum
RCBD	Randomized complete block design
RH	Relative humidity
SR	Seeding rate
SS	Sums of squares
TMDI	Transformed mean disease incidence

1. INTRODUCTION

Various management strategies have been developed to prevent severe plant disease epidemics. Some, such as fungicide application, can be expensive to implement on a routine basis. For diseases which vary among years, regions and crops, and which are not effectively controlled by less expensive practices, such as crop rotation, a farmer generally needs to know "if", "when", "where", and "how often" expensive control measures are justified (Bourke 1970, Fry 1982, Johnson 1987, Pennypacker & Stevenson 1982). It is through disease forecasting that a farmer is able to obtain answers to these questions (Agrios 1988).

In western Canada, sclerotinia stem rot of canola, caused by Sclerotinia sclerotiorum (Lib.) de Bary, is a disease which has the potential to cause substantial losses, is variable in occurrence, and is not effectively controlled by crop rotation or host resistance. The stem rot fungus produces ascospores from apothecia that have developed from sclerotia in the soil. Ascospores require an external source of nutrients for host infection (Abawi & Grogan 1975, Newton & Sequeira 1972). In canola, petals serve as this source of nutrients (Kapoor et al. 1983, Krüger 1975b, Morrall & Dueck 1982). Ascospores land on intact inflorescences or on dislodged petals that are adhering to various plant structures. Host infection from infested petals is then favored by humid conditions within the canopy (Brün et al. 1983, Le Coz 1981, Williams & Stelfox 1980a).

To control stem rot of canola many farmers consider fungicide application during the flowering period (Morrall et al. 1985, Thomas 1984). However, the costs associated with spraying and the variable nature of stem rot (Harrison 1990, Jesperson 1990, Morrall et al. 1976, Platford & Bernier 1975) make routine fungicide application questionable. Thus, for economical control farmers must be able to identify those crops where disease risk is high and fungicide application is worthwhile.

Several forecasting systems for sclerotinia stem rot of canola have been developed

(Ahlers 1989, Buchwaldt 1986, 1989, Thomas 1984). These produce mainly qualitative forecasts that only indicate whether to spray or not. Losses due to stem rot have been related to disease incidence (Davies 1986, Morrall et al. 1984a). Therefore, a quantitative disease forecast might allow the farmer to consider more effectively the cost/benefit ratio of applying fungicide. This would become especially important if farmers begin to adopt some of the more recent control strategies developed by Morrall et al. (1985, 1989), Rude et al. (1987) and Rude (1989). These strategies include late-bloom application of fungicide, nozzles which produce small spray droplets and reduced rates of fungicide.

There are two components of the disease cycle of sclerotinia stem rot that a quantitative forecasting system could be based on. Both apothecial density and the frequency of petal infestation with ascospores could be used to relate inoculum density to disease incidence. Based on experiments in 1983 and 1984, Gugel & Morrall (1986) suggested that monitoring petal infestation might provide a quantitative approach to forecasting that would also account for inoculum produced from sources extrinsic to the crop. In 1985 and 1986, Turkington (1988) investigated the relationship between disease incidence (DI) and percentage infestation of canola petals with S. sclerotiorum (PPI) in greater depth. In a pilot project petal samples were collected at early bloom by farmers or research personnel and PPI assessed using an agar plate test. A forecast of disease risk based on PPI was then issued to farmers. Disease incidence was assessed later in the growing season in crops where petal samples were collected. Studies on the sample size required to reliably estimate PPI in commercial crops were also conducted (Turkington et al. 1988).

Results from the pilot project demonstrated that using PPI to forecast DI was commercially feasible. Farmers were able to sample petals quickly since the required sample size was relatively small. Further processing of petal samples and determination of PPI were found to be manageable on a commercial scale, with results of the agar plate test available in 3-5 days. This provided farmers with enough time to spray while chemical

control was still considered effective (Morrall et al. 1985, Thomas 1984).

Simple regression analysis was used to relate DI to PPI at early bloom for 1985 and 1986 (Turkington 1988). Significant positive relationships were demonstrated between DI and PPI, but the strength of these relationships varied. Assessing PPI at a single growth stage (early bloom) accounted for an average of only about 20% of the variation in DI, and about half of the regressions were not significant. Forecasts of disease risk were also divided into three categories (low, moderate, and high) and the results showed that forecasts were most accurate when disease risk and DI were low, but less so when they were moderate to high. These results demonstrated that factors in addition to PPI at early bloom determined DI and influenced the accuracy of forecasts.

Moisture has a significant effect on host infection by Sclerotinia sclerotiorum (Abawi & Grogan 1975, Boland & Hall 1987, Brün et al. 1983, Krüger 1974, 1975a, 1975b, Le Coz 1981). Thus, any factor that modifies humidity in the microenvironment of the host will influence the relationship between DI and PPI. One factor expected to do this is canopy density. Studies in commercial fields from 1985 to 1986, included subjective assessments of canopy density (Turkington 1988). Crops were classified as either light, moderate or heavy based on relative crop height and ground coverage. Disease incidence was found to increase as canopy density increased, suggesting that canopy density influenced the relationship between DI and PPI.

Studies in New Zealand, Germany, and Israel have suggested that ascospore levels of S. sclerotiorum fluctuate diurnally and in response to other environmental conditions (Ben-Yephet & Bitton 1985, Hartill 1980, Krüger 1974, 1975a, 1975b). In Germany, Krüger (1974, 1975a, 1975b) has shown that rainfall can prevent ascospore release by catching spores in droplets of water lodged on apothecia. Turkington (1988) found that, for some crops in 1986, PPI at early bloom had underestimated DI. In these crops petal samples had been collected during rainfall, and it was suggested that the rainfall may have reduced PPI by preventing ascospore release, washing ascospores from the air and perhaps

even off petals. Diurnal and short-term weather-mediated fluctuations in PPI may be important factors to consider in a forecasting system for sclerotinia stem rot.

In contrast with the results of Gugel & Morrall (1986), the majority of regressions of DI on PPI calculated by Turkington (1988) had intercepts significantly different from zero. This implied that inoculum other than infested petals at early bloom was responsible for some of the disease that developed. Direct mycelial infection of canola from soil-borne sclerotia can occur, but is usually relatively unimportant compared with ascospores (Kolte 1985, Krüger 1975a, 1975b, Morrall & Dueck 1982). Changes in PPI over the flowering period have been reported (Gugel 1985). At some locations in 1986, wetter conditions during flowering probably increased airborne ascospore levels and PPI, and produced more favorable conditions for infection at later stages of flowering (Turkington 1988). Hence, reliable forecasts may depend on sampling petals more than once during flowering. Changes in PPI with time would cause under- or over-estimation of DI based on PPI determined at only a single growth stage.

Based on work by Turkington (1988), three factors that may influence DI and the accuracy of forecasts based on PPI have been identified: short- and long-term fluctuations in PPI and variations in canopy density. Studies investigating the influence of these factors formed the basis of this Ph.D. project, which was conducted from 1987 to 1990. The objectives were: (1) to investigate the influence of canopy density on disease risk and incidence; (2) to determine if diurnal fluctuations in PPI on canola occur, how these fluctuations may be related to prevailing weather conditions, and whether they are of significance for commercial forecasting; and (3) to determine if changes in PPI occur during the flowering period, how such changes might influence disease risk and incidence, and if they relate to changing weather conditions.

2. LITERATURE REVIEW

2.1. Disease forecasting systems

2.1.1. Introduction

Plant disease occurs as the result of the interaction of a susceptible host and virulent pathogen in a favorable environment (Fry 1982, Walker 1969). Forecasting systems are based on one or more of these three factors. Most systems are weather-based, while those based on the host, pathogen or some combination are less common (Johnson 1987, Zadoks 1984). The development of dependable systems requires sufficient knowledge and understanding of the interactions of host, pathogen, and environment (Fry 1982, Fry & Fohner 1985, Johnson 1987, Zadoks & Schein 1979). Forecasting systems may also require that suitable methods (direct or indirect) for detection of pathogen and disease are available. Finally, there must be an adequate understanding of the characteristics of disease development.

In general it is the epidemiology of a particular disease that will dictate the basis of forecasting (Fry 1982). For example, systems for monocyclic pathogens, or polycyclic pathogens that produce high levels of initial inoculum and have few infection cycles per host generation, will focus on some aspect of initial inoculum (Agrios 1988, Fry 1982). Forecasting is more likely to concentrate on some aspect of secondary inoculum when the pathogen is polycyclic and has a low level of initial inoculum and many infection cycles per host generation. Since each disease is unique both in expression and the methods for its control, forecasting systems are often composed of a myriad of diverse components (Fry & Fohner 1985).

Krause & Massie (1975) and Madden & Ellis (1988) have suggested that forecasting systems may be derived from either empirical or fundamental relationships.

Empirical (deductive) systems are typically developed from relationships observed between pathogen, host and environment; a cause and effect relationship is not necessarily implied, only that specific factors are related (Campbell & Madden 1990, Krause & Massie 1975, Madden & Ellis 1988). Ultimately, a set of particular conditions are identified as being important for disease development and are used to forecast disease risk. Although these types of systems are usually developed for particular locations, Krause & Massie (1975) suggested they may have wider applicability if care is taken to study the host-pathogen interaction in several areas with diverse environmental conditions. This allows the evaluation of all critical components of the host-pathogen-weather interaction (Krause & Massie 1975).

Fundamental (inductive, logical) systems are developed through laboratory and field experimentation, where relationships between the various components of the host-pathogen-weather interaction are established and quantified (Campbell & Madden 1990, Krause & Massie 1975, Madden & Ellis 1988). With fundamental forecasting systems a "cause and effect" relationship has been established. Krause & Massie (1975) suggested that the differentiation of predictive systems into fundamental and empirical classes is arbitrary, since a fundamental system may have been developed from an existing set of empirical rules or guidelines.

2.1.2. The infection cycle

Central to the development of any disease forecasting system is the concept of the infection cycle, which represents a cyclic series of stages and processes through which a pathogen passes. For example, the infection cycle for a hypothetical fungal foliar pathogen is depicted in Figure 2.1 (Shrum 1978). The inner circle depicts a series of stages (state variables) through which the pathogen passes during an epidemic. For monocyclic

pathogens there is only a single cycle of dissemination, infection, and disease development during the host growing season; polycyclic pathogens may have many infection cycles per growing season (Fry 1982, Zadoks & Schein 1979). Although Figure 1 represents an infection cycle for a foliar fungal pathogen it can be easily altered to represent cycles for other types of fungal and bacterial pathogens. Various physical factors influence the states of the infection cycle as well as the rate of change from one state to another (Fig. 2.1). These factors play an important role in the progress of the cycle and may have a positive, negative or neutral influence depending on the particular state (Shrum 1978). It is from these relationships that disease forecasting systems are developed.

Forecasting systems based on the weather depend on direct or indirect relationships that exist between disease development and the environment (Pennypacker & Stevenson 1982). They often express some component of the pathogen's infection cycle (Fig. 2.1) as a function of one or several critical variables. In general, the most common environmental variables used are: temperature, relative humidity, duration of leaf wetness, precipitation, cloud cover, and wind conditions.

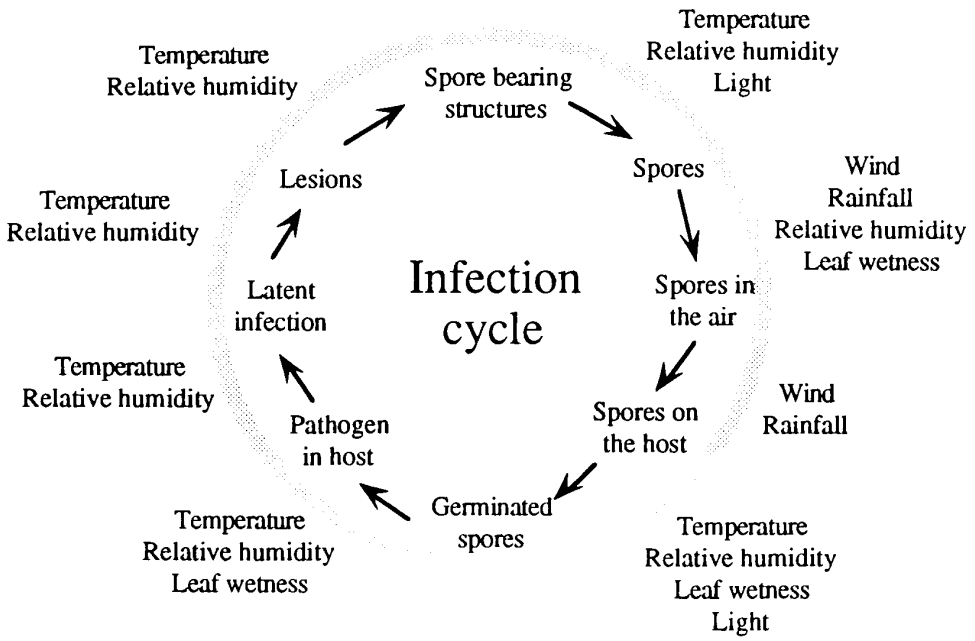

Figure 2.1. An infection cycle for a foliar plant pathogen.

Forecasting systems based on the pathogen often utilize some form of inoculum density-disease incidence relationship to estimate risk (Johnson 1987). In these there may be direct or indirect assessment of the pathogen. Host-based forecasting systems tend to be the least frequent, because the host is relatively stable compared with weather and pathogen variability (Johnson 1987, Zadoks 1990). Zadoks (1984) and Berger (1977) have suggested that the host is most often used to schedule management practices according to "host phenological events". Examples of this include the use of apple bud and leaf tissue development to schedule spraying for apple scab (Venturia inaequalis) (Berger 1977), and flowering in canola to schedule spraying for sclerotinia stem rot of canola (Morrall & Dueck 1982, Morrall et al. 1985, 1989, Thomas 1984).

2.1.3. Models

The biological relationships used in forecasting systems are often complex; as a result pathologists have constructed models to depict the relationship of various independent variables (predictor variables) to the occurrence of disease (Bourke 1970, Campbell & Madden 1990). Typically these models represent "simplifications of reality" and form the basic functional unit of the forecasting system (Fry 1982). Models range from simple qualitative decision rules or guidelines, to simulation models whose complexity rivals that of the original biological system. Shrum (1978) suggested that models can be divided into two categories; holistic and systems analytic. However, Seem & Haith (1986) have suggested that systems analysis represents "holistic and transdisciplinary thinking". Kranz & Hau (1980) refer to "input-output" and systems analysis models; these terms will be used in the rest of this section.

2.1.3.1. Input-output models

Input-output models view the epidemic as a "single biological entity" in which disease is considered to be a function of one or several critical variables (Pennypacker & Stevenson 1982, Shrum 1978) (Fig. 2.2). Moreover, input-output models assume that the influence of these variables remains the same throughout the epidemic (Shrum 1978). Generally, these types of models do not account for differential effects due to independent variables like temperature and leaf wetness. For example, the presence of moisture may be used to identify critical periods during which host infection occurs (Jones 1986). However, for some pathogens moisture may have an inhibitory effect on spore production and liberation (Krüger 1974, 1975a, 1975b, Sutton & Hildebrand 1985). Existing types of input-output models include simple qualitative and quantitative models, and complex

numerical and statistical models.

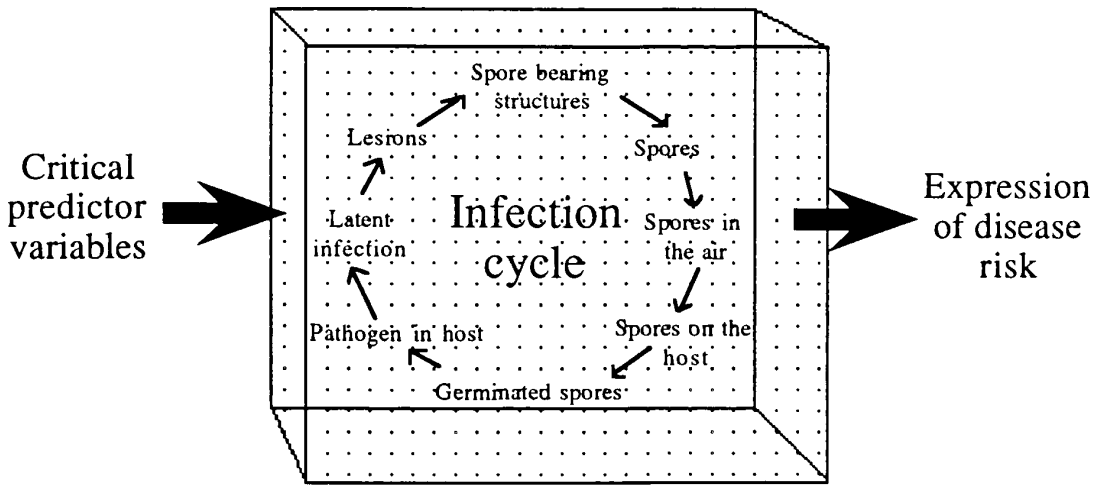

Figure 2.2. Symbolic representation of a simple input-output model for disease forecasting.

2.1.3.1.1. Simple qualitative and quantitative models

Simple models often consist of a set of qualitative or quantitative "decision rules" which the farmer uses to assess disease risk. Qualitative models appear to be relatively rare. In general, these models may relate phenological or geographical information to disease risk (Bourke 1970). In some crops host development is used to schedule fungicide application at growth stages which correspond to maximum host susceptibility (Berger 1977, Seem & Russo 1984, Thomas 1984). Furthermore, disease development in one geographic area may be used to indicate disease risk in adjacent areas. Such a system is used as part of the "North American Blue Mold Warning System"; where initial disease occurrence and subsequent development are monitored and used to coordinate state and regional warnings (Nesmith 1984).

A relatively simple forecasting model, that is based mainly on qualitative consideration of various host, pathogen, and weather factors thought to influence disease development, is the risk assessment scheme (Johnson 1987). This type of system has been used for scheduling fungicide application for control of pod and stem blight of soybean, septoria brown spots of soybean, white mold of snap bean, various winter wheat diseases and sclerotinia stem rot of canola (Kelly 1982, Shurtleff et al. 1980, Stuckey et al. 1984, Thomas 1984, Wienzierl et al. 1982). Each factor is assigned a series of point values based on the magnitude of its influence on disease. The higher the point value the greater the risk of disease. Point values for all factors are eventually totalled and if the total is greater than a decision threshold the farmer is advised that disease management practices may be needed (Johnson 1987).

Perhaps the most common simple models are numerical and derived from weather and disease records (Bourke 1970). Some quantitative models use the relationship between infection and duration of leaf wetness at various temperatures. Mills' system for apple scab (Mills 1944) uses this relationship to forecast the severity of host infection by ascospores of Venturia inaequalis. Beaumont (1947) developed a "temperature-humidity rule" for potato late blight which identified the past occurrence of infection based on temperature and relative humidity data.

A simple numerical model for forecasting sclerotinia stem rot of rapeseed has been developed in Denmark by Buchwaldt (1986, 1989). Forecasts are based on carpogenic germination of sclerotia in depots established throughout the country. Once the crop canopy has covered the soil surface, agricultural advisors monitor germination and send in weekly reports. These reports are used to produce regional forecasts throughout the flowering period; the system is not designed to identify individual crops requiring chemical control. If sclerotial germination is >26% for 7-10 days before full flowering, control measures are recommended for crops within 15 km of the depot. Other factors including crop and disease history, environmental conditions, presence of apothecia within individual

crops, and crop development are also considered before forecasts are issued.

Often simple quantitative models utilize some function of an independent variable to forecast disease risk (Johnson 1987). Stevens (1934) used a "winter temperature index" to predict the severity of Stewart's bacterial wilt of sweet corn. The index was calculated as the sum of the mean monthly temperature for three winter months, and indicated the relative survival of the pathogen's insect vector. For some models the function is derived from a combination of independent variables. Gillespie & Sutton (1979) developed a "weather-timed scheme" for alternaria leaf blight of carrot in Southern Ontario. This system used forecast temperature and wetness duration to predict infection and schedule the application of protectant fungicides. When a threshold of 1-2% diseased foliage has been reached the actual forecasting system is implemented. Forecasts of temperature and probable wetness duration are used to derive an infection index ranging from 0 (no infection) to 3 (severe infection). Spraying is recommended if the infection index is ≥ 2 (moderate infection). Subsequent fungicide applications are considered after 7 day intervals, using the same criteria. Forecast temperature is obtained from Environment Canada, and wetness duration is based on forecasts of rain, cloud cover, and surface wind speeds.

Sutton & Gillespie (1983) simplified the earlier criteria for determining favorable weather for infection. Fungicide application is recommended "before forecasted rain or before the next night when the forecasted minimum temperature is 16°C or higher". The simplified criteria reflected the relationship between leaf wetness duration at various temperatures and host infection by conidia of the fungus. In southern Ontario, leaf wetness duration resulting from dew is generally 9-12 hours in the absence of rain, and host infection can occur if the temperature is ≥ 16°C during this period (Sutton & Gillespie 1983).

2.1.3.1.2. Complex numerical and statistical models

These models will often utilize either a relatively complex function of an independent variable, or an established statistical relationship between independent and dependent variables. Sutton et al. (1986) modeled the development of botrytis leaf blight of onions using a "cumulative disease severity index (CDSI)", calculated from a daily "disease severity index (DSI)". The DSI was derived from two other values which reflected the influence of weather on inoculum production and host infection. A "daily inoculum value (DINOV)" of either "0" (no inoculum produced) or "1" (inoculum produced) was based on established relationships between sporulation, temperature, relative humidity, and leaf wetness. The second value was a "daily infection value (DINFV)" of either "0" (none), "1" (light or moderate) or "2" (severe), and was based on the duration of leaf wetness at various temperatures. The DINOV and DINFV were multiplied to give the DSI, which was then summed to give the CDSI. The CDSI was monitored until two critical thresholds were reached and initial fungicide application was recommended.

Regression models have also been used to relate various critical predictor variables to the occurrence of disease and infection. Eisensmith & Jones (1981a) used multiple regression to derive an "environmental favorability index (EFI)" for the cherry leaf spot fungus (Coccomyces hiemalis), based on the duration of leaf wetness and temperature. The EFI was used to determine the severity of host infection by conidia. Predicted EFI values of ≥14, ≥28, and ≥42 corresponded to low, moderate, and high infection severities, respectively (Eisensmith & Jones 1981b). Fungicide application was recommended when the EFI was ≥28 for an identified infection period.

Regression models which relate the number of pathogen propagules to the occurrence of infection have also been developed. Backman et al. (1981) found a significant relationship between the number of viable sclerotia of Sclerotium rolfsii in 500 g

soil samples and the incidence of infected sugar beet roots. Soil samples were obtained from field samples and residues left in beet delivery trucks. The numbers of viable sclerotia were then determined using a "soil-tray technique" (Backman et al. 1981). The resulting relationship was then exploited and used as a management tool to aid with planting decisions. Adams (1979, 1981) developed a similar system for white rot of onion caused by Sclerotium cepivorum, where sclerotial populations were related to disease at harvest time.

2.1.3.2. Systems analysis models

Systems analysis models utilize the systems approach which views the epidemic as a series of components and subcomponents. These are then subdivided into various individual models which express each state of the infection cycle as a function of one to several critical factors (Kranz & Hau 1980). Each of these individual models are then reconnected to form a functional representation of the epidemic. With system analysis models the influence of any independent variable may be positive, negative or neutral which allows the modeling of complicated interactions among various components of the epidemic (Shrum 1978). Although simulation analysis may be complex and difficult to incorporate in a forecasting system, it may provide an useful tool for developing, comparing and evaluating various disease management strategies (Bruhn & Fry 1981, Butt & Jeger 1985, Fry & Fohner 1985, Seem & Haith 1986, Shtienberg & Fry 1990, Zadoks & Rabbinge 1985).

Several simulators of plant disease have been developed (Alderman et al. 1987, Teng et al. 1980, Waggoner & Horsfall 1969, Waggoner et al. 1972). In general, these simulators have modeled various components of the pathogen's infection cycle including: (1) infection, (2) incubation, (3) lesion development, (4) sporulation, and (5) dispersal

(Hau 1988, Teng 1985). Weather variables "drive" these simulators, but models may require "initialization" with parameters such as: level of inoculum, disease incidence or severity, and various crop characteristics (Pennypacker & Stevenson 1982, Teng 1987, Zadoks & Rabbinge 1985). Few models have been evaluated as part of an actual disease forecasting system (Butt & Jeger 1985, Hau 1988, Pennypacker & Stevenson 1982, Seem & Haith 1986, Teng et al. 1978).

Simulation of potato late blight (Bruhn & Fry 1981, Fry et al. 1983) has been used to evaluate the influence of rate-reducing resistance (Fry 1977, Fry 1978) and fungicides (Bruhn & Fry 1982a, 1982b) on late blight epidemiology and various disease management strategies. Fry et al. (1983) demonstrated that, compared to a regular schedule, fewer applications of fungicide were scheduled by the BLITECAST system (Krause et al. 1975, MacKenzie 1981) and a simulation forecast that incorporated the influence of host resistance and fungicide weathering. Using models developed previously (Bruhn & Fry 1981, Bruhn & Fry 1982a, 1982b), Fohner et al. (1984) and Fry & Fohner (1985) compared a regular schedule of fungicide application with a schedule according to BLITECAST. It was concluded that BLITECAST offered no advantage over a regular schedule of fungicide application, especially when the environment was conducive to disease. However, Fohner et al. (1984) suggested that BLITECAST may be useful in reducing the number of fungicide applications when the environment is less conducive to disease and inoculum levels are low.

Recently Shtienberg et al. (1989) and Fry & Shtienberg (1990) used simulation analysis to compare and integrate management strategies for both early and late blight of potato. These studies suggested that the most effective approach for management of both diseases may be to schedule initial fungicide applications according to BLITECAST. Subsequent applications up to week 7 of the growing season would then be scheduled based on cultivar resistance, with a weekly schedule of application followed afterwards.

Teng et al. (1978) developed a simulator for leaf rust of barley (Puccinia hordei)

and evaluated it as a method of forecasting crop loss and scheduling fungicide application. The model was developed in three phases. As part of the first phase an initial model was constructed based on existing data from the literature. For initial simulation experiments several components of the pathogen's infection cycle were used. After experimentation with the initial model the critical processes of the system were identified.

In phase 2, "controlled-environment" experiments were conducted to evaluate the influence of various factors on the following variables: (1) spore production, (2) spore liberation, (3) spore survival, (4) spore deposition, (5) spore germination, (6) penetration, and (7) latent period (Teng et al. 1978). From these experiments various "mathematical functions" describing a particular process were found to be suitable for the development of a combined model of the pathogen's infection cycle. Yield loss experiments were also conducted and the resulting relationship was integrated into the simulation model (Teng et al. 1977, 1978). Then using historical crop, weather, and disease records the simulation model was compared with actual field data. In general, disease and yield loss data from the field were found to be "statistically in agreement" with data produced from the model (Teng et al. 1978).

The phase 3 model used historical records of various environmental parameters to simulate "key weather variables", and create a probability distribution of forecast disease levels (Teng et al. 1978, 1980, Thornton & Dent 1984a). Probable disease levels were then input to a "multiple-point yield loss function" which determined probable yield loss. As the epidemic progressed, disease and environmental monitoring were used to revise forecasts of probable disease severity and yield loss (Teng et al. 1978, 1980, Thornton & Dent 1984a).

The simulator (BARSIM) developed by Teng et al. (1978, 1980) was then implemented as part of an information system (FUNGINFO) for brown rust of barley (Puccinia hordei). The FUNGINFO system used the forecasts of probable disease and yield loss to evaluate two alternative strategies: (1) "spray now", and (2) "do not spray".

The expected cost of not spraying was then compared with the expected cost from spraying to determine which of the alternative strategies would be recommended (Thornton & Dent 1984a). Preliminary validation of FUNGINFO indicated that recommended strategies were correct in all assessment trials. Thornton & Dent (1984b) have suggested that implementation of FUNGINFO in New Zealand may be a problem, since the availability of suitable computing facilities was limited. In an attempt to solve this problem, Thornton & Dent (1984b) used BARSIM to develop recommendation tables for weekly spray decisions based on the date of disease appearance, number of days with dew, and date of sowing.

2.1.4. Implementation

One of the principal objectives of forecasting is the production of an effective management tool; however, in order for a system to be effective it must be used by the farmer (Madden & Ellis 1988). Thus it is essential that during the development and implementation of a forecasting system the concerns and objectives of the farmer be given careful consideration (Campbell & Madden 1990, Johnson 1987, Royle & Shaw 1988). Butt & Jeger (1985) have suggested that to ensure that a forecasting system is eventually used and accepted by farmers consideration should be given to the production of an "overall delivery and support system". Thus, some type of scheme should be in place that would allow the transmission of appropriate information between the farmer and various support personnel.

In general, farmer acceptability of a management system involves three factors: "(1) the farmer is able to understand the background and the reason for the recommendation; (2) he is willing to accept a calculated risk; and (3) he is willing to pay a fee for a recommendation which may save him money" (Zadoks & Rabbinge 1985). The nature of the individual farmer is very important; is the farmer risk averse, does he follow a

predetermined schedule or will he accept some of the risk involved in a forecasting system and use a novel management tool (Butt & Jeger 1985, Campbell & Madden 1990, Madden & Ellis 1988)?

Poor acceptability of forecasting systems may result because researchers fail to produce a simplified version of the system which can be easily transferred to the farmer (Butt & Jeger 1985). Also, implementation of a system not properly validated may produce incorrect forecasts which lead the farmer to adopt a negative attitude towards forecasting systems in general (Butt & Jeger 1985). Another potential limitation is the cost of implementing and using a forecasting system (Campbell & Madden 1990). Costs may be high if specialized equipment or services are required, especially if needed on short notice. Also, a farmer may not be able to implement disease control recommendations if suitable equipment and conditions are not available, or if recommendations interfere with "other farm duties" (Butt & Jeger 1985, Campbell & Madden 1990).

In general two major forms of system implementation exist: regional-scale and field-scale (on-farm) (Campbell & Madden 1990, Madden & Ellis 1988, Zadoks 1984, 1990). Regional-scale forecasting systems are generally issued by mail, phone, television, or radio. For example the system developed by Buchwaldt (1986, 1989) in Denmark uses germination of sclerotia at specific locations to produce regional forecasts of the risk of sclerotinia stem rot of rapeseed and recommendations for control. However, regional forecasts may not have wide applicability when forecast regions are large and climate and soil conditions are variable (Buchwaldt 1989). Under these conditions regional forecasts would likely over-generalize and avoid risk, thereby leading to the unnecessary application of control measures (Zadoks 1984, 1990). Alternatively, forecasts can be issued on an individual field basis so that much closer contact with the farmer is established and the probability of unnecessary application of control practices is decreased.

Field-scale systems often utilize environmental data from in-field monitoring equipment rather than regional weather stations (Madden & Ellis 1988, Zadoks & Rabbinge

1985). For example, a computerized on-farm monitoring and forecasting system has been developed for apple scab (Ellis et al. 1984, Jones 1986, Jones et al. 1980, 1984). The apple scab system is based on relationships among leaf wetness, temperature and host infection by ascospores of Venturia inaequalis (Mills 1944), and is modified to account for the influence of relative humidity and discontinuous wet periods (Jones & Fisher 1980, Jones et al. 1980). In this system a microcomputer and appropriate sensors are used to monitor leaf wetness, temperature, and relative humidity, and from these data produce a field-specific forecast of infection (none, low, moderate or high). One potential disadvantage of this type of system is the relatively high cost (Campbell & Madden 1990, Madden & Ellis 1988) which could restrict its use to the "higher" value crops. Farmers may prefer to use fungicide label recommendations rather than absorb the cost of in-field monitoring equipment. Furthermore, maintenance and field placement of the equipment may be a problem (Campbell & Madden 1990).

Disease forecasting has the potential to incorporate a range of subject areas including: (1) epidemiology, (2) disease control, (3) crop loss assessment, and (4) the economics of disease management. With such a diversity of areas many authors have suggested that the systems approach should be more widely used for developing and implementing forecasting models (Johnson 1987, Kranz & Hau 1980, Pennypacker & Stevenson 1982, Zadoks 1984). Moreover, an epidemic only represents one component of the overall "agroecosystem" which also includes the: "biological-constraint system", "pest management system", and "crop management system" (Kranz & Hau 1980).

One of the few forecasting systems that uses the overall systems approach is EPIPRE (EPIdemiology and PREdiction and PREvention) for the management of several fungal diseases and aphid pests of wheat in the Netherlands (Rijsdijk 1982, Zadoks 1984, 1989). Field-specific forecasts are produced by a centralized computer system using farmer-supplied crop, disease, and insect information. At the start of the growing season the farmer mails in information concerning field identification, crop history, seeding rate

and date, expected yield, soil conditions, and cultivar (Rijsdijk 1982, Zadoks 1984). Later he submits information obtained from field inspections 2-5 times during the growing season (Zadoks 1989). Data collected include date, field identification, crop growth stage, disease and aphid counts, and fertilizer and pesticide usage. This information is submitted to the central computer, where it is entered and used in conjunction with a database of information concerning models for disease and pest development, pesticide and crop prices, and cultivar resistance. Using this information EPIPRE produces recommendations which are returned to the farmer. Three potential recommendations are produced for each disease: (1) crop loss < cost of pesticide, no control measures required, (2) crop loss > pesticide cost, but < total cost (application, labour, crop damage etc.), make specific control decision after considering other potential treatments, and (3) crop loss > total cost, control measures required. EPIPRE allows the farmer to consider the economics of disease management before a control decision is made. Over the past several years it has been evaluated in several European countries. Although EPIPRE is mainly run from a centralized computer in the Netherlands, a commercial micro-computer version of the program has been developed; however, it has not been widely used since the Dutch government provides the same service at a reduced cost.

Recently a similar management system for several fungal diseases of wheat has been developed in Israel (Shtienberg et al. 1990). However, it is designed to be used on a microcomputer and also incorporates simplified meteorological information whereas EPIPRE does not. The wheat disease control advisory (WDCA) system in Israel is a decentralized public domain program, which can be used on the farm.

2.2. The influence of crop canopy on the microenvironment and plant disease

2.2.1. Introduction

Terminology with respect to the environment often varies depending on the author or discipline (Campbell 1977, Campbell & Madden 1990, Chirkov 1979, Zadoks & Schein 1979). In this thesis microenvironment refers to the environment created by the crop canopy and macroenvironment refers to the environment outside the canopy. However, any spatial subdivision of the environment is arbitrary, since the atmosphere represents a continuum rather than separate independent levels (Oke 1987). The microenvironment is where the interaction between host and pathogen takes place. The host plant is the agent responsible for creating the unique conditions that exist within the crop canopy (Aust & Hoyningen-Huene 1986). In field crops the host begins to modify the microenvironment after plant emergence. The extent of modification increases as the host develops, eventually producing conditions which can be distinct from the macroenvironment (Rotem 1982, Wallin 1967, Zadoks & Schein 1979).

The microenvironment is a result of the interaction among attributes of the canopy, soil and atmosphere (Carlson 1982, Gates 1980). In general these interactions represent fluxes of energy, gas and liquid (Oke 1987, Zadoks & Schein 1979). In-depth descriptions of these fluxes (Campbell 1977, Gates 1980, Monteith 1973) are beyond the scope of this thesis. However, simplified diagrammatic representations of energy and water fluxes for a volume of crop canopy (Oke 1987, Tanner 1960) are depicted in Figure 2.3.

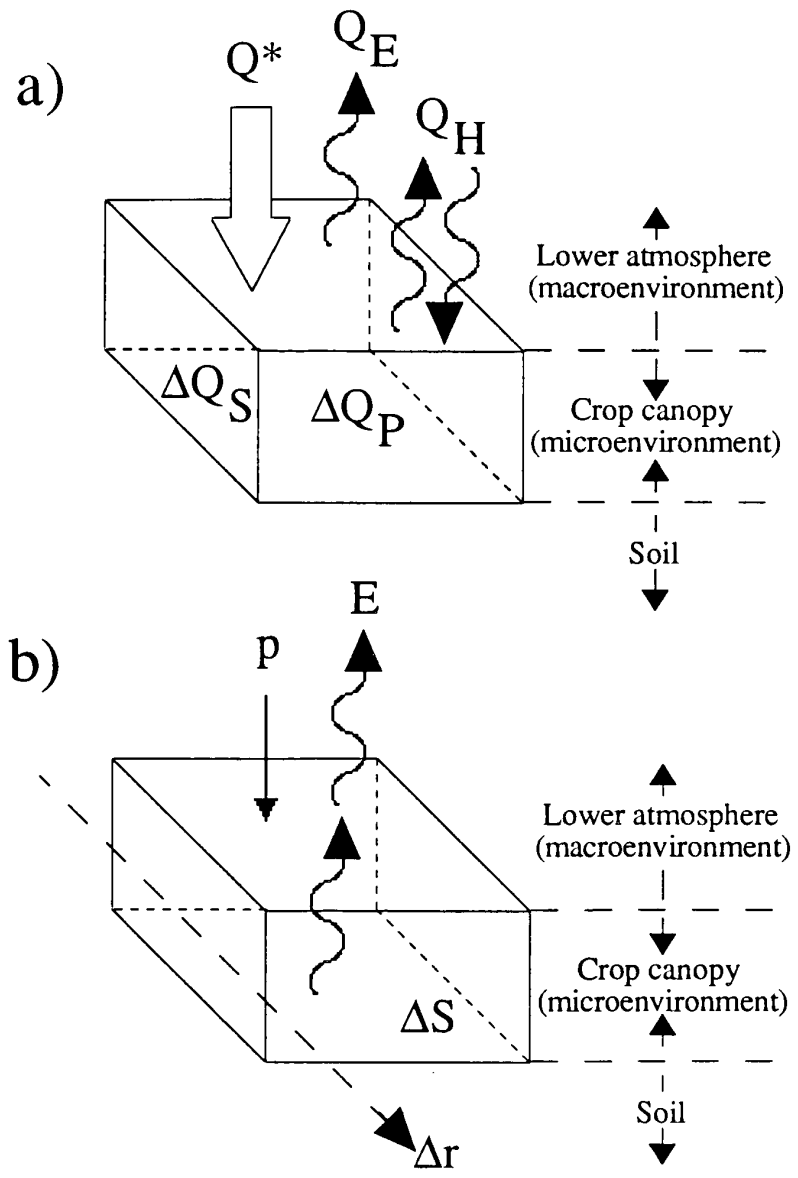

Figure 2.3. Simplified representations of the energy (a) and water (b) balances for a volume of crop canopy (Adapted from Oke 1987 and Tanner 1960). See equations 1 & 2 in text for explanation of symbols.

2.2.2. Temperature

During the day, the incoming solar and terrestrial radiation fluxes are partially absorbed, reflected and transmitted by the crop canopy (Carlson 1982, Oke 1987, Zadoks & Schein 1979), with the net effect of increasing the temperature of the microenvironment. As solar radiation penetrates into the canopy it decreases logarithmically so that lower layers of the canopy receive much less radiation than the upper layers. There is also a qualitative change since most photosynthetically active radiation (0.4-0.7 μm) is absorbed by the upper layers of the canopy. The extent of penetration of solar radiation is dependent on the density and architecture of the crop canopy (Campbell 1977, Oke 1987, Rosenberg 1974). Reflective (albedo) and absorptive (absorptivity) properties of the crop canopy will also influence penetration of solar radiation and heating of the microenvironment. Oke (1987) pointed out that the ability of leaves to reflect near infra-red radiation reduces the heat load on them. In addition, leaves have a high emissivity for the longer wavelengths, which helps them radiate surplus heat and prevent excessive temperatures.

Oke (1987) gave a simplified equation to express the energy balance of a volume of crop canopy (Figure 2.3):

$$Q^* = Q_H + Q_E + \Delta Q_S + \Delta Q_P \quad \text{.....(Equation 1)}$$

where Q^* = net radiation

Q_H = sensible heat flux

Q_E = latent heat flux (due to evapotranspiration)

ΔQ_S = net rate of physical heat storage by substances in the system

ΔQ_P = net rate of biochemical energy storage due to photosynthesis (ΔQ_S & ΔQ_P may be small compared with Q_H & Q_E).

For a crop with adequate moisture, Q_E is the dominant component of the energy flux, and

on most days is approximately equal to Q^* and may even exceed it. Thus, a large portion of net radiation is being used for evapotranspiration and only a small portion is left to heat the crop. However, under less favorable moisture conditions more net radiation goes into heating the crop.

During the day shading by the upper portions of the canopy and higher evapotranspiration result in microenvironmental temperatures that may be lower than those outside the crop canopy or above a non-vegetated surface (Aust & Hoyningen-Huene 1986, Oke 1987, Rotem et al. 1978, Zadoks & Schein 1979). At night long-wave radiation will be emitted by the crop canopy to the atmosphere as well as being transmitted from one plant to another within the canopy (Aust & Hoyningen-Huene 1986, Zadoks & Schein 1979). Thus, microenvironmental temperatures will decrease, but not as much as those above the crop canopy or above a non-vegetated surface.

In field experiments, Hatfield (1982) found that when leaf area index (LAI) of soybean was high, microenvironmental temperatures were lower than macroenvironmental temperatures. In canola, Gugel (1985) also found that temperatures within the canopy were slightly lower than ambient temperatures. Similar results were found by Blad et al. (1978) in dry edible bean where microenvironmental temperatures were generally lower for a cultivar (Tara) with a high LAI and viny growth habit than for a cultivar (Aurora) with a lower LAI and a more open upright growth habit. They also studied the influence of furrow-irrigation on the microenvironment using two irrigation regimes (high and low) and the same cultivars. Canopy temperatures were consistently lower in plots under a high irrigation regime, with the greatest difference between Tara (high irrigation) and Aurora (low irrigation). Furthermore, daytime temperatures in the Aurora plots under low irrigation were often $\geq 30°C$, while values in the Tara plots under high irrigation never reached this level. Blad et al. (1978) suggested that in the low irrigation plots more of the energy from solar radiation went into raising microenvironmental temperatures rather than into transpiration.

Weiss et al. (1980a) conducted similar experiments using the same dry edible bean cultivars and found that canopy temperatures were typically lower in plots with high rates of furrow-irrigation than with low rates. Differences between plots were not only attributed to irrigation regime, but also to canopy density. Leaf area index was generally higher for both cultivars with high irrigation; however, Tara had a greater LAI than Aurora regardless of irrigation regime.

2.2.3. Moisture

The crop canopy also has a significant effect on moisture levels in the microenvironment. Oke (1987) gave an equation that describes the water balance of a volume of crop canopy (Figure 2.3):

$$p = E + \Delta r + \Delta S \quad \text{.....(Equation 2)}$$

where p = incoming moisture (rain, dew, etc.)

E = evapotranspiration

Δr = net runoff (i.e. the net change in runoff over a distance, negligible on level terrain)

ΔS = net water storage in the volume of crop canopy and soil.

Moisture arrives in the crop canopy from various sources including rain, dew, fog, and irrigation and is stored in various components of the crop volume. Interception of moisture by the canopy depends on the type and quantity of precipitation and the architecture and density of the crop canopy (Oke 1987, Zadoks & Schein 1979). The "interception efficiency" of precipitation is high during the initial stages of rainfall and if the intensity is

low. Eventually a threshold of moisture storage is reached and the efficiency of interception declines as excess moisture runs off to the soil. Excess moisture may be absorbed into the soil or remain in puddles on the surface.

Although moisture is lost from the canopy by evaporation from wet surfaces, the major route for loss is through transpiration (Oke 1987). Both processes release water vapour into the microenvironment (Aust & Hoyningen-Huene 1986, Zadoks & Schein 1979). However, transport of this moisture into the macroenvironment is restricted by the crop canopy and is dependent on the height, architecture and density of the crop. The restriction is mainly through an influence on turbulent exchange between the micro- and macroenvironment (Campbell 1977, Grace 1983, Rosenberg 1974). Wind speed typically decreases logarithmically with depth near the top of the canopy, but deviates from this pattern further down (Burrage 1976, Campbell 1977, Zadoks & Schein 1979). Because the canopy reduces transfer of water vapour into the macroenvironment, moisture has a greater tendency to remain in the microenvironment than over a non-vegetated soil surface.

In field experiments, Hatfield (1982) found that relative humidity (RH) was higher and dew persisted for longer periods of time within a soybean canopy than outside. Gugel (1985) also found that RH within a canola canopy was consistently higher and more stable than ambient RH. In addition, he found that water droplets persisted longer in canola leaf axils close to the soil surface than in those near the top of the canopy. He suggested this difference may have been related to the occurrence of larger leaf axils towards the plant base as well as reduced evaporation in the lower canopy. In potato canopies Cappaert & Powelson (1990) found that leaf wetness duration generally increased with increasing LAI and was greatest when plant density was high. They also found that when plants began to senesce the canopy started to open up and the duration of leaf wetness decreased.

Using two irrigation regimes (low and high) and two cultivars (Tara and Aurora) with different canopy structures, Blad et al. (1978) demonstrated that canopy density also influenced leaf wetness duration in dry edible beans. The duration of wetness was highest

in plots of Tara under high irrigation and lowest in plots of Aurora under low irrigation. As mentioned above (Section 2.2.2) Tara has a more viny growth habit with a higher LAI than Aurora which has a more open upright growth habit and lower LAI.

2.2.4. Impact on disease

Crop canopy structure can have a significant influence on disease development. Cappaert & Powelson (1990) investigated the influence of plant density on the microenvironment in potato and on development of aerial stem soft rot caused by Erwinia carotovora subsp. carotovora. Four treatment combinations were established using two within-row plant spacings (23 or 46 cm) and two between-row spacings (83 or 173 cm). They demonstrated that disease levels, LAI and the duration of leaf wetness were significantly higher for heavy plant densities than for light densities. Moreover, they found that the area under the disease progress curve was significantly related to the area under the leaf area index curve, with coefficients of determination of 95-99%.

Crop canopy is also thought to be an important factor influencing the development of diseases caused by Sclerotinia sclerotiorum. In 1969 and 1970, Haas & Bolwyn (1972) surveyed the incidence of sclerotinia wilt on white bean in southern Ontario. They found that in crops with disease the number of plants per m^2 was significantly lower and dry weight per plant and canopy density (plant population/m^2 x dry weight/plant) were significantly higher than in crops without disease.

A number of papers have been published on the influence of plant architecture in dry edible beans on the development of white mold caused by Sclerotinia sclerotiorum. Steadman et al. (1973) demonstrated that narrow row spacing increased the severity of white mold. Furthermore, it was found that a near-isogenic line with a determinate bushy growth habit had significantly less disease than a cultivar with an indeterminate viny

growth habit. Coyne et al. (1974) modified the architecture of two dry bean cultivars by pruning, application of a growth regulator and utilization of trellis supports. They found that application of a growth regulator and pruning resulted in disease levels similar to the control. However, trellis-supported plants had generally less disease than the other treatments. Presumably this difference was the result of enhanced turbulence and drying in the trellis supported plants which would contribute to a microenvironment less suitable for disease development.

Using two near-isogenic breeding lines and three cultivars with varying growth habits, Schwartz et al. (1978) evaluated the influence of dry edible bean canopies on white mold. One breeding line (Code P #82) and two cultivars (Aurora, Tara) had indeterminate growth habits, with most of their leaf area close to the ground. However, a third cultivar (Charlevoix) and a second breeding line (Code P #92) had determinate growth habits and a more uniform distribution of leaf area. Tara usually had the greatest canopy dry weight and within- and between-row LAI, while Aurora and Charlevoix had the lowest; however, these differences were not always significant. The two near isogenic lines P #82 and P #92 tended to have intermediate LAI and canopy dry weight.

Schwartz et al. (1978) found that white mold was most severe on Tara and P #92, while P #82 was moderately infected. Aurora and Charlevoix had low disease levels in one year of the study, while in the following year very little disease was found. They concluded that plant architecture had a significant influence on the development of white mold and that an indeterminate growth habit was not always associated with more disease. Plants with the most disease tended to have a more compact, dense and viny canopy structure, while plants with the least disease tended to have a more upright, open and bushy canopy structure. Schwartz et al. (1978) suggested that the latter growth habit did not favor disease development.

Fuller et al. (1984) also demonstrated that dry edible bean canopy architecture had a significant influence on white mold development. They indicated that certain cultivars with

dense, viny and compact canopy structures and indeterminate growth habits developed less disease because the canopy formed a "tunnel" between the rows. As a result there is enhanced air circulation producing a less favorable microenvironment for disease development. Fuller et al. (1984) demonstrated the "tunnel effect" in a commercial field of dry edible beans by creating large and small artificial tunnels using wire fencing. In addition, they constructed wire trellis supports in the same field and compared them with controls. White mold severity was highest in the control and lowest in the trellis-supported treatment. The tunnel treatments had intermediate disease levels, with more disease in the small tunnel than in the large tunnel. Fuller et al. (1984) suggested that differences among treatments may have partly reflected better air circulation within the canopy, which would have created a less favorable microenvironment for disease development.

Studies by Blad et al. (1978) and Weiss et al. (1980a), described in Sections 2.2.2 & 2.2.3, demonstrated differences in the microenvironment and canopy structure of the dry edible bean cultivars Tara and Aurora. In addition, substantial differences were demonstrated in white mold severity between cultivars and irrigation regimes. In both studies Tara had substantially higher disease levels under both irrigation regimes than Aurora. Both Blad et al. (1978) and Weiss et al. (1980a) concluded that irrigation and canopy architecture had a significant influence on the development of white mold, through microenvironmental effects (Sections 2.2.2 & 2.2.3).

Literature concerning the influence of canopy density on sclerotinia stem rot of canola is very limited. Morrall and Dueck (1982) have suggested that crop phenology may influence inoculum production and host infection. Experiments by Gugel & Morrall (1986) demonstrated that no significant relationship existed between the number of canola plants per m^2 and the incidence of sclerotinia stem rot. In other studies, Turkington (1988) made subjective estimates of canopy density (light, moderate and heavy) in commercial canola crops and found a consistent increase in disease as canopy density increased. Part

of a prediction scheme for sclerotinia stem rot of canola (Thomas 1984) indicates that disease risk increases as the yield potential of the crop increases. Presumably higher yielding crops would have denser plant canopies, which would contribute to a more favorable microenvironment for disease development.

Modification of the microenvironment by a crop canopy and its subsequent influence on the host-pathogen interaction may be limited under certain conditions. Rotem (1982) and Rotem & Palti (1980) discussed the influence of cultural control measures, such as plant canopy modification, on disease. They suggested that these measures may have less influence when macroenvironmental conditions are either extremely unfavorable or extremely favorable for disease development (Figure 2.4). With extremely unfavorable conditions modification of the microenvironment by the crop may be limited and neither macro- nor microenvironmental conditions favor disease development (Rotem & Palti 1980).

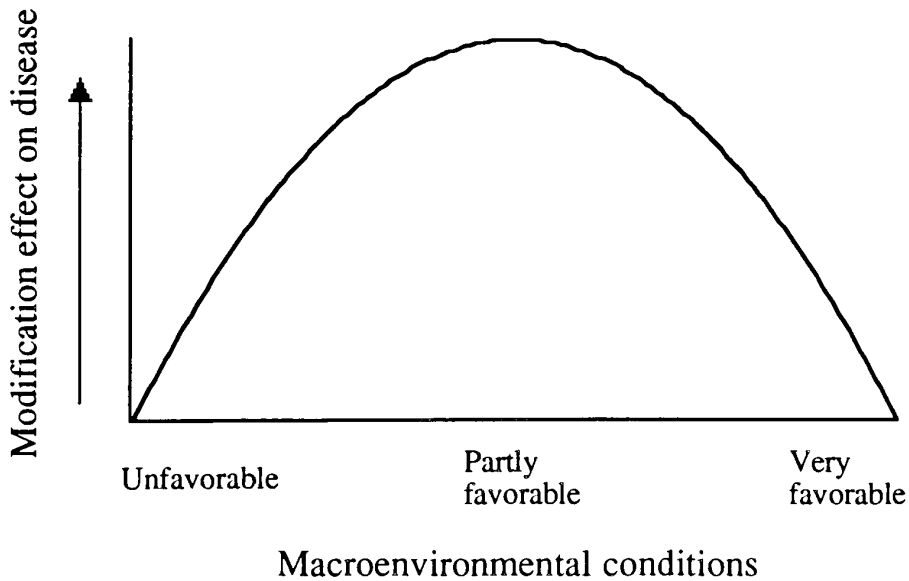

Figure 2.4. The degree of influence of canopy modification on disease in relation to changing macroenvironmental conditions (From Rotem 1982).

With more favorable macroenvironmental conditions, modification of the environment by the crop canopy may be sufficient to produce microenvironmental conditions which are conducive for disease. Here variation between crops may produce differences in some critical microenvironmental variable which result in noticeable differences in disease (Rotem & Palti 1980). For example Rotem (1982) described the situation in Israel where potato canopy modification does not influence late blight development during August when high temperatures are common and neither macro- nor microenvironmental conditions are favorable. However, by October macroenvironmental conditions have started to moderate so that modification has a much greater influence on the microenvironment, which in turn may affect disease.

If macroenvironmental conditions are extremely favorable disease development may occur regardless of any modification of the microenvironment by the host. In Israel, in May and June, Rotem & Ben-Joseph (1970) found substantial differences in the severity of late blight between dense and light stands of potatoes produced by altering planting density. However, by November environmental conditions were much more favorable and similar levels of disease developed in both dense and light stands.

With respect to the control of plant diseases, Rotem and Palti (1980) indicated general weather conditions which may influence the effectiveness of cultural control through crop canopy modification (Table 2.1). These characteristics also indicate the conditions under which it may be necessary to account for the influence of crop canopy on plant disease. This is especially important when trying to develop a better understanding of the factors that influence the interaction of host, pathogen and environment so that more effective management strategies can be produced.

Table 2.1. Characteristics of the environment which may influence the effectiveness of cultural control measures, such as canopy modification (Rotem & Palti 1980).

	Effectiveness of cultural control	
	Increases when	Decreases when
Suitability of weather conditions	usually suboptimal	mostly optimal
Variation in air masses	common	uncommon
Rainfall distribution	nonuniform	uniform
Seasonal and daily temperature ranges	broad	narrow
Radiation	high	low

3. ENVIRONMENTAL DATA

3.1. Introduction

Environmental data were collected for 1987-90. These data were used to interpret the results of studies reported in Sections 4-6 and are presented, as appropriate, in those sections. Daily temperature, rainfall and sunshine data for May-August at Melfort in 1987, at Outlook in 1988 and at Meadow Lake from 1988 to 1990 were obtained from Environment Canada meteorological stations. Hourly wind data were also obtained for Melfort and Meadow Lake. Measurements of temperature, RH, leaf wetness and rainfall were also made in either commercial canola crops or small-plot field experiments with in-crop monitoring equipment. Although data from these sources represent conditions at a particular location, they do provide information concerning general microenvironmental and weather trends.

3.2. Microenvironmental monitoring

In 1987, two Campbell Scientific Canada Corp. (CSC) microloggers were set up in the Melfort study area. On June 11 a CSC CR21 (Micrologger 1) was placed 16 km N.E. of Melfort in a crop of Brassica napus cv. Tribute at growth stage (GS) 2.5 (Harper & Berkenkamp 1975). Measurements of temperature, RH and leaf wetness were made every 60 sec using a CSC 201 temperature-RH sensor and a CSC 231 leaf wetness sensor coated with a thin layer of flat white latex paint (Gillespie & Kidd 1978). These measurements were then averaged by the micrologger every 15 min. A Sierra-Misco Inc. RG-2501 tipping bucket rain gauge was also connected to the micrologger and recorded total rainfall every 15 min in increments of 1 mm. A CSC 21X (Micrologger 2) was placed in a crop of

B. napus cv. Westar (GS 2.5) 37 km S.W. of Melfort on June 18. It was connected to three CSC 207 temperature-RH sensors, three CSC 237 leaf wetness sensors, and a Sierra-Misco RG-2501 tipping bucket rain gauge. Micrologger 2 was programmed to average measurements of temperature, RH and leaf wetness at 15 min intervals, and to record total rainfall, measured in increments of 0.25 mm, every 15 min. Data presented for temperature, RH and leaf wetness represent means for the three sensors. All sensors for both microloggers were mounted within the canopy at heights of 15-30 cm above the soil surface. Small areas were cleared within the crops so that plant canopies did not interfere with rainfall collection.

In 1988, two CSC CR21 microloggers were set up in the Meadow Lake area using the same program, sensors, and placement as described for the CR21 in 1987. The first micrologger was set up on July 2 in a crop of cv. Westar (GS 4.2) located 9 km N.W. of Meadow Lake, and the second micrologger was set up on July 3 in a crop of cv. Westar (GS 4.2) located 13.5 km N.E. of Meadow Lake.

In 1989, three microloggers were set up in two small-plot experiments on canopy density in the Meadow Lake area (Section 4.2.1). On June 26 a CSC CR21 and a CSC 21X were placed in plots (Experiment 1) of cv. Westar (GS 2.8-3.1) located 16 km N.W. of Meadow Lake. Attached to the CR21 were three CSC 231 leaf wetness sensors and a Sierra-Misco RG-2501 tipping bucket rain gauge (0.25 mm increment). Six CSC 207 temperature-RH sensors and three CSC 237 leaf wetness sensors were attached to the 21X. Microenvironmental conditions were monitored in six plots with seeding rates of 1.5, 4.0, 6.5, 9.0, 11.5 and 14.0 kg/ha. A second CSC CR21 was set up on July 3 in plots (Experiment 2) of cv. Westar (GS 2.8-3.1) located 10 km N.W. of Meadow Lake. Attached to this CR21 were three CSC 231 leaf wetness sensors placed in plots with seeding rates of 1.5, 9.0 and 14 kg/ha and a Sierra-Misco RG-2501 tipping bucket rain gauge (0.25 mm increment). All three microloggers in 1989 operated with similar programs and sensor placement as described for the CR21 and 21X in 1987.

Microloggers were also set up in canopy density experiments in the Meadow Lake area in 1990 (Section 4.2.2). On June 20 a CSC 21X with three CSC 207 temperature-RH sensors, three CSC 237 leaf wetness sensors and a Sierra-Misco RG-2501 tipping bucket rain gauge (1 mm increment) was placed in plots of cv. Westar (GS 2.5-3.0) (Experiment 3) located 16 km N.W. of Meadow Lake. Microenvironmental conditions were monitored in three plots with seeding rates of 2.0, 9.5, and 17.0 kg/ha. On July 5 a second CSC 21X with similar sensors was placed in plots (Experiment 4) of cv. Westar (GS 3.3-4.1) located 5.5 km N.E. of Meadow Lake. Temperature, RH and leaf wetness were monitored in plots with seeding rates of 0.5, 12.5, 15.5, and 17.0 kg/ha. Rainfall data were collected starting July 11. On June 20 a CR21 was placed in plots (Experiment 5) of cv. Westar (GS 2.5-3.0) located 11.5 km N.W. of Meadow Lake. Temperature, RH and leaf wetness were monitored in a single plot with a seeding rate of 9.5 kg/ha. Rainfall data were not collected. All three microloggers in 1990 operated with similar programs and sensor placement as described for the CR21 and 21X in 1987.

4. CANOPY DENSITY

4.1 Introduction

Diseases caused by Sclerotinia sclerotiorum are influenced by several environmental variables. For example, moisture affects carpogenic germination of sclerotia (Abawi & Grogan 1975, Morrall 1977, Teo & Morrall 1985a, 1985b), ascospore germination and host infection (Boland & Hall 1987, Brün et al. 1983, Le Coz 1981). Crop canopy is also an important factor influencing these diseases. Modification of the microenvironment by the crop canopy may produce conditions which are more favorable for disease development. For example, in the United States crop canopy has been shown to have a significant effect on white mold of dry edible bean (Section 2.2.4). However, information concerning the effect of crop canopy on stem rot of canola is limited. Turkington (1988) suggested that crop canopy may have an influence on the relationship between the incidence of sclerotinia stem rot and the level of infestation of canola petals by S. sclerotiorum. The current section describes experiments to investigate this influence as well as the more general effect of crop canopy on the incidence of stem rot.

4.2. Materials and methods

4.2.1. 1989

Two small-plot experiments were conducted in commercial canola fields at Meadow Lake, Saskatchewan, an area with a history of sclerotinia stem rot. The experiments were set up using a five-replicate randomized complete block design (RCBD) with a factorial treatment arrangement. A total of 12 treatment combinations were used based on two

cultivars (B. napus cv. Westar and B. campestris cv. Tobin) and six seeding rates (1.5, 4.0, 6.5, 9.0, 11.5, and 14.0 kg/ha). Plots were seeded on May 17 (Experiment 1) and May 25 (Experiment 2) using a small-plot tractor-drawn seeder. Individual plots were 5.5 m x 4.9 m and consisted of 24 rows with row spacing of 17.8 cm. Individual plots were surrounded by a 1.2 m pathway of barley.

In July, PPI was assessed and measurements of canopy density were made in each experiment. Percentage petal infestation was assessed for both cultivars at early (GS 4.1-4.2), full (GS 4.3) and late bloom (GS 4.3-4.4) from plots with seeding rates of 1.5, 9.0, and 14.0 kg/ha. The collection of petals and assessment of PPI were done according to procedures described by Turkington (1988) and Turkington et al. (1988). A total of 40 petals from each plot were plated in petri dishes containing Difco potato dextrose agar amended with 25 ppm anhydrous ampicillin and 25 ppm streptomycin sulfate. Plates were incubated at 25°C for 3-4 days before PPI was assessed.

Measurements of plant height, stem thickness, and light penetration were taken at full bloom for all plots of both cultivars, and at early and late bloom for all plots of cv. Westar. In each plot stem thickness was measured using calipers on ten plants and five measurements of crop height were taken. Five above and below crop measurements of light intensity were also made in each plot using a LI-COR LI-190SB Quantum sensor attached to a LI-COR LI 185B Quantum/ Radiometer/ Photometer. Percentage light penetration was calculated as the percentage of above-canopy light intensity that penetrated the canopy to the soil surface. Measurements of stem thickness, crop height, and light penetration were made nonselectively in the plots and provided objective estimates of factors that were thought to be related to canopy density.

An attempt was also made to measure leaf area index (LAI) at full bloom for all plots in both experiments. Plants were pulled and counted from a 0.58 m^2 area (0.82 m length of 4 rows spaced 17.8 cm apart). Then, using a procedure similar to that of Clarke & Simpson (1978) a random sample of ten plants was used for determination of LAI using

a LI-COR Model LI-3000 Portable Area Meter with attached Model LI-3050A Transparent Belt Conveyer Accessory. Because of time constraints, samples of cv. Tobin collected at full bloom from Experiments 1 and 2 were initially stored in plastic bags and placed in a refrigerator set at approximately 5 °C; however, before leaf area measurements could be made on all samples, rotting of plant tissue occurred. Hence leaf area measurements were made only on cv. Westar in Experiment 1. It was decided to omit measurements on cv. Westar in Experiment 2.

Disease incidence was assessed in both experiments in mid-August by counting the number of infected plants out of a random sample of 200 plants in each plot. Plant counts from the 0.58 m^2 sampling areas used for LAI measurements were used to calculate the number of plants per m^2 for both cultivars in Experiment 1, and for cv. Tobin in Experiment 2. For cv. Westar in Experiment 2, the number of plants per m^2 was assessed in August using a one m^2 quadrat.

The Statistical Analysis System (SAS Institute 1985) was used to conduct an analysis of variance (ANOVA) of mean DI (MDI), which was partitioned into the following sources: block, cultivar, seeding rate (SR), linear component of SR, quadratic component of SR, cubic component of SR, and the interaction of SR and cultivar. Covariance analysis was then used to investigate the nature of the treatment effects (Snedecor & Cochran 1980). Mean percentage light penetration (MPLP) at full bloom was used as a covariate to determine if MPLP accounted for variation in MDI not accounted for by the various treatment effects. Moreover, covariance analysis was used to indicate if variation due to unadjusted treatment effects (especially seeding rate) simply reflected variation due to the covariate MPLP. Several null and alternative hypotheses were tested for Experiments 1 and 2 and are listed in Appendix A.

Plots of the residuals from MDI and arcsine-transformed MDI (TMDI) were used to determine if the underlying assumptions of the analyses were valid. Residuals for the transformed data appeared to more closely approximate a normal distribution and had

greater equality of variances. Thus, interpretations were based on analyses of arcsine-transformed data for both experiments.

4.2.2. 1990

Three small-plot experiments were set up in commercial canola fields at Meadow Lake using a five-replicate RCBD, with treatments consisting of 12 seeding rates (0.5, 2.0, 3.5, 5.0, 6.5, 8.0, 9.5, 11.0, 12.5, 14.0, 15.5, and 17.0 kg/ha). Experiments 3 and 4 were seeded with Brassica napus cv. Westar, but in Experiment 5 a mixture of B. napus cv. Westar and B. napus cv. Tristar (triazine tolerant) was used. Plots were seeded on May 22 (Experiment 3), May 23 (Experiment 4), and May 24 (Experiment 5) using a small-plot tractor-drawn seeder with 17.8 cm row spacing. Individual plots were 5.5 m x 4.9 m and consisted of 24 rows. Plots were separated by a 1.2 m border of either cv. Westar or cv. Tristar, and each experiment was surrounded by a 2.4-4.9 m border of canola. By seeding the mixture of cultivars in Experiment 5 an attempt was made to reduce compensation in plant growth. Tristar was planted according to the 12 seeding rates, but cv. Westar was added to the seed to make each treatment up initially to a seeding rate of 17 kg/ha. In order to eliminate cv. Westar, on June 27 when the plants were in the early bud stage (GS 3.1), Bladex (cyanazine, 480 g a.i./l) was sprayed at recommended rates (Anonymous 1990).

Seedling and stand establishment in Experiments 3 and 4 were satisfactory and produced consistent differences among treatments; however, poor seedling germination and establishment in Experiment 5 produced inconsistent differences among treatments. These differences persisted even after application of Bladex.

In July, PPI was assessed and measurements of canopy density were made. In Experiments 3 and 4, petals were collected at early, full, and late bloom from plots with

seeding rates of 0.5, 8.0, and 17.0 kg/ha. Percentage petal infestation was then determined using the same procedure as in 1989. Petal infestation values representative of Experiment 5 were obtained from survey sampling sites in the commercial canola field near where the plots were located. Non-destructive assessment of LAI was done using a LI-COR LAI-2000 plant canopy analyzer which computes LAI from measurements of light interception by the canopy. Five measurements of canopy light interception were made in each plot for derivation of LAI. Leaf area index was assessed at early, full, and late bloom in all plots for Experiments 3 and 4, but in Experiment 5 LAI was only assessed at full and late bloom. Since measurements of light penetration were used in 1989 to assess canopy density, for purposes of comparison the same measurements were made in Experiments 3, 4 and 5 at late bloom, using the same procedure as in 1989.

Disease incidence was assessed in all experiments in mid-August by counting the number of infected plants out of a random sample of 200 in each plot. However, as a result of extremely low disease levels in Experiments 3, 4 and 5 it was decided to omit the measurements of the number of plants per m^2, since no additional useful information would be obtained. As in 1989 several environmental variables were monitored in the experimental plots (Section 3.2) in order to assist in interpretation of the results.

4.3 Results

4.3.1. 1989

Disease levels were higher in Experiment 1 than Experiment 2 (Tables 4.1, 4.2). In Experiment 2, MDI generally increased as the seeding rate increased; however, a similar trend was not observed in Experiment 1. Mean disease incidence was similar for both cultivars in Experiment 1, but in Experiment 2 cv. Tobin had higher MDI than cv. Westar.

The mean number of plants per m^2 (MNPS) was similar in both experiments and increased as the seeding rate increased. Cultivar Tobin had a higher MNPS than cv. Westar. Mean percentage petal infestation (MPPI) was slightly higher in Experiment 1 and was generally higher for cv. Tobin than cv. Westar. In addition, MPPI tended to be greatest either at early or full bloom and declined substantially by late bloom.

Mean crop height (MHT) at full bloom was similar in both experiments and among the various seeding rates tested; however, cv. Westar was taller than cv. Tobin (Tables 4.1, 4.2). For cv. Westar MHT increased from early to late bloom. Mean stem thickness (MST) at full bloom was also similar for both experiments, and decreased as the seeding rate increased. No change in MST was observed between early and late bloom for cv. Westar. Mean percentage light penetration was measured in both experiments and would be expected to decrease as crop canopy density increased. In both experiments MPLP tended to decrease as the seeding rate increased. Cultivar Westar in Experiment 1 and cv. Tobin in Experiment 2 tended to show the lowest MPLP. Mean leaf area index (MLAI) for cv. Westar in Experiment 1 increased as the seeding rate increased from 4.0 to 14.0 kg/ha. The lowest seeding rate (1.5 kg/ha) had a relatively high MLAI, which may have been due to the extremely large leaves produced by plants in this treatment.

Table 4.1. Mean values for measurements† of inoculum, disease and crop characteristics, cvs. Tobin and Westar, Experiment 1, Meadow Lake, 1989.

Cultivar & SR§	MDI	MNPS	Early bloom				Full bloom					Late bloom			
			MPPI	MHT	MST	MPLP	MPPI	MHT	MST	MPLP	MLAI	MPPI	MHT	MST	MPLP
Tobin															
1.5	24.1	32	4.0				74.5	79.0	0.78	5.0		11.5			
4.0	19.4	85						77.5	0.65	3.1					
6.5	22.4	129						81.7	0.58	2.2					
9.0	16.8	186	8.0				64.0	80.6	0.46	2.3		15.0			
11.5	32.7	231						81.3	0.40	1.6					
14.0	24.8	304	7.0				61.7	77.2	0.37	1.9		13.5			
Cultivar mean	23.4	161	6.3				66.7	79.6	0.54	2.7		13.3			
Westar															
1.5	18.8	25	44.0	75.1	0.82	7.3	31.0	99.0	0.80	4.0	1.9	0.5	108.2	0.81	3.4
4.0	27.8	51		81.8	0.62	4.5		100.2	0.65	2.6	1.2		108.2	0.64	3.0
6.5	28.8	84		80.0	0.44	4.5		98.6	0.48	2.5	1.5		106.2	0.43	2.7
9.0	23.6	134	43.5	77.8	0.41	4.4	37.0	98.3	0.38	2.0	1.9	0.5	105.4	0.45	2.5
11.5	36.7	163		78.6	0.38	3.2		99.9	0.41	1.5	2.2		105.4	0.43	2.2
14.0	24.0	220	36.5	78.0	0.37	3.5	35.0	98.0	0.35	2.1	2.4	0.5	101.8	0.38	2.3
Cultivar mean	26.6	113	41.3	78.6	0.51	4.6	34.3	99.0	0.51	2.4	1.8	0.5	105.9	0.52	2.7
Exp. mean	25.0	137	23.8				50.5	89.3	0.52	2.6		6.9			

† MDI = Mean disease incidence (%) from untransformed data, MNPS = Mean number of plants per m^2, MPPI = Mean percentage petal infestation, MHT = Mean crop height (cm), MST = Mean stem thickness (cm), MPLP = Mean percentage light penetration, MLAI = Mean leaf area index.

§ Seeding rate (kg/ha).

Table 4.2. Mean values for measurements† of inoculum, disease and crop characteristics, cvs. Tobin and Westar, Experiment 2, Meadow Lake, 1989.

Cultivar & SR§	MDI	MNPS	Early bloom				Full bloom				Late bloom			
			MPPI	MHT	MST	MPLP	MPPI	MHT	MST	MPLP	MPPI	MHT	MST	MPLP
Tobin														
1.5	4.1	32	49.6				33.5	69.6	0.84	2.9	14.0			
4.0	10.7	109						76.6	0.67	1.7				
6.5	10.9	139						78.5	0.50	1.7				
9.0	15.3	187	44.0				42.0	77.8	0.44	1.1	7.0			
11.5	9.9	231						74.6	0.41	1.3				
14.0	19.3	276	49.0				38.5	73.8	0.36	1.0	10.6			
Cultivar mean	11.7	162	47.5				38.0	75.1	0.53	1.6	10.5			
Westar														
1.5	4.2	36	23.0	78.7	0.91	5.7	31.0	98.4	0.87	4.4	2.5	103.1	0.87	4.6
4.0	5.4	79		84.2	0.68	2.8		101.2	0.65	3.3		105.4	0.67	3.2
6.5	6.0	121		84.1	0.52	2.5		99.5	0.48	3.4		103.8	0.54	3.5
9.0	6.6	144	27.5	82.7	0.47	2.3	31.5	100.6	0.48	2.9	3.0	106.7	0.45	2.6
11.5	8.9	168		84.9	0.44	2.2		98.8	0.45	3.0		104.2	0.47	2.5
14.0	7.2	176	27.6	83.4	0.43	2.2	31.5	99.9	0.42	2.8	2.5	103.6	0.47	2.6
Cultivar mean	6.4	121	26.0	83.0	0.57	2.9	31.3	99.7	0.56	3.3	2.7	104.4	0.58	3.2
Exp. mean	9.0	141	36.8				34.7	87.4	0.55	2.4	6.6			

† MDI = Mean disease incidence (%) from untransformed data, MNPS = Mean number of plants per m^2, MPPI = Mean percentage petal infestation, MHT = Mean crop height (cm), MST = Mean stem thickness (cm), MPLP = Mean percentage light penetration.

§ Seeding rate (kg/ha).

Canopy temperature, RH and leaf wetness duration were monitored in single plots of cv. Westar for all seeding rates in Experiment 1 (Section 3). In Experiment 2, leaf wetness duration was monitored in single plots of cv. Westar for seeding rates of 1.5, 9.0 and 14.0 kg/ha. Average mean, minimum and maximum temperatures and RH's and daily leaf wetness duration were similar for most seeding rates in Experiment 1 (Table 4.3). However, with a seeding rate of 11.5 kg/ha there were slightly higher mean and minimum RH values and longer periods of leaf wetness than with the other seeding rates. In Experiment 2, the duration of leaf wetness was similar for the three seeding rates monitored. Frequent showers were observed in June 1989, especially during the last half of the month (Figure 4.1). Based on data collected after July 3 more rainfall was recorded in Experiment 1 than Experiment 2 (Fig. 4.2).

Table 4.3. Average mean, minimum and maximum daily temperature and relative humidity and daily leaf wetness duration for various seeding rates and periods in Experiments 1 and 2, Meadow Lake, 1989 (Section 3).

		Daily temperature			Daily relative humidity			
Exp.†	SR‡	Mean	Min.	Max.	Mean	Min.	Max.	DLWD§
1	1.5	17.9	10.1	27.4	87.2	63.1	99.7	4.9
	4.0	17.4	10.1	25.3	87.5	66.9	99.1	4.6
	6.5	17.8	10.0	26.9	87.0	62.9	99.6	5.8
	9.0	17.7	9.9	26.4	87.9	65.6	99.5	5.3
	11.5	17.2	10.4	24.9	90.2	72.4	99.5	8.9
	14.0	17.7	10.0	26.5	86.7	63.0	99.3	6.1
2	1.5							5.9
	9.0			No data				6.3
	14.0							4.9

† Data from June 27 to August 17 in Experiment 1 and from July 4 to August 20 in Experiment 2.

‡ Seeding rate (kg/ha).

§ Daily leaf wetness duration.

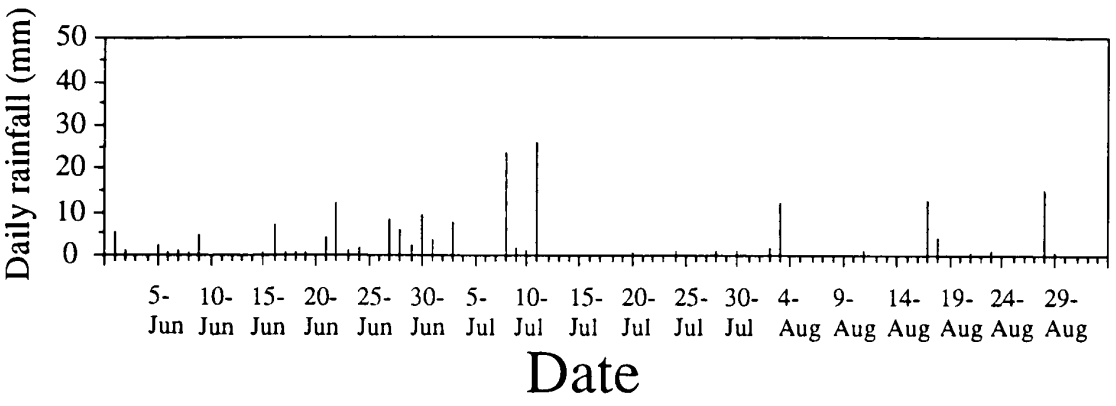

Figure 4.1. Daily total rainfall from June to August at the Environment Canada reporting station at Meadow Lake, 1989.

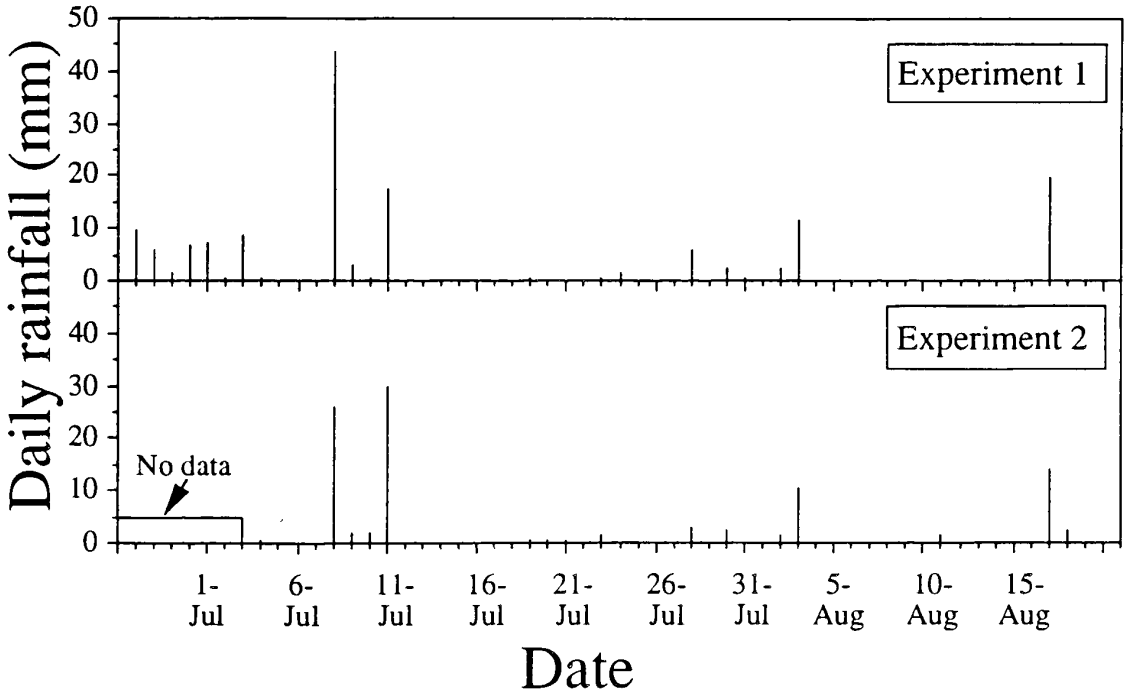

Figure 4.2. Daily total rainfall from June 27 to August 17 in Experiment 1 and from July 4 to August 20 in Experiment 2, Meadow Lake, 1989.

Analysis of variance of data from Experiment 1 indicated that none of the sources of variation had a significant effect on TMDI (Table 4.4). In Experiment 2, seeding rate and cultivar had highly significant effects on TMDI, but no significant interaction between seeding rate and cultivar was found (Table 4.4). The relationship between seeding rate and TMDI was best described by linear effects. Appendix B contains mean TMDI and corresponding standard errors for each seeding rate in Experiments 1 and 2.

The incidence of stem rot also depends on the amount of inoculum that is present (Gugel & Morrall 1986, Turkington 1988); however, in both experiments MPPI was similar among the three seeding rates in which it was measured (Tables 4.1, 4.2). This was confirmed by ANOVA of MPPI at early, full and late bloom; no significant differences were found among the three seeding rates. However, significant differences ($p = 0.01$) between cvs. Westar and Tobin were found in Experiment 1 at early, full and late bloom and at early and late bloom in Experiment 2. These differences were attributed to variation in the time of flowering of cultivars in each experiment. Mean percentage light penetration was used as a covariate for analysis of covariance in Experiments 1 and 2 (Table 4.5). In both experiments only MPLP was found to be significantly related to TMDI. In Experiment 2, seeding rate, the linear component of seeding rate and cultivar were no longer significant after inclusion of MPLP as a covariate indicating that variation in MDI was related to canopy density.

Table 4.4. Analysis of variance for arcsine-transformed mean disease incidence, Experiments 1 and 2 Meadow Lake, 1989.

Experiment 1			
Source	df	SS	F
Blocks	4	299	1.3
Seeding Rate	5	548	1.9
Linear comp.	1	118	2.0
Quadratic comp.	1	8	0.1
Cubic comp.	1	37	0.6
Cultivar	1	67	1.2
Seeding Rate * Cultivar	5	177	0.6
Error	44	2563	
Total	59	3654	
Coefficient of variation: 25.9%			

Experiment 2			
Source	df	SS	F
Blocks	4	87	0.9
Seeding Rate	5	515	4.2**
Linear comp.	1	431	17.7**
Quadratic comp.	1	36	1.5
Cubic comp.	1	32	1.3
Cultivar	1	335	13.7**
Seeding Rate * Cultivar	5	221	1.8
Error	44	1074	
Total	59	2232	
Coefficient of variation: 29.8%			

** Significant at p = 0.01.

Table 4.5. Analysis of covariance for arcsine-transformed mean disease incidence, Experiments 1 and 2 Meadow Lake, 1989.

Experiment 1			
Source	df	SS	F
Blocks	4	96	0.5
Seeding Rate	5	399	1.6
Linear comp.	1	26	0.5
Quadratic comp.	1	39	0.8
Cubic comp.	1	64	1.2
Cultivar	1	32	0.6
Seeding Rate * Cultivar	5	258	1.0
Covariate			
MPLP†	1	342	6.6*
Error	43	2221	
Total	59	3654	
Coefficient of variation: 24.4%			

Experiment 2			
Source	df	SS	F
Blocks	4	116	1.5
Seeding Rate	5	24	0.2
Linear comp.	1	1.5	0.1
Quadratic comp.	1	4	0.2
Cubic comp.	1	0.7	0.04
Cultivar	1	36	1.8
Seeding Rate * Cultivar	5	166	1.7
Covariate			
MPLP†	1	237	12.2**
Error	43	838	
Total	59	2232	
Coefficient of variation: 26.6%			

† Mean percentage light penetration at full bloom.
* Significant at p = 0.05.
** Significant at p = 0.01.

4.3.2. 1990

In all experiments in 1990, MPPI never exceeded 50% and values remained similar among the three seeding rates used in the assessment (Tables 4.6-4.8). Petal infestation levels were very low at early bloom, but generally increased as the crop progressed into full and late bloom. In August, MDI for all experiments was <1%; therefore no analyses of disease incidence data will be presented. Mean leaf area index at early, full and late bloom in Experiments 3 and 4 generally increased as the seeding rate increased. A similar trend was not observed in Experiment 5. In Experiments 3 and 4, MLAI generally increased between early and full bloom, but decreased slightly at late bloom. Mean leaf area index in Experiment 5 was highest at late bloom. However, measurements of MLAI for the respective growth stages in Experiment 5 were made when plants were progressing into full bloom and from full bloom to late bloom. As with MLAI, MPLP in Experiments 3 and 4 generally decreased as the seeding rate increased; however, no consistent trend was found in Experiment 5.

Canopy temperature, RH and leaf wetness duration were monitored for three seeding rates (2.0, 9.5 and 17.0 kg/ha) in Experiment 3 and four seeding rates (0.5, 12.5, 15.5 and 17.0 kg/ha) in Experiment 4. However, because of malfunctioning sensors in the plot seeded at 0.5 kg/ha, data from only three seeding rates were available in Experiment 4. Average mean, minimum and maximum temperature were similar for all seeding rates in both experiments (Table 4.9). However, average mean and minimum RH and daily leaf wetness duration increased slightly as the seeding rate increased. Rainfall data recorded by Environment Canada (Fig. 4.3) and collected at Experiments 3 and 4 (Fig. 4.4) indicated a general lack of substantial rainfall in the Meadow Lake area in 1990 during most of June and after July 9.

Table 4.6. Mean values for measurements† of inoculum, disease and crop characteristics, Experiment 3 Meadow Lake, 1990.

		Early bloom		Full bloom		Late bloom		
SR‡	MDI	MPPI	MLAI	MPPI	MLAI	MPPI	MLAI	MPLP
0.5	0.8	3.0	0.8	21.0	1.8	39.8	2.5	31.6
2.0	0.3		1.8		2.9		3.3	11.9
3.5	0.1		2.3		3.5		3.7	11.9
5.0	0.1		2.7		3.6		3.6	8.4
6.5	0.1		2.8		3.9		3.6	8.6
8.0	0.5	3.0	3.2	12.5	4.5	41.5	3.7	9.2
9.5	0.1		3.0		4.4		3.9	8.7
11.0	0.3		3.4		4.5		3.7	10.9
12.5	0.2		3.8		4.5		3.8	9.4
14.0	0.4		3.5		4.4		3.4	8.7
15.5	0.5		3.6		5.0		3.8	7.6
17.0	0.3	1.0	3.5	8.5	4.9	40.5	4.0	8.0
Exp. mean	0.3	2.3	2.9	14.0	4.0	40.6	3.6	11.2

† MDI = Mean disease incidence (%), MPPI = Mean percentage petal infestation, MLAI = Mean leaf area index, MPLP = Mean percentage light penetration.

‡ Seeding rate (kg/ha).

Table 4.7. Mean values for measurements† of inoculum, disease and crop characteristics, Experiment 4 Meadow Lake, 1990.

		Early bloom		Full bloom		Late bloom		
SR‡	MDI	MPPI	MLAI	MPPI	MLAI	MPPI	MLAI	MPLP
0.5	0.0	2.0	0.6	19.0	1.5	16.0	1.4	35.7
2.0	0.0		1.5		2.2		1.9	20.3
3.5	0.0		1.5		2.5		1.8	15.1
5.0	0.0		1.9		2.4		1.8	17.7
6.5	0.0		2.1		2.7		1.7	19.1
8.0	0.0	1.5	2.1	20.5	2.5	21.0	1.7	15.1
9.5	0.5		2.2		2.8		1.9	14.0
11.0	0.0		2.4		2.9		2.0	19.4
12.5	0.1		2.3		2.8		1.9	17.5
14.0	0.2		2.7		2.9		2.0	13.8
15.5	0.1		2.2		2.8		1.9	17.5
17.0	0.3	3.5	2.5	20.0	3.1	17.0	2.1	13.8
Exp. mean	0.1	2.3	2.0	19.8	2.6	18.0	1.9	18.2

† Abbreviations as in Table 4.6.
‡ Seeding rate (kg/ha).

Table 4.8. Mean values for measurements† of inoculum§, disease and crop characteristics, Experiment 5 Meadow Lake, 1990.

		Early bloom	Full bloom		Late bloom		
SR‡	MDI	MPPI	MPPI	MLAI	MPPI	MLAI	MPLP
0.5	0.8			3.6		4.9	7.7
2.0	0.8			4.0		4.9	9.1
3.5	0.4			3.8		4.7	8.8
5.0	1.0			3.7		4.5	7.5
6.5	0.6			4.0		5.2	10.9
8.0	0.2			3.8		5.0	11.8
9.5	0.6			3.9		4.7	10.9
11.0	0.4			4.3		5.0	4.5
12.5	0.6			3.8		4.9	10.5
14.0	0.7			3.7		4.8	14.7
15.5	0.9			3.8		4.7	9.7
17.0	0.5			4.7		5.4	5.1
Exp. mean	0.6	4.5	50.0	3.9	49.0	4.9	9.3

† Abbreviations as in Table 4.6.

§ Obtained from five sampling sites located in the commercial canola field near where the plots were located.

‡ Seeding rate (kg/ha).

Table 4.9. Average mean, minimum and maximum daily temperature and relative humidity and daily leaf wetness duration for various seeding rates and periods in Experiments 3 and 4, Meadow Lake, 1990 (Section 3).

		Daily temperature			Daily relative humidity			
Exp.†	SR‡	Mean	Min.	Max.	Mean	Min.	Max.	DLWD§
3	2.0	17.0	8.6	25.5	81.2	56.2	99.0	3.5
	9.5	17.1	8.9	25.5	82.1	58.3	98.5	6.2
	17.0	16.9	8.7	25.8	83.1	59.5	98.3	7.4
4	12.5	17.5	8.7	26.8	81.5	54.4	99.8	5.8
	15.5	17.8	8.8	27.8	82.9	56.8	99.8	7.7
	17.0	17.8	9.4	27.3	85.0	61.8	99.8	7.8

† Data from June 21 to August 21 in Experiment 3 and from July 6 to August 15 in Experiment 4.
‡ Seeding rate (kg/ha).
§ Daily leaf wetness duration.

4.4. Discussion

Moisture conditions had an important influence on the results of the experiments in 1989 and 1990. Higher disease incidence in 1989 resulted from more ascospore inoculum being available, since the amount of rainfall in July was greater in 1990 (107 mm) than in 1989 (68 mm) (Figs. 4.1, 4.3). In 1989, frequent rainfall in June promoted ascospore production in late June and early July when moisture conditions were also favorable for host infection. However, in 1990 well below average rainfall in June restricted sclerotium germination and ascospore production during the first half of July, even though by then moisture conditions appeared somewhat favorable for infection. Measurements of MPLP suggested differences in canopy density between 1989 and 1990 may have also affected MDI. Substantially lower values for MPLP were observed at late bloom in 1989 than in 1990. Denser canopies in 1989 probably promoted greater ascospore production, as indicated by MPPI, and disease development.

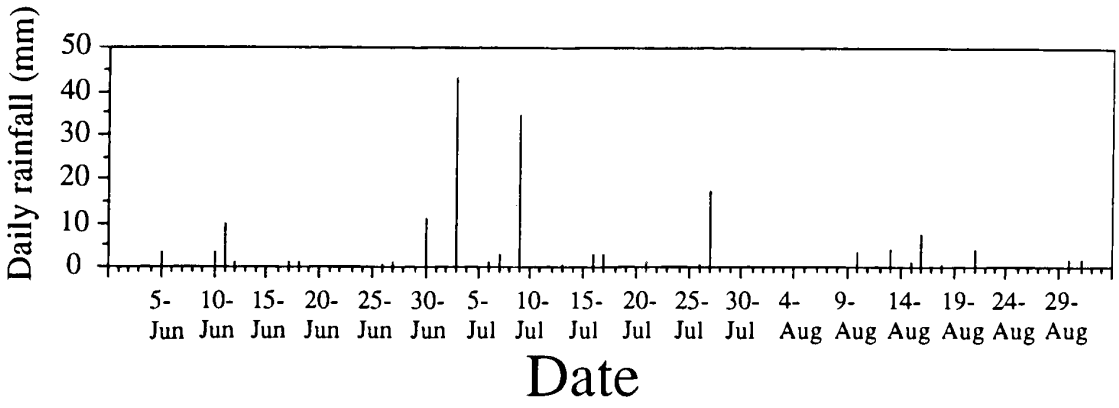

Figure 4.3. Daily total rainfall from June to August at the Environment Canada reporting station at Meadow Lake, 1990.

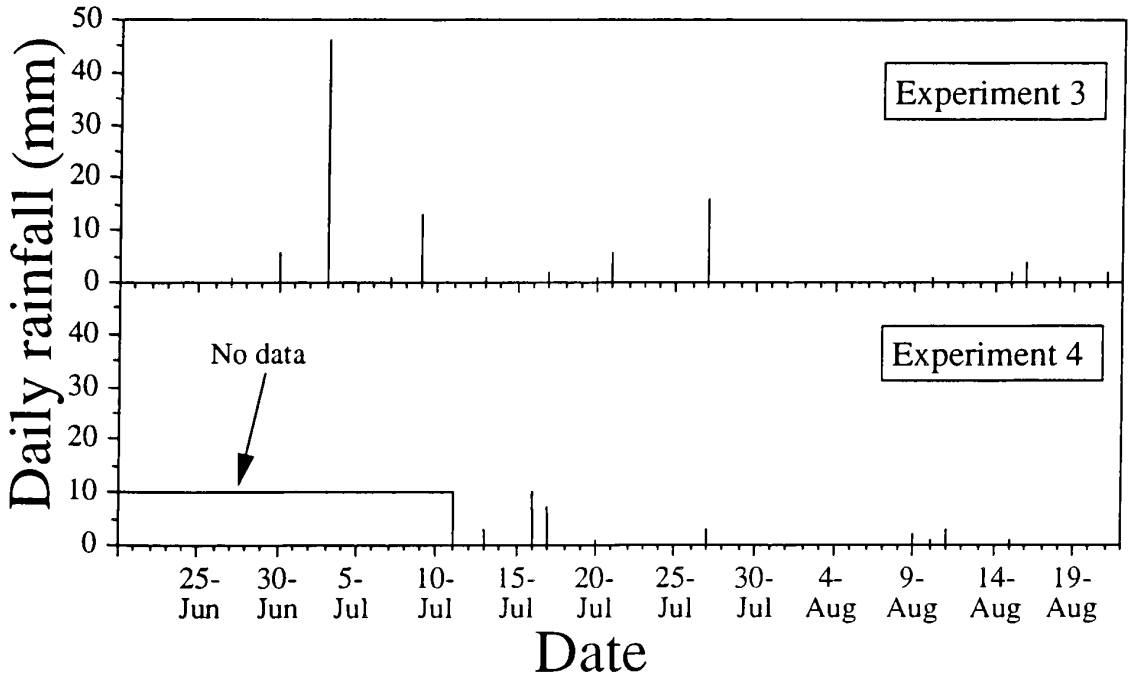

Figure 4.4. Daily total rainfall from June 21 to August 21 in Experiment 3 and from July 12 to August 15 in Experiment 4, Meadow Lake, 1990.

Variations in rainfall relative to critical growth stages were also responsible for differences in MDI between Experiments 1 and 2 in 1989. Experiment 1 was seeded 8 days before Experiment 2 and flowering started earlier in July. In Experiment 1, cv. Tobin came into early bloom during the last week of June, while cv. Westar came into early bloom during the first week of July. In Experiment 2, cv. Tobin came into early bloom during the first week of July, while cv. Westar came into early bloom during the second week of July. The presence of ascospores (MPPI) in Experiment 1 coincided with suitable conditions for host infection. In Experiment 2, the presence of ascospores coincided with moisture conditions less favorable for infection, especially for cv. Westar.

More rainfall in Experiment 1 not only contributed to higher MDI than in Experiment 2, but may also have allowed more compensation in plant growth so that differences among seeding rates were not as great as expected. Significant differences in disease did occur among seeding rates in Experiment 2, but MDI was relatively low. In 1989 and 1990, variations among seeding rates in canopy temperature, RH and leaf wetness duration were also not as great as expected. Plots seeded at the lowest rates tended to produce extremely large plants with numerous branches which may have negated the desired effect on the microenvironment of using low seeding rates. The formation of large water droplets in leaf axils and bases was also enhanced by the large leaf size in plots at the lower seeding rates. Furthermore, in these plots there may have been a greater tendency for larger numbers of petals to be retained in the leaf axils and bases (T.K. Turkington, personal observation). The petals may have then acted as "sponges" restricting evaporation and prolonging the presence of water droplets allowing the fungus to infect the host. In Sweden, Nordin & Svensson (1987) also found that three seeding rates of 4.0, 12.0 and 16.0 kg/ha produced similar levels of sclerotinia stem rot. They suggested that at the low seeding rate more lateral shoots were produced so that variation in crop density was not as wide as variation in seeding rate.

Experiments in 1989 demonstrated that TMDI was significantly related to MPLP.

In general varying the seeding rate influenced disease incidence by changing the canopy density, as indicated by MPLP. In the analysis of covariance for Experiment 2 there were no longer any significant treatment effects after TMDI was adjusted for MPLP. Variations in inoculum concentration were not a factor in this relationship, since MPPI was similar among the three seeding rates tested. However, significant differences in MPPI were found between cultivars for some of the flowering stages. In Experiment 1, these differences did not result in a significant effect of cultivar on TMDI. However, a significant cultivar effect was found in Experiment 2, and the effect was removed after the covariate MPLP was added to the analysis. Thus, it can be concluded that for given levels of MPPI, TMDI increased as MPLP decreased. Decreasing MPLP was associated with denser crop canopies which would favor the production of higher RH's and longer periods of leaf wetness, thus increasing the probability of host infection from infested petals. However, microenvironmental conditions were generally similar for those seeding rates that were monitored in Experiments 1 and 2. Nevertheless, in Experiment 1 TMDI on average was highest for the seeding rate of 11.5 kg/ha, although the ANOVA indicated that it was not significantly different from the other seeding rates. This seeding rate was also associated with the lowest MPLP and slightly higher RH and longer periods of leaf wetness. Other workers have also found that canopy density, through microenvironmental modification, is an important factor influencing diseases caused by S. sclerotiorum (Section 2.2.4).

In general, only limited success in simulating different canopy densities and microenvironmental conditions was achieved by varying the seeding rate over a very wide range. Moreover, under normal agronomic conditions farmers follow the recommended seeding rates of 4-9 kg/ha (Thomas 1984). Nevertheless, in commercial fields variations in canopy density do occur due to other factors such as: rainfall, soil fertility, seed quality and agronomic practices other than seeding rate. Thus canopy density is an important factor to consider in a petal-based forecasting system for sclerotinia stem rot of canola, but

manipulating it experimentally and assessing it may be difficult since it is a function of several variables. Experiments in 1989 illustrated the usefulness of measuring light penetration as an objective method of assessing canopy density and disease risk. Plots with low MPLP had higher MDI than plots where MPLP was relatively high. In 1990, a LI-COR plant canopy analyzer was used to assess canopy density; however, because of low MDI in the canopy density experiments the relationship between TMDI and MLAI could not be evaluated.

5. DIURNAL AND WEATHER-MEDIATED FLUCTUATIONS IN PERCENTAGE PETAL INFESTATION

5.1 Introduction

Based on studies in 1985 and 1986, Turkington (1988) suggested that diurnal and other weather-mediated fluctuations in PPI may have influenced the accuracy of forecasting sclerotinia stem rot based on PPI. Fluctuations of this type in atmospheric ascospore levels have been demonstrated (Ben-Yephet & Bitton 1985, Hartill 1980, Krüger 1974, 1975a, 1975b). However, no information exists concerning the occurrence, magnitude or importance of diurnal or other short-term fluctuations in PPI on canola. Studies described in this section were designed to address this question.

5.2. Materials and methods

In 1987, PPI was monitored from June 28 to July 22 in three commercial crops (#1-3) of B. napus cv. Westar in the Melfort area of Saskatchewan. In 1988, four commercial crops (#4-7) of B. napus were monitored from June 28 to July 21 at Meadow Lake, Saskatchewan; Crop 6 was cv. Tribute and the others were cv. Westar. For different periods during late June and July petal samples were collected three times a day at approximately 0800 (morning), 1300 (early afternoon) and 1800 hours (late afternoon). However, on some days petal samples were collected only once or at 0800 hours and then again at either 1300 or 1800 hours. Sampling and processing of petals were done according to procedures outlined by Turkington (1988) and Turkington et al. (1988) (See also Section 4.2.1). In both years petal samples were normally collected from five marked sites in each crop; however, only three sites were used for Crop 7 in 1988. An agar plate

test (Turkington et al. 1988) was then used to assess MPPI per crop for each sampling time.

Analyses of variance were performed on MPPI for each crop using time of sampling and day as sources of variation. Only those days on which samples were collected at all three sampling times were used for the analyses. Time of sampling was considered a fixed effect, while day was considered a random effect (Snedecor & Cochran 1980). Single degree of freedom contrasts were made of MPPI levels in the morning versus combined levels for the afternoon and of early afternoon versus late afternoon levels.

5.3 Results

For each crop average MPPI values were calculated for all samples collected in the morning, early afternoon and late afternoon. Only those days on which samples were collected at all three sampling times were used for the calculations. In 1987, a general pattern was observed where MPPI was lowest in the morning and increased by the afternoon when values tended to level off (Table 5.1). This pattern was less evident in Crop 2 than in Crops 1 and 3. Overall the change from morning to either of the afternoon sampling times ranged from 2.2 to 26.5% MPPI. For individual days the increase from morning to either of the afternoon sampling times ranged from 0.6 to 33% MPPI (Figs. 5.1 & 5.2). On 3 of 26 sampling days MPPI decreased from morning to afternoon by 2-7% MPPI.

In Crops 1 and 3, time of sampling and day were found to significantly affect MPPI (Table 5.2). The interaction of time of sampling and day was also significant for Crop 3. Significant differences were found between the morning and afternoon sampling times, but not between the two afternoon sampling times. None of the sources of variation were

found to be significant for Crop 2.

Table 5.1. Daily patterns in mean percentage petal infestation for crops at, Melfort in 1987 and Meadow Lake in 1988.

Year & crop	n‡	Average mean percentage petal infestation per crop†		
		Morning	Early afternoon	Late afternoon
1987				
Crop 1	3	45.7 (13.5)§	69.7 (13.1)	72.2 (12.4)
Crop 2	4	17.9 (8.2)	20.1 (7.8)	21.4 (7.3)
Crop 3	7	44.4 (16.3)	56.4 (19.8)	59.8 (16.2)
1988				
Crop 4	11	58.8 (23.1)	67.5 (22.5)	71.5 (17.9)
Crop 5	4	24.1 (11.2)	22.2 (16.6)	25.8 (13.8)
Crop 6	4	47.4 (18.2)	51.1 (18.6)	58.8 (14.0)
Crop 7	5	56.4 (11.5)	72.0 (18.0)	69.3 (15.5)

† Only those days on which samples were collected at all three sampling times were used for the calculations.

‡ Number of days.

§ Standard error.

In 1988, similar patterns were observed (Table 5.1). The increase from morning to afternoon was most evident for Crops 4, 6, and 7, but not for Crop 5 where overall MPPI remained similar for all three sampling times. The average increase from morning to afternoon ranged from 1.7 to 15.6% MPPI. For individual days the increase from morning to afternoon ranged from 0.3 to 46% MPPI (Figs. 5.3-5.4). However, on 9 of 28 sampling days MPPI decreased from morning to afternoon and this reduction ranged from 0.5 to 14% MPPI. Time of sampling significantly affected MPPI in Crop 4, but not in crops 5, 6, and 7 (Table 5.2). Day and the interaction of time of sampling and day were significant for Crops 4, 6, and 7; however only day was significant for Crop 5. Single degree of freedom contrasts demonstrated significant differences in MPPI between morning and afternoon sampling periods for Crops 4 and 7. No significant differences were demonstrated between the afternoon sampling times in any crop.

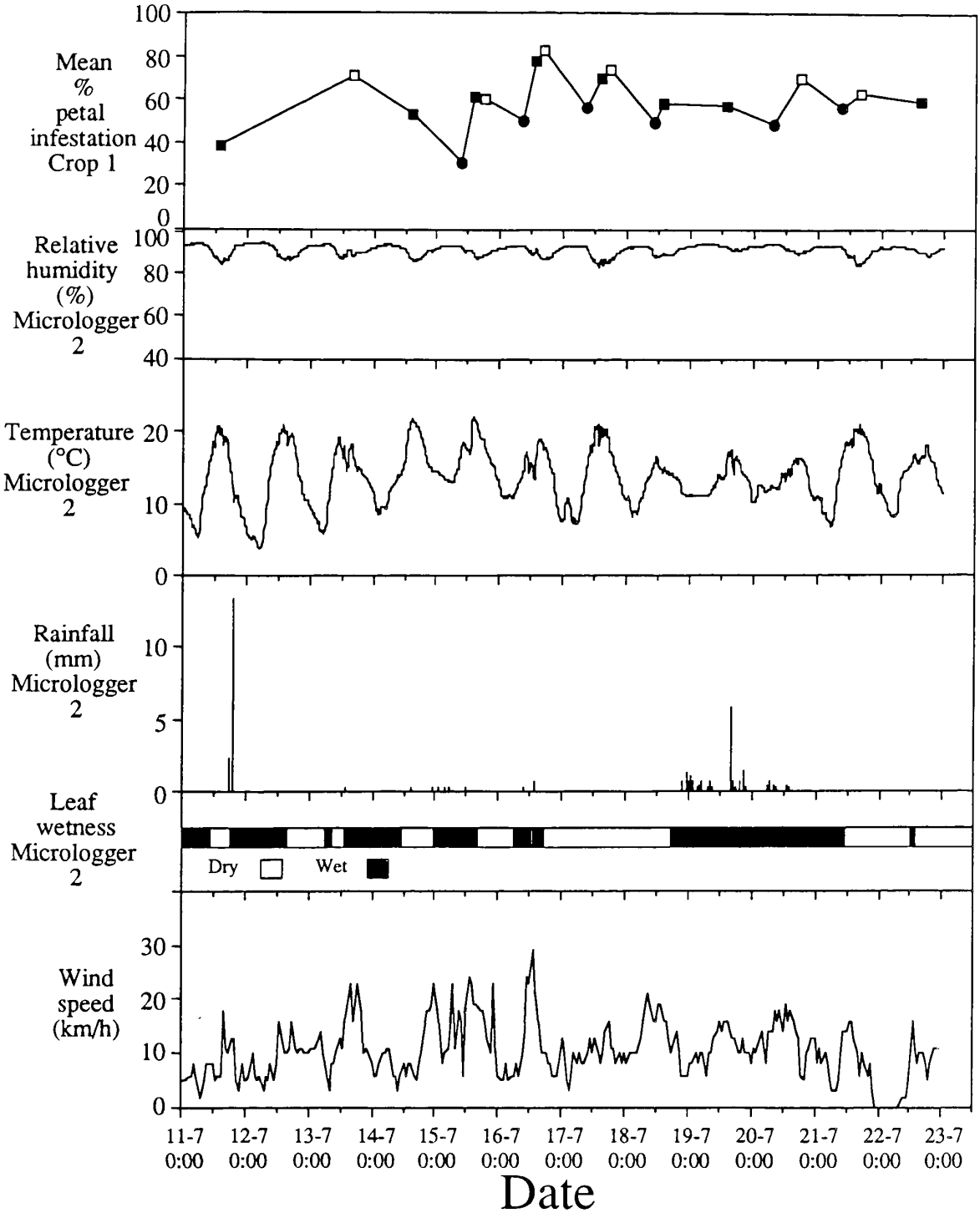

Figure 5.1. Mean percentage petal infestation for Crop 1 (morning ●, early afternoon ■, late afternoon □); relative humidity, temperature, rainfall and leaf wetness from Micrologger 2 located in Crop 1; wind speed from Environment Canada; Melfort July 11-23, 1987.

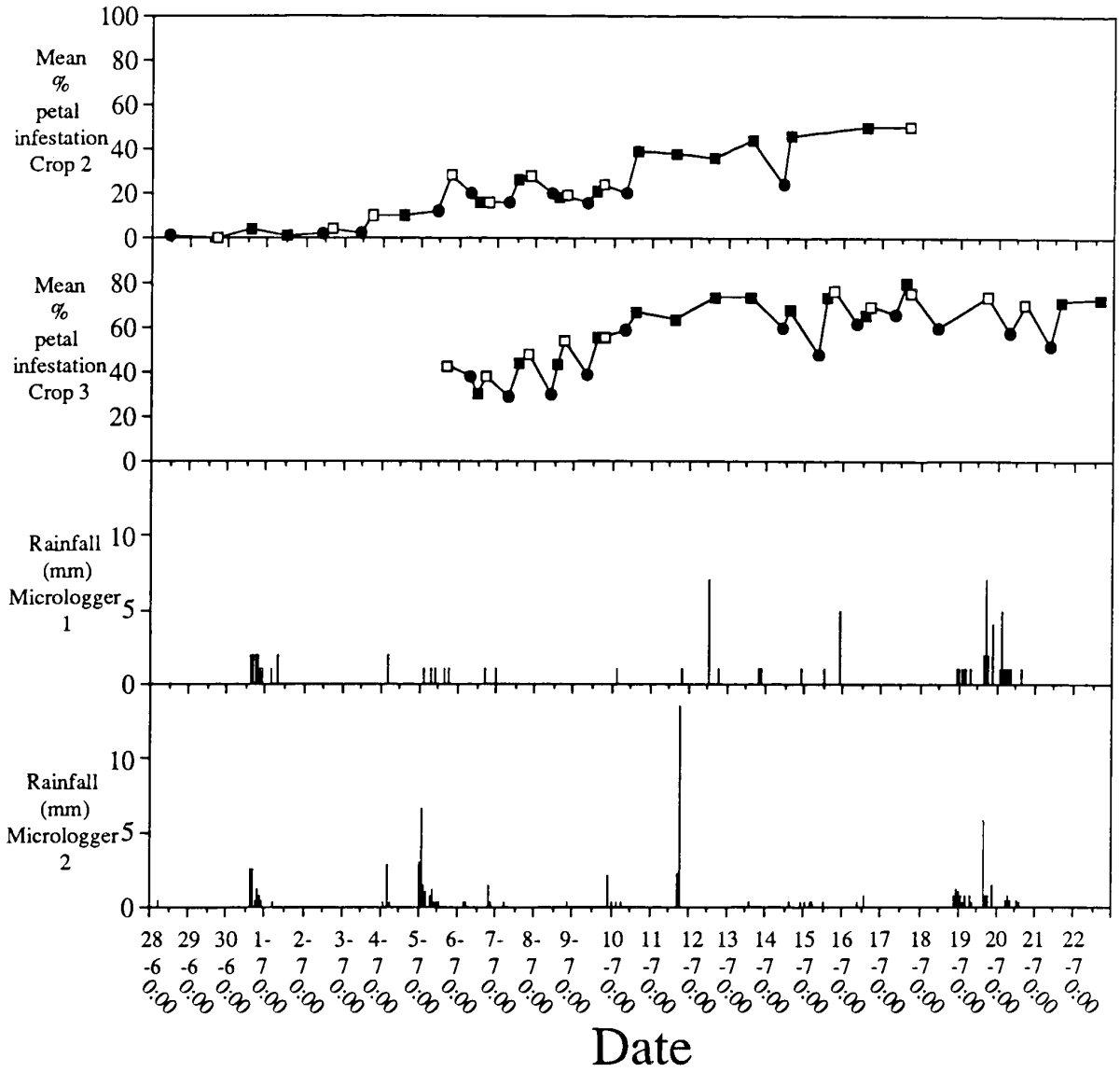

Figure 5.2. Mean percentage petal infestation for Crops 2 and 3 (morning ●, early afternoon ■, late afternoon □); rainfall from Micrologger 1 located 19 km SE of Crop 2 and 26 km SE of Crop 3; rainfall from Micrologger 2 located 29 km SW of Crop 2 and 33 km SW of Crop 3; Melfort June 28-July 22, 1987.

Table 5.2. Analyses of variance of percentage petal infestation in relation to sampling in the, morning (M), early afternoon (EA), or late afternoon (LA) and date of sampling, Melfort, 1987 and Meadow Lake, 1988.

Year & crop	Source of variation	df	SS	F
1987				
Crop 1	Time of sampling	2	6438	25.1**
	M vs EA & LA	1	6389	49.9**
	EA vs LA	1	49	0.4
	Day	2	3090	15.9**
	Time of sampling * Day	4	512	1.3
	Error	36	3503	
Crop 2	Time of sampling	2	124	0.7
	M vs EA & LA	1	108	1.3
	EA vs LA	1	16	0.2
	Day	3	314	1.9
	Time of sampling * Day	6	514	1.6
	Error	48	2626	
Crop 3	Time of sampling	2	4577	11.6**
	M vs EA & LA	1	4368	22.2**
	EA vs LA	1	209	1.1
	Day	6	20400	33.9**
	Time of sampling * Day	12	2358	2.0*
	Error	84	8431	
1988				
Crop 4	Time of sampling	2	4665	3.9*
	M vs EA & LA	1	4237	7.1*
	EA vs LA	1	428	0.7
	Day	10	42311	28.8**
	Time of sampling * Day	20	11938	4.1**
	Error	132	19412	
Crop 5	Time of sampling	2	127	1.0
	M vs EA & LA	1	0.3	0.005
	EA vs LA	1	126	2.0
	Day	3	6884	27.8**
	Time of sampling * Day	6	376	0.8
	Error	48	3967	
Crop 6	Time of sampling	2	1347	2.3
	M vs EA & LA	1	764	2.6
	EA vs LA	1	583	2.0
	Day	3	10438	37.7**
	Time of sampling * Day	6	1750	3.2*
	Error	48	4431	
Crop 7	Time of sampling	2	2085	3.7
	M vs EA & LA	1	2031	7.1*
	EA vs LA	1	54	0.2
	Day	4	4964	14.8**
	Time of sampling * Day	8	2278	3.4**
	Error	30	2516	

** Significant at p = 0.01.

* Significant at p = 0.05.

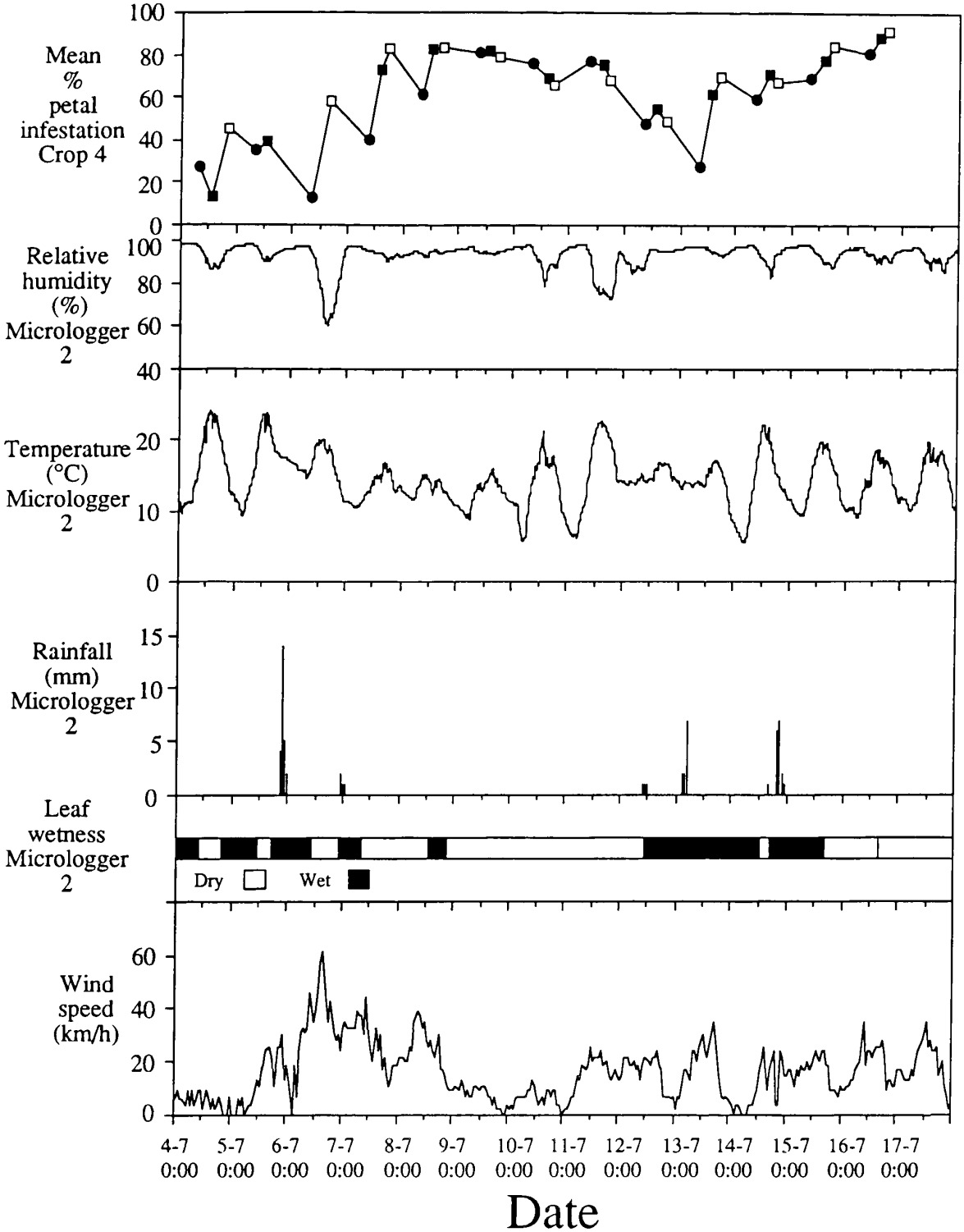

Figure 5.3. Mean percentage petal infestation for Crop 4 (morning ●, early afternoon ■, late afternoon □); relative humidity, temperature, rainfall and leaf wetness from Micrologger 2 located in Crop 4; wind speed from Environment Canada; Meadow Lake July 4-17, 1988.

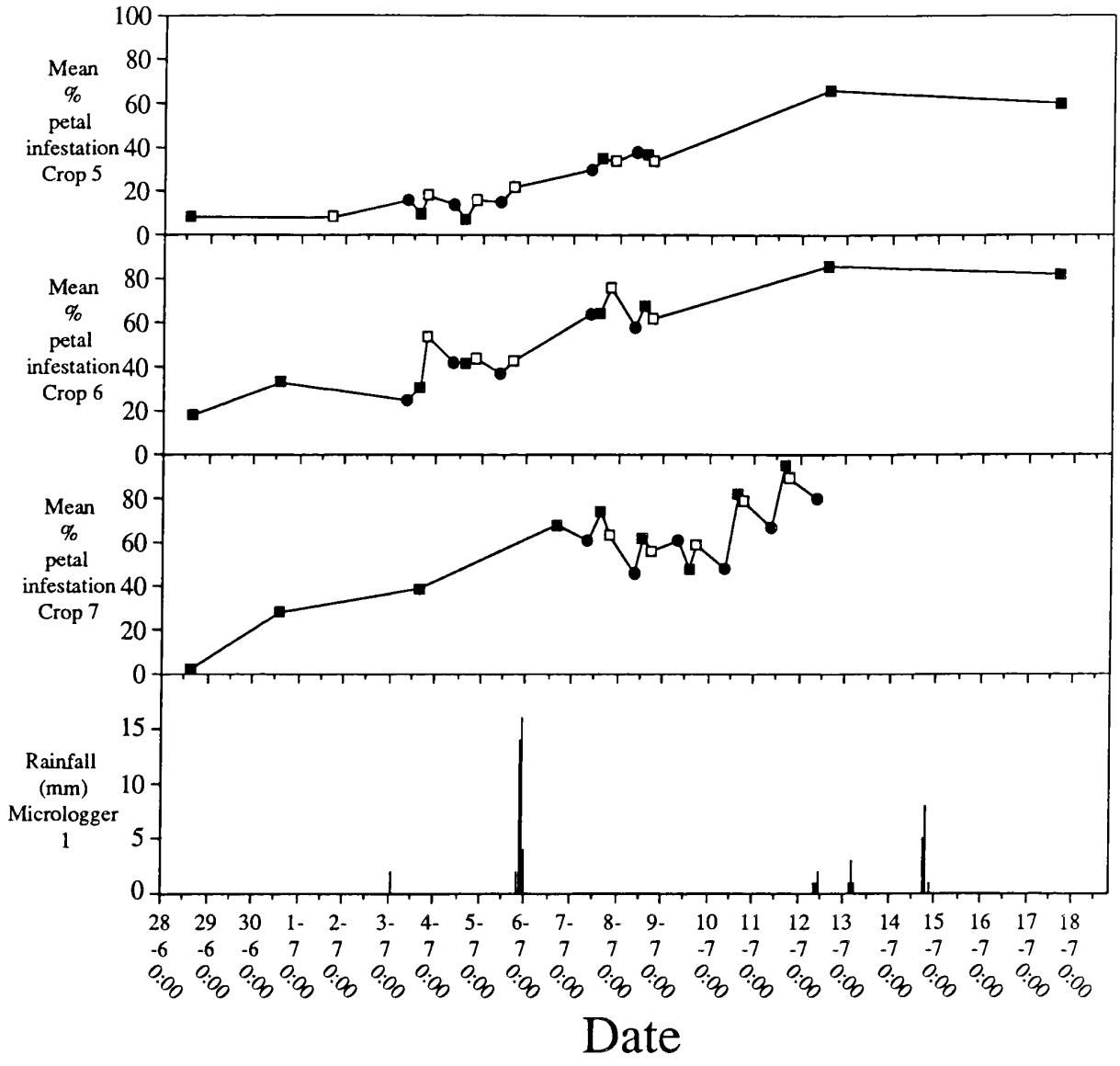

Figure 5.4. Mean percentage petal infestation for Crops 5, 6 and 7 (morning ●, early afternoon ■, late afternoon □); rainfall from Micrologger 1 located 9 km SE of Crop 5, 8 km SE of Crop 6 and 6 km SE of Crop 7; Meadow Lake June 28-July 18, 1988.

Several environmental variables were monitored in the study areas in both 1987 and 1988 (Section 3) in order to assist in the interpretation of results. In both years, daily patterns in several environmental parameters were observed (Figs. 5.1, 5.3). Relative humidity increased during the evening, but decreased during the day. Temperature and wind speed usually decreased during the evening, but increased during the day. In general leaf wetness reflected the occurrence of rainfall or dew and usually persisted until late morning or early afternoon.

5.4. Discussion

The results demonstrated that diurnal fluctuations in MPPI occur. The most distinct and consistent pattern was where MPPI was lowest in the morning, but increased by the afternoon. Single degree of freedom contrasts demonstrated a significant increase in MPPI from morning to afternoon for 4 of 7 crops. However, on some dates in both 1987 and 1988 MPPI either remained the same or actually declined from morning to afternoon. These reductions were usually much smaller than the increases in MPPI that occurred. For some crops day and its interaction with time of sampling were significant. This was expected since MPPI levels changed during the study period as a result of variation in rainfall and diurnal patterns in MPPI were more evident on some days than others. Crop 4 (Fig. 5.3) provides a good example of this.

The overall pattern of increasing MPPI during the day was probably the result of diurnal patterns in atmospheric ascospore levels which have been demonstrated by other workers. Hartill (1980) and Ben-Yephet & Bitton (1985) both demonstrated a similar pattern where the number of airborne ascospores was highest around mid-day. In western Canada, Williams & Stelfox (1979) exposed petri plates containing potato dextrose agar and found that a greater percentage developed colonies of S. sclerotiorum if exposed during

the day than if exposed during the night. Data from Hartill (1980) suggested that very few ascospores were trapped during the evening. Furthermore, Ben-Yephet & Bitton (1985) reported that only 2% of the daily total of ascospores were trapped at night and suggested that these represented "residual ascospores from the daytime".

In both years patterns in MPPI were clearly not as distinct as the patterns in ascospore levels reported by Hartill (1980) and Ben-Yephet & Bitton (1985). Rapeseed petals can remain in the inflorescence for up to six days and are most susceptible to contamination with ascospores for a two day period when flowers are fully expanded and petals have not yet started to wilt (Penaud 1984). Thus, petal infestation not only represents inoculum levels on the date of sampling, but also for several days before. This would act to dampen any diurnal pattern in PPI that might result from diurnal patterns in ascospore release. However, continuous production of new flowers and petals would make patterns in PPI possible, although not as distinct as those reported for airborne ascospores.

The influence of radiation, RH and temperature on ascospore survival may also create the potential for diurnal patterns in MPPI. Radiation has been shown to influence spore survival for many fungi including S. sclerotiorum (Boland 1984, Caesar & Pearson 1983, Leach & Anderson 1982, Rotem et al. 1985). Caesar & Pearson (1983) found that average ascospore survival was 51% and 22% after two and four days field exposure on the upper leaves of a bean canopy. Survival rates of <10% were observed after six days exposure. Ascospore survival also decreased rapidly at RH's >35% and temperatures of ≥25°C. Grogan & Abawi (1975) also found a rapid reduction in percentage survival when RH was >75%.

Boland (1984) also demonstrated decreased ascospore viability, with average survival rates of <50% after two days and <1% after three days field exposure of ascospores on Millipore filter paper. Higher ascospore survival was observed by Boland (1984) and Caesar & Pearson (1983) when ascospores were shielded from UV radiation.

Caesar & Pearson (1983) also found that survival was increased on shaded leaves in the lower part of a bean canopy. Canola petals that are in the inflorescence and infested with ascospores of S. sclerotiorum are exposed to substantial amounts of radiation and higher temperatures, which would result in decreased ascospore survival. This would then create further potential for the appearance of diurnal patterns in MPPI.

Ingold (1971) has suggested that patterns in spore release may be due to the periodicity of external factors. Ascospore release in the Ascomycetes is mainly by violent liberation from a turgid ascus, and Discomycetes like S. sclerotiorum exhibit the phenomenon of "puffing", which is a simultaneous mass release of ascospores from apothecia (Ingold 1971). In other Discomycetes, such as Ascobolus, spore release is induced by illumination, reduction in RH, wide temperature changes, and physical contact (Ingold 1971). Although Abawi & Grogan (1979) have suggested that studies of ascospore release in S. sclerotiorum are "limited", the process may be similar to other Discomycetes. Decreasing moisture during the day may trigger spore release from apothecia.

In the current study, daily patterns in several environmental factors may have accounted for the overall pattern of increasing MPPI during the day. Decreasing RH during the day may have induced ascospore release, thereby increasing MPPI from morning to afternoon. Wind and temperature may have also contributed to the pattern. These factors would lead to increased evapotranspiration and a reduction in RH, thereby inducing ascospore release. In both years the greatest reduction in RH and highest wind speed and temperature usually occurred around mid-day (Figs. 5.1 & 5.3).

Ingold (1971) has suggested that light may be important for producing the circadian patterns of spore release observed in many Ascomycetes. In "light-conditioned" patterns, spore release is maximal around mid-day, but then decreases towards the beginning of the night. In Ascobolus light has been found to have a direct influence on spore release, causing "puffing" of ascospores when apothecia are subjected to blue light (Ingold 1971).

Hartill (1980) has suggested that light may play a role in initiating ascospore release in S. sclerotiorum. He also suggested that ascospores "can be expected to be liberated in increasing numbers as the sun rises.". This is consistent with the diurnal patterns observed in the present study where MPPI was generally higher in the afternoon than morning.

In Germany, Krüger (1974, 1975a, 1975b) studied the influence of weather on ascospore release by S. sclerotiorum. Turgid apothecia released the greatest quantity of ascospores; however, if they were subjected to dry conditions the number of ascospores decreased. Dry, warm, windy conditions promoted release, but "extreme drought" reduced ascospore production and release. Ascospore release was also reduced during wet, overcast, and calm conditions, with the greatest reduction occurring in rainy, calm weather. Krüger (1974, 1975a) suggested that during these periods ascospores were released into water droplets formed on apothecia and were subsequently washed into the soil. He also found that ascospore release could be decreased by artificially moistening apothecia.

In the present study, water droplets were observed on apothecia after heavy dew or rainfall. Leaf wetness was used as an indicator of the presence of water within the canola canopy and was typically initiated by rainfall or dew. The end of a period of leaf wetness generally occurred in the late morning or early afternoon. However, this pattern was easily altered by rainfall. For example in Crop 4 on the afternoon of July 8, a trace of rainfall produced a short period of leaf wetness (Fig. 5.3). In general the occurrence of rainfall or dew may have helped to enhance the observed daily pattern in MPPI, since water droplets present on apothecia probably did not evaporate until late morning or early afternoon.

The results did not appear to indicate that rainfall reduced MPPI by washing ascospores off petals. In fact on a few dates in 1987 and 1988 rainfall during the day did not produce any substantial reductions in MPPI. However, rainfall may have the effect of scrubbing ascospores from the air so that newly expanded flowers are exposed to reduced inoculum levels. Furthermore, rain may also have the effect of dislodging older more contaminated petals from the inflorescence (Penaud 1984), thereby reducing PPI when

samples are collected afterwards. These phenomena may be partly responsible for the reductions in MPPI that occurred between afternoon samples and samples taken the following morning, especially for Crop 4 from July 5 to 7 and 12 to 13 (Fig. 5.3).

For several dates in 1987 and 1988, MPPI remained similar for the three sampling times. These dates often occurred during relatively dry conditions. On these dates the absence of rain or substantial dew may have allowed the apothecia to begin discharge of ascospores earlier in the day in response to changes in other environmental factors. The lack of a distinct diurnal pattern was especially evident in Crops 4 and 5 from July 7 to 12 (Figs. 5.3 & 5.4). In fact, by the end of this period lack of rainfall had started to cause a general decrease in MPPI for Crop 4. Leaf wetness sensors in Crop 4 indicated the absence of free water in the canopy for most of the period. However, RH remained relatively high and probably maintained the apothecia in a sufficiently hydrated state to permit ascospore discharge. In Crop 4, cooler temperatures from July 8 to 12 may have also been a factor responsible for the observed lack of diurnal patterns. Lamarque (1983) has found that cooler temperatures delay petal fall in rapeseed. In addition, cooler temperatures would have also favored ascospore survival (Caesar & Pearson 1983). Thus, the occurrence of cooler temperatures from July 8 to 12 may have delayed petal fall and increased ascospore survival, thereby eliminating distinct patterns in MPPI.

6. LONG-TERM FLUCTUATIONS IN PETAL INFESTATION

6.1. Introduction

The variable incidence of sclerotinia stem rot of canola in western Canada emphasizes the need for a forecasting system which identifies disease risk on an individual crop rather than a regional basis (Harrison 1990, Jesperson 1990, Morrall et al. 1976, Van den berg & Platford 1990). Using infestation of canola petals with S. sclerotiorum provides an opportunity to achieve this. However, although disease risk can be assessed precisely at a particular time, whether the risk is accurately reflected by DI depends partly on moisture conditions after petal sampling (Turkington 1988, Turkington et al. 1988). This suggests that PPI and disease risk may fluctuate in relation to changing moisture conditions during flowering. Hence, reliable forecasts might depend on sampling several times during flowering to establish when, and for how long, inoculum may be present. The objectives of this part of the project were to determine the extent to which PPI in commercial crops varies during the flowering period and how variations relate to changing moisture conditions and influence forecast and actual DI.

6.2. Materials and methods

From 1987 to 1990 PPI was assessed in a number of commercial canola crops located in various areas of Saskatchewan. In 1987, PPI was monitored from June 28 to July 30 in 5 crops of B. napus and one crop of B. campestris in the Melfort area. In 1988, 25 crops of B. napus and 4 crops of B. campestris were sampled in the Meadow Lake area from June 24 to July 21 and 9 irrigated crops of B. napus were sampled from June 28 to July 22 at Outlook. In 1989 and 1990, all crops monitored were located in the Meadow

Lake area; 17 crops of B. napus and one crop of B. campestris were sampled from July 4 to July 25 in 1989; 35 crops of B. napus and one crop of B. campestris were sampled from July 5 to August 2 in 1990.

In each crop, inflorescences were collected and growth stage recorded several times during the flowering period. Samples were typically obtained from 5 sites in each crop; however, in a small number of crops, samples were collected at only 1 or 4 sites. All sampling sites were located at least 10 m from the edge of the crop and were spaced >25 m apart and marked with 1.8 m wooden stakes. Enough inflorescences were collected to provide 40 petals per site on each sampling date. General procedures for collection and processing of samples and determination of PPI were as outlined in Section 4.2.1.

From 1988 to 1990 at Meadow Lake, measurements of MHT and MST were made at each site when the crops were at late bloom. In 1988 at Outlook, MHT was derived from several subjective estimates made during the flowering period. At Meadow Lake in 1988 and 1989, MPLP was also measured at each sampling site when the crops were at late bloom. In 1990, MLAI was assessed at each sampling site when the crops were at full bloom, using a LI-COR LAI-2000 plant canopy analyzer. Except at Outlook in 1988, the measurements of MHT, MST, MPLP and MLAI were made according to procedures outlined in Sections 4.2.1 and 4.2.2. In August, shortly before swathing, DI was assessed by counting the number of infected plants out of a random sample of 200 at each site. In 1989 and 1990, after the crops had been swathed, the number of plants per m^2 was counted at each site using a 1 m^2 quadrat.

The Statistical Analysis System (SAS Institute 1985) was used to regress DI values for particular years on several independent variables. Residual analysis was initially performed with MDI and arcsine-transformed MDI (TMDI) to determine if the underlying assumptions of the regression were met. The analyses indicated that TMDI more closely satisfied the assumptions. Thus, TMDI was used for all regressions.

6.3. Results

Average MDI and MPPI were lowest at Outlook in 1988 and at Meadow Lake in 1990 and were highest at Meadow Lake in 1989 (Table 6.1). Intermediate MDI and MPPI were observed at Melfort in 1987 and Meadow Lake in 1988. In 1987, average MPPI never exceeded 45% and was highest at late bloom. In 1988 at Outlook, MPPI increased after early bloom; however, average MPPI never exceeded 31%. At Meadow Lake in 1988, MPPI was lowest at early bloom, but increased as crops progressed into full and late bloom. Average MPPI never exceeded 60%; however, in a few individual crops MPPI did increase to >90%. In 1989 at Meadow Lake, average MPPI was >50% at early bloom, but decreased to <30% as crops progressed into late bloom. In 1990 at Meadow Lake, average MPPI was <10% at early bloom; however by late bloom it had increased to 34%.

Substantial changes in MPPI during the flowering period occurred in all years (Table 6.2). In 1987, 1988 and 1990, the changes were mostly increases; however, in 1989 MPPI generally decreased as the crop progressed from early to late bloom. The largest average change in MPPI occurred at Meadow Lake in 1988, while the smallest occurred at Outlook. The largest increases and decreases in MPPI in a single crop were observed at Meadow Lake in 1988 and 1989, respectively.

Various crop characteristics were measured from 1988 to 1990 (Table 6.1). Average MHT was similar at Outlook and Meadow Lake in 1988, but was slightly higher at Meadow Lake in 1989 and 1990. Similar values for average MST were observed at Meadow Lake from 1988 to 1990. Average MPLP was slightly higher at Meadow Lake in 1988 than in 1989. Mean leaf area index ranged from 1.7 to 5.8 in 1990; these values were consistent with those reported by Clarke and Simpson (1978) and in the Canola Growers Manual (Thomas 1984).

From 1987 to 1990, environmental data for the study areas were obtained from two sources: Environment Canada reporting stations or CSC microloggers. In 1987, below

Table 6.1. Average, minimum and maximum values for measurements† of disease, inoculum and crop characteristics at Melfort, 1987, Outlook, 1988 and Meadow Lake, 1988-90.

Year and location		N‡	MDI	Mean percentage petal infestation			MHT	MST	MPLP	MLAI	MNPS
				Early bloom	Full bloom	Late bloom					
1987											
Melfort	Average	6	10.8	19.1	31.1	41.8					
	Minimum	6	0.8	0	15.4	8.8					
	Maximum	6	27.1	48.0	67.5	82.7					
1988											
Outlook	Average	9	2.7	7.0	23.6	30.2	92.5				
	Minimum	9	0	0	2.2	6.8	65.0				
	Maximum	9	8.6	44.5	69.6	76.7	150.0				
Meadow Lake	Average	29	7.2	14.4	40.3	58.8	89.8	0.65	3.2		
	Minimum	29	0.2	0	9.5	26.5	66.8	0.46	0.6		
	Maximum	29	59.7	63.0	91.0	95.5	113.2	0.90	12.6		
1989											
Meadow Lake	Average	18§	20.7	58.0	46.1	27.5	104.1	0.56	3.0		132.4
	Minimum	18	2.8	19.5	14.0	0	94.6	0.44	1.0		69.4
	Maximum	18	63.5	88.5	84.5	78.6	127.2	0.73	5.2		217.6
1990											
Meadow Lake	Average	36	3.0	7.1	18.3	33.6	102.9	0.64		3.6	103.6
	Minimum	36	0	0	0	2.0	83.8	0.48		1.7	31.4
	Maximum	36	14.0	31.0	62.1	77.1	114.8	0.83		5.8	145.0

† MDI = Mean disease incidence (%), MHT = Mean crop height (cm), MST = Mean stem thickness (cm), MPLP = Mean percentage light penetration, MLAI = Mean leaf area index, and MNPS = Mean number of plants per m^2.

‡ Number of crops.

§ Mean percentage petal infestation at late bloom assessed in only 17 crops.

Table 6.2. Changes in mean percentage petal infestation during flowering† at Melfort, 1987, Outlook, 1988 and Meadow Lake, 1988-90.

Year and location	n‡	Change in mean percentage petal infestation during flowering§		
		Mean absolute	Minimum	Maximum
1987				
Melfort	6	51	38	82
1988				
Outlook	9	24	-1	67
Meadow Lake	29	60	-22	94
1989				
Meadow Lake	18	38	5	-88
1990				
Meadow Lake	36	32	-2	71

† Based on maximum MPPI - minimum MPPI for each crop sampled.
‡ Number of crops.
§ Positive values are increases and negative values are decreases.

average rainfall was recorded in June; however, above average rainfall was observed in July, with frequent showers occurring from June 30 to July 23 (Table 6.3, Figs. 6.1-6.3). Mean and minimum relative humidity and daily leaf wetness duration remained fairly high from July 3 until the last week of July (Figs. 6.2, 6.3). At Outlook in 1988, relatively high temperatures, increased hours of sunshine, and infrequent, below average rainfall were observed for most of June and July (Table 6.3, Fig. 6.4). At Meadow Lake in 1988, near average rainfall was recorded in June, with most precipitation occurring on June 29 (Table 6.3, Fig. 6.1). For July an average level of rainfall was recorded, with most occurring before mid-month (Table 6.3, Figs. 6.1, 6.5, 6.6). Leaf wetness duration and mean and minimum RH decreased during the second half of July (Figs. 6.5, 6.6), while the amount of sunshine per day increased (Fig. 6.7). In 1989, slightly below average rainfall was recorded in June and July (Table 6.3). However, frequent rainfall did occur from June 20

Table 6.3. Total and long-term average (LTA) rainfall (mm) for June, July and August from Environment Canada reporting stations at Melfort, 1987, Outlook, 1988 and Meadow Lake, 1988-90.

	June		July		August	
Year & Location	Total	LTA	Total	LTA	Total	LTA
1987						
Melfort	25	71	88	64	74	54
1988						
Meadow Lake	67	74	81	82	198	74
Outlook	28	64	37	50	53	33
1989						
Meadow Lake	69	74	68	82	50	74
1990						
Meadow Lake	33	74	107	82	24	74

to July 11 (Figs. 6.1, 6.8). Hours of sunshine per day (Fig.6.7) and temperature (Fig. 6.9) increased from July 11 to 21, while RH and leaf wetness duration tended to decrease (Fig. 6.9). In 1990, well below average rainfall was recorded for June; however, in July two very heavy showers on July 3 and 9 contributed to well above average rainfall for the month (Table 6.3, Fig. 6.1, 6.10). Nevertheless, daily hours of sunshine remained relatively high for most of July (Fig. 6.7). Mean and minimum RH (Fig. 6.11) measured by the sensors in Experiments 3 and 4 (Sections 3 & 4) remained fairly high until after the third week of July, but in Experiment 5 (Fig. 6.12, Sections 3 & 4) mean and minimum RH did not start to decline until the end of July. No distinct trends in the daily duration of leaf wetness were observed in July (Figs. 6.11, 6.12).

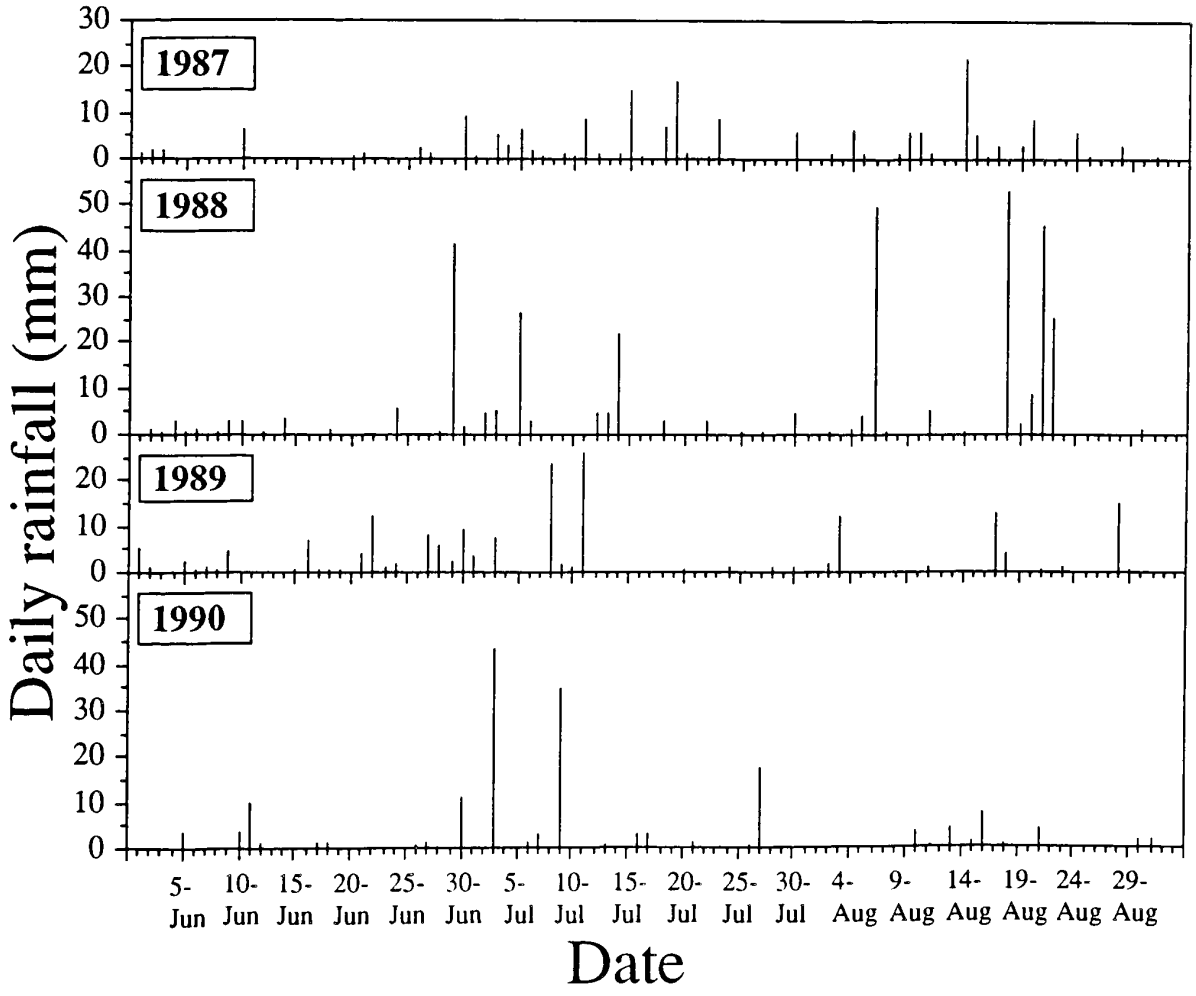

Figure 6.1. Daily total rainfall from June to August at Environment Canada reporting stations at Melfort, 1987 and Meadow Lake, 1988-90.

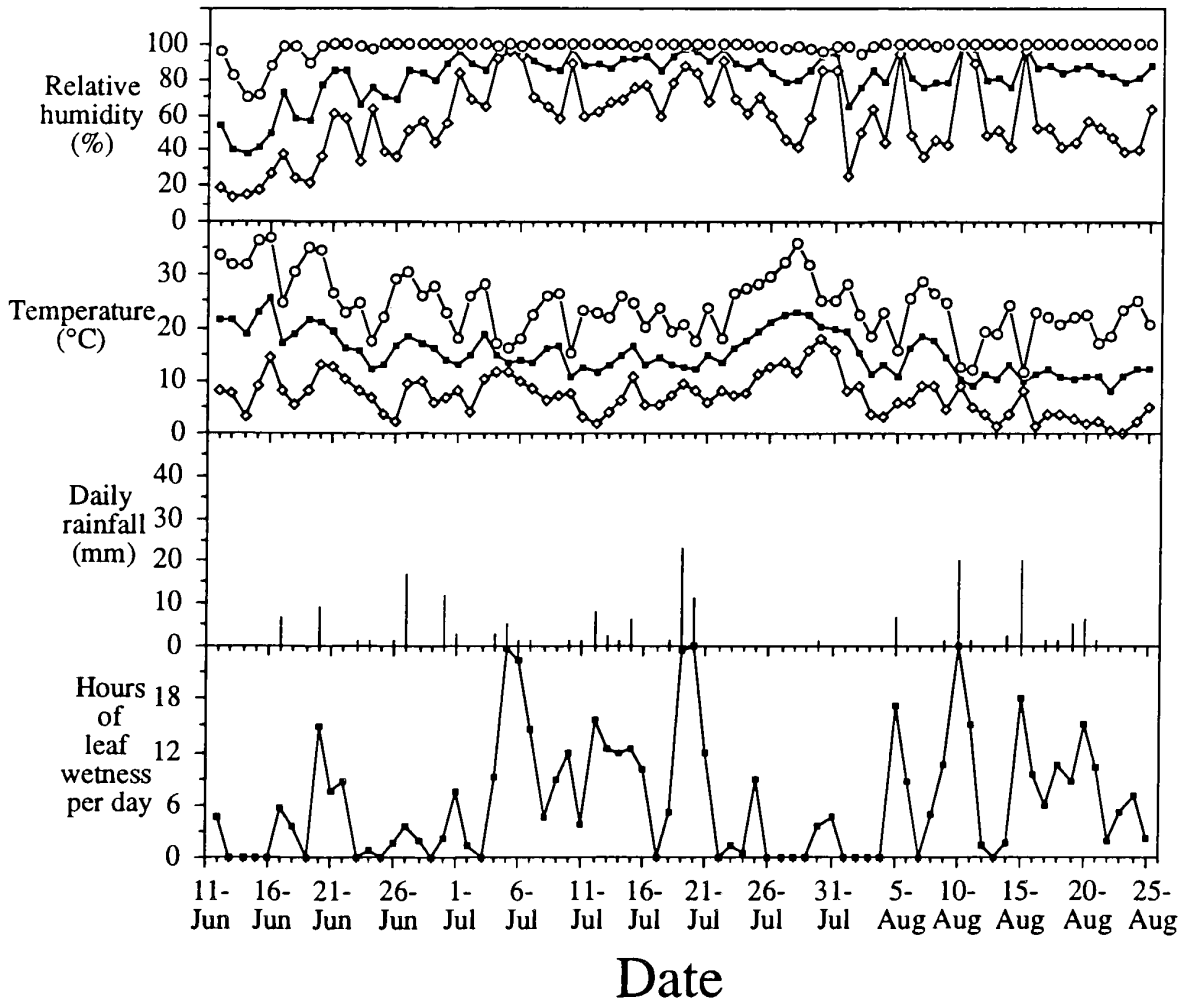

Figure 6.2. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature, daily total rainfall and leaf wetness duration from Micrologger 1, Melfort, 1987 (Section 3.2).

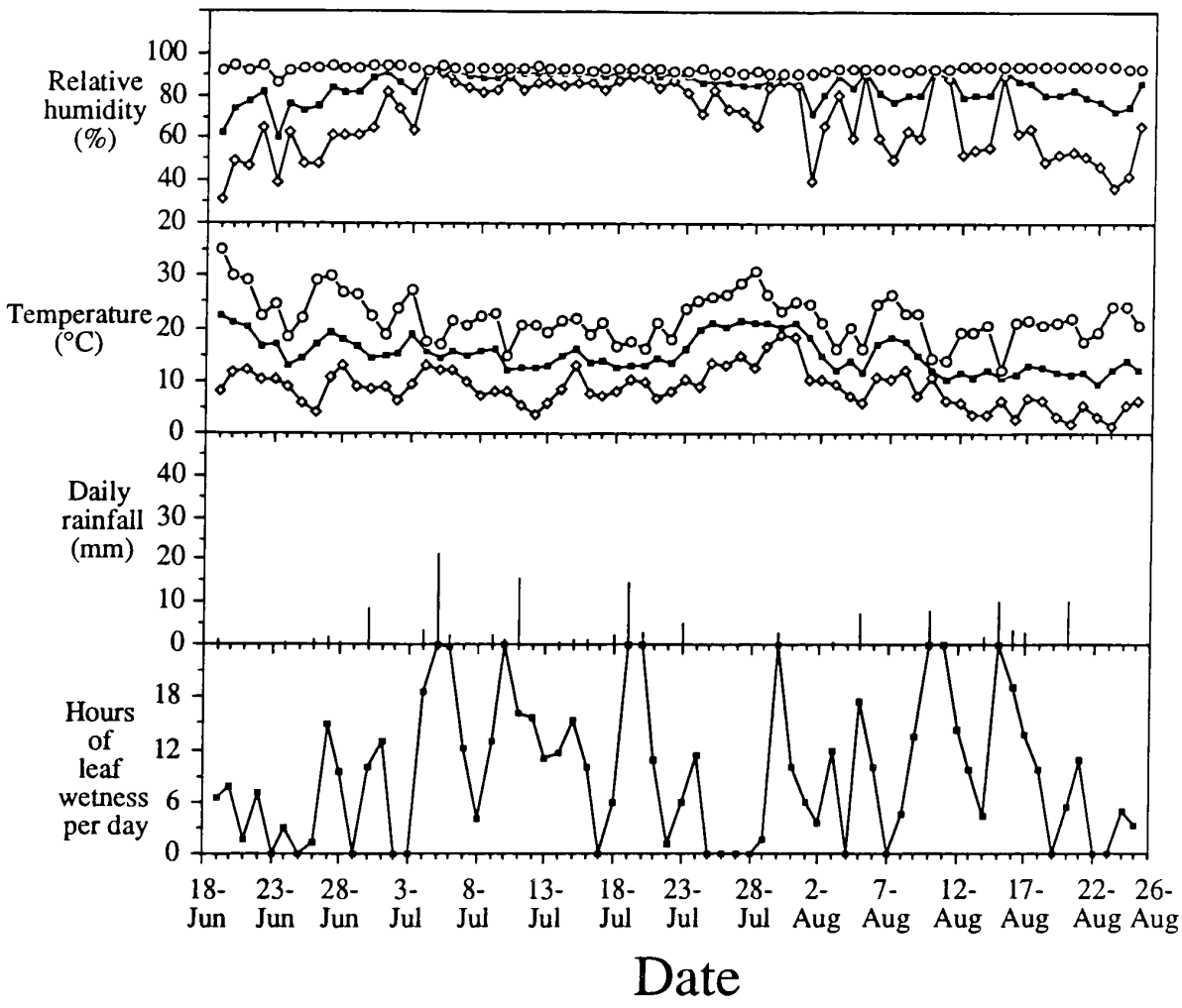

Figure 6.3. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature, daily total rainfall and leaf wetness duration from Micrologger 2, Melfort, 1987 (Section 3.2). Data for relative humidity, temperature and leaf wetness represent mean values from three sensors.

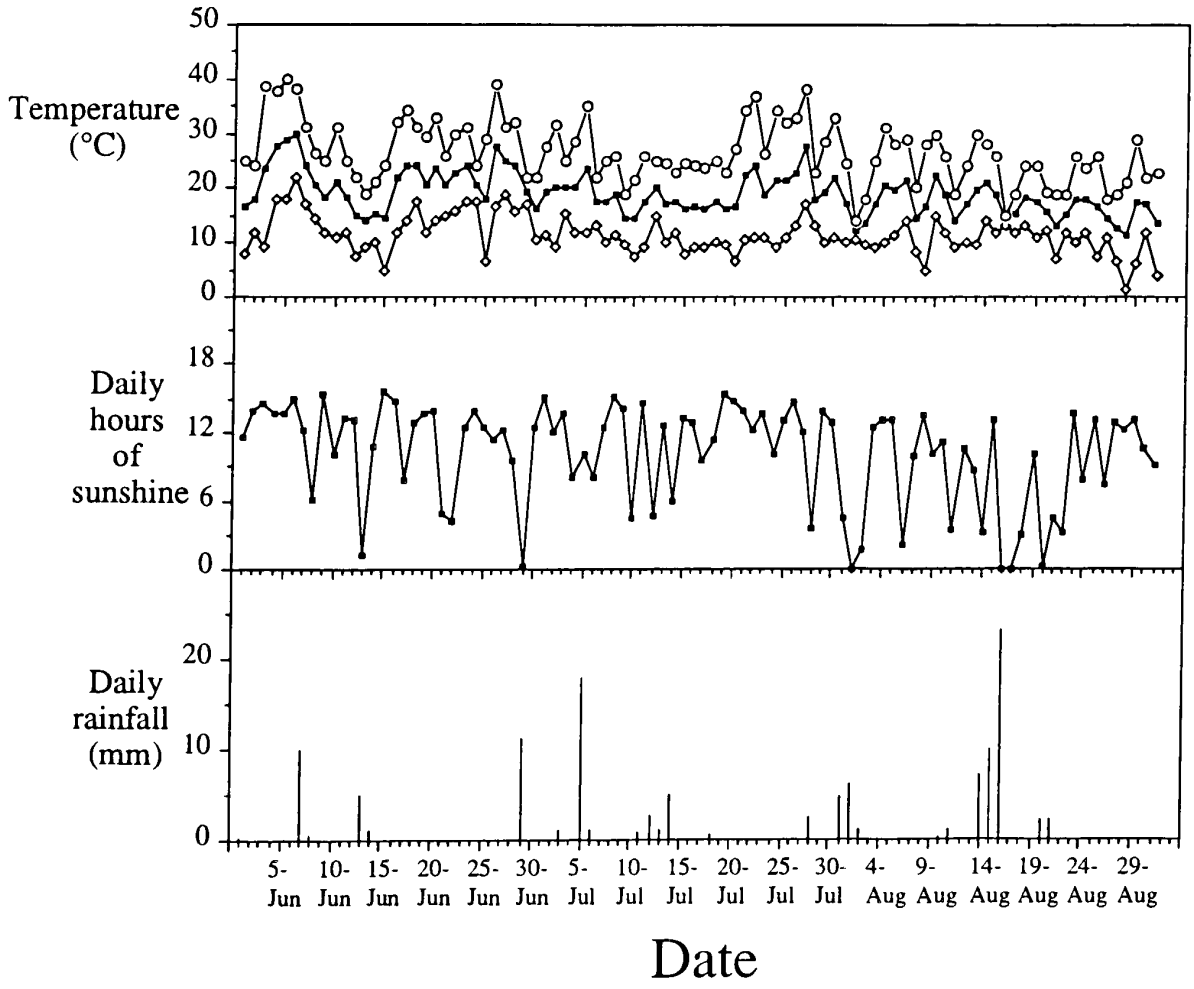

Figure 6.4. Mean (■), minimum (◊) and maximum (o) temperature, daily hours of sunshine and rainfall from June to August at the Environment Canada reporting station at Outlook, 1988.

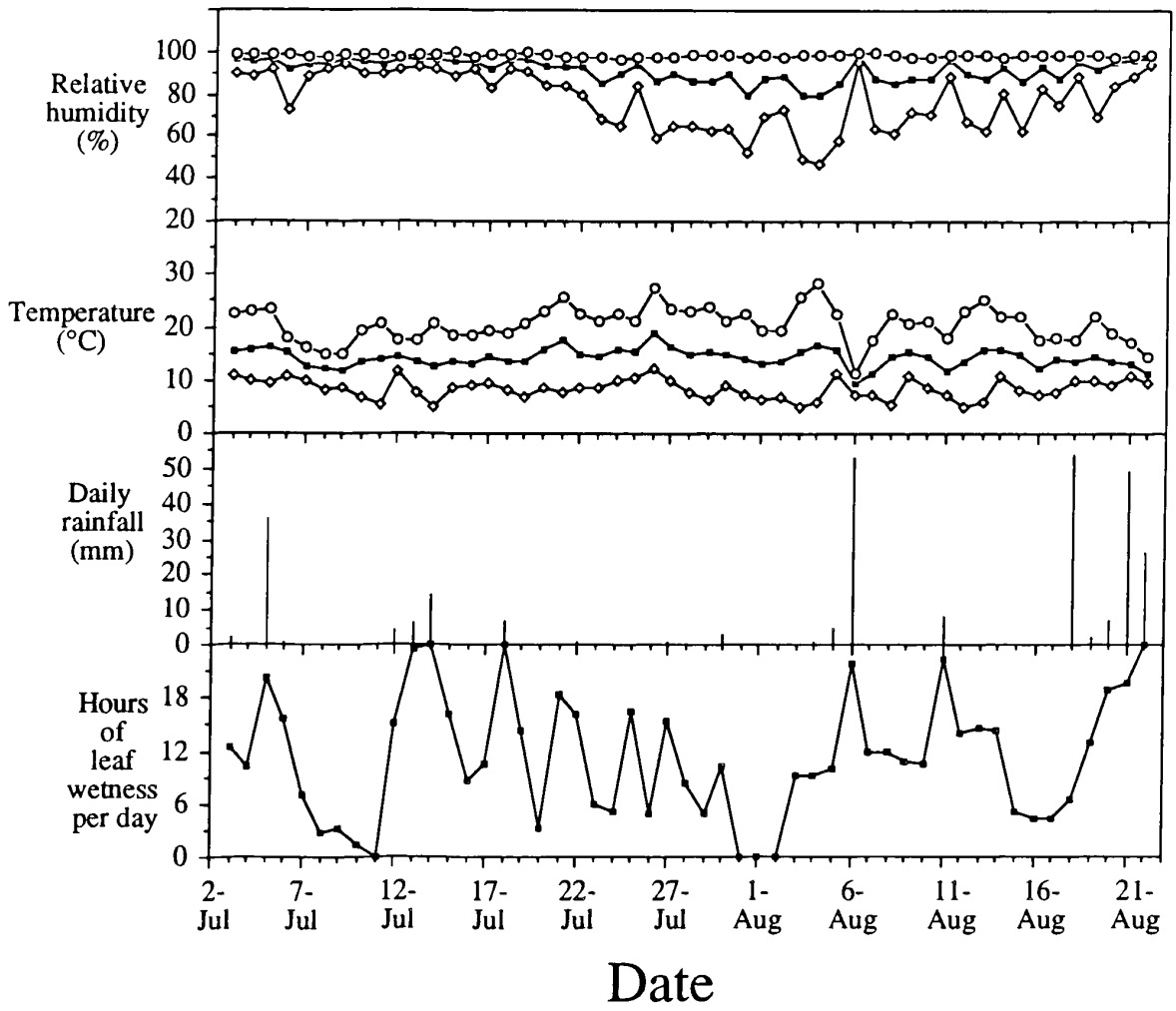

Figure 6.5. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature, daily total rainfall and leaf wetness duration from Micrologger 1, Meadow Lake, 1988 (Section 3.2).

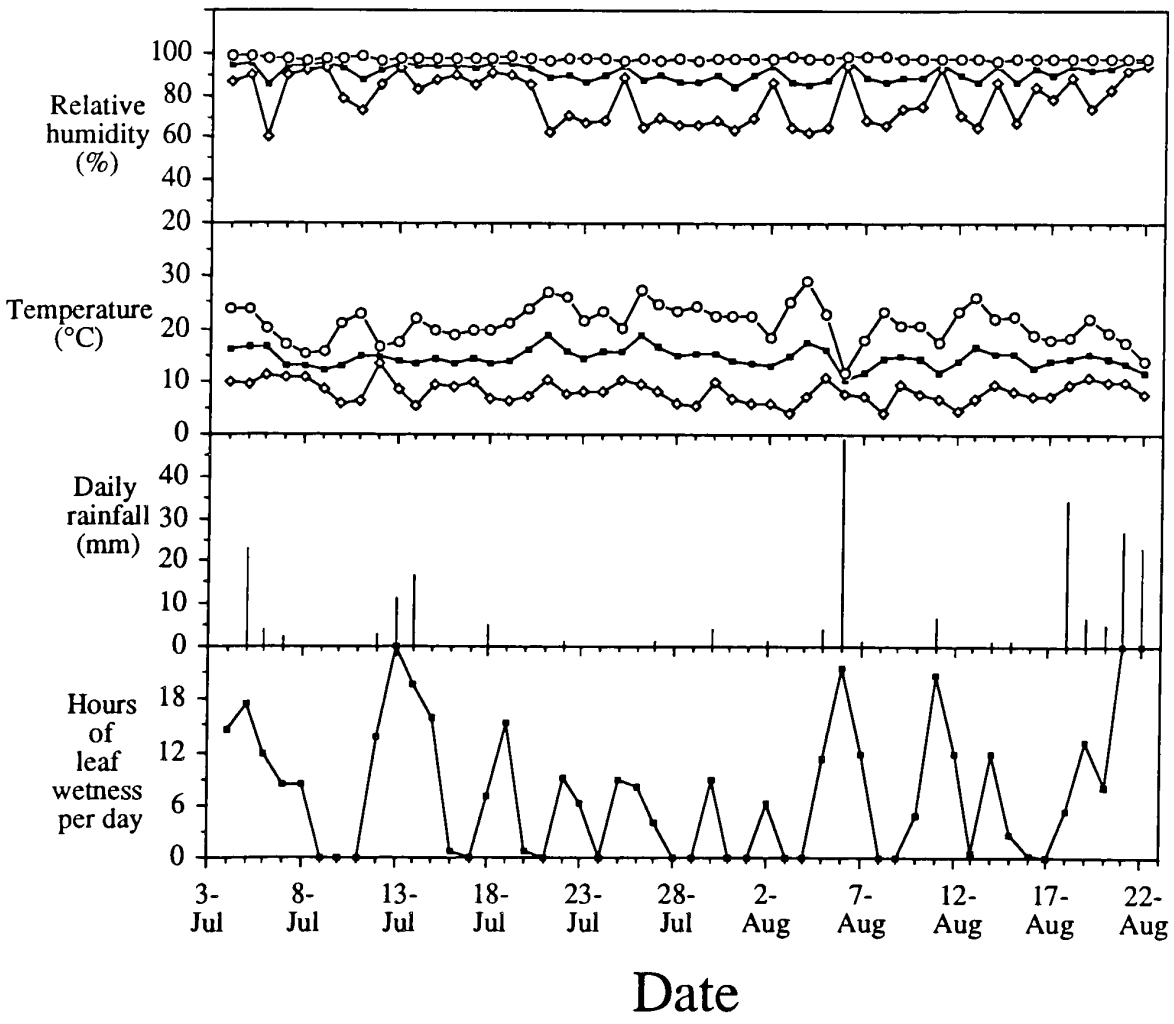

Figure 6.6. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature, daily total rainfall and leaf wetness duration from Micrologger 2, Meadow Lake, 1988 (Section 3.2).

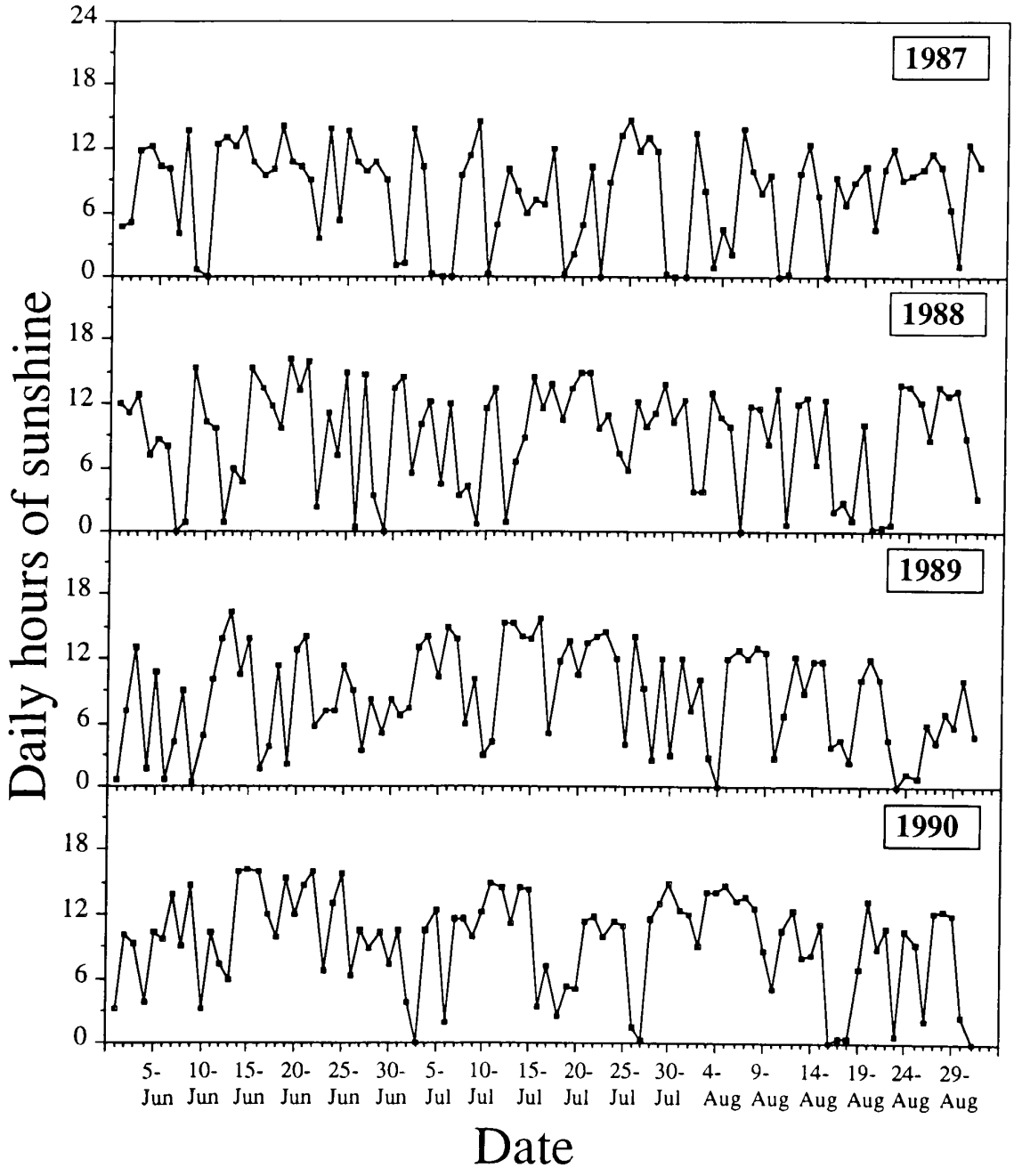

Figure 6.7. Daily hours of sunshine from June to August at Environment Canada reporting stations at Melfort, 1987 and Meadow Lake, 1988-90.

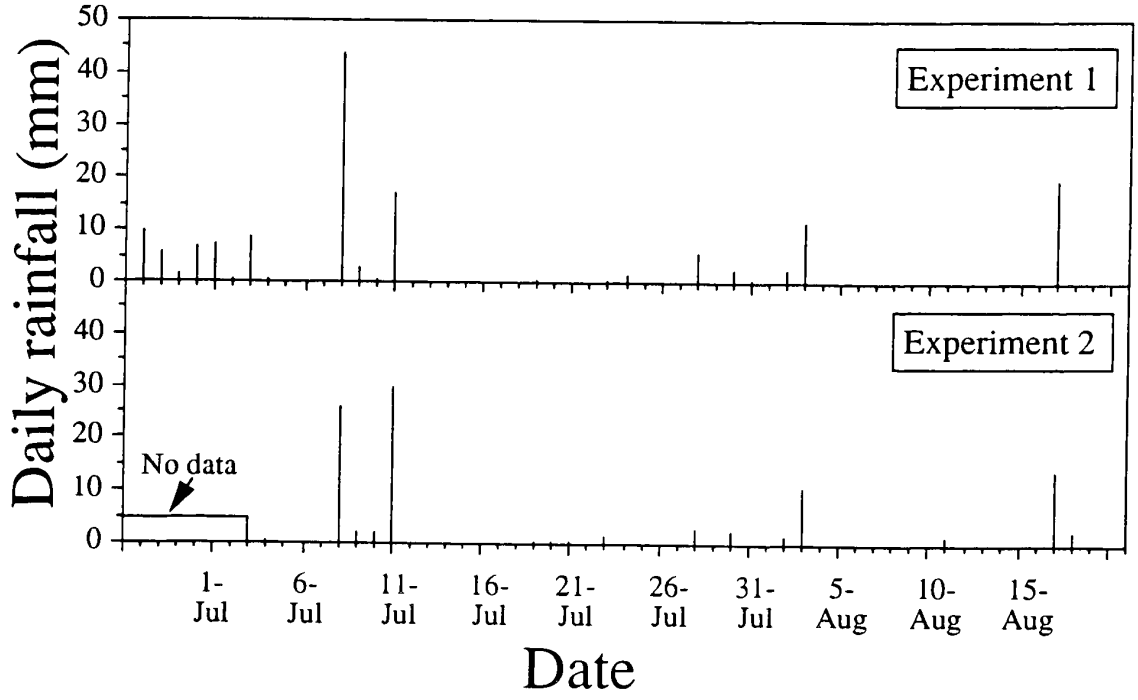

Figure 6.8. Daily total rainfall from June 27 to August 17 in Experiment 1 and from July 4 to August 20 in Experiment 2, Meadow Lake, 1989.

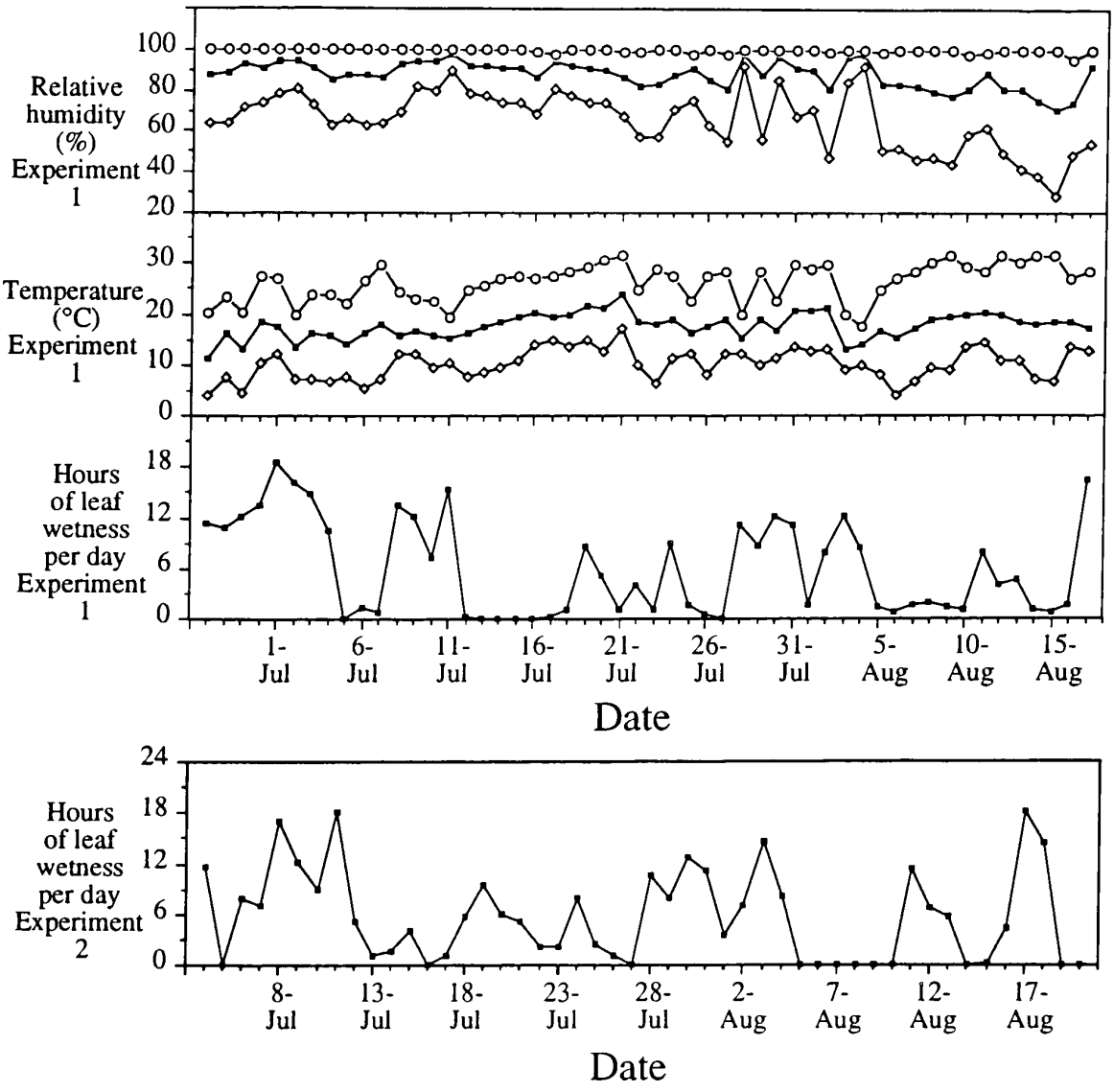

Figure 6.9. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature and daily leaf wetness duration from Experiment 1 June 27 to August 17 and daily leaf wetness duration from Experiment 2 July 4 to August 20, Meadow Lake, 1989. Data for relative humidity, temperature and leaf wetness represent mean values from six sensors in Experiment 1 and three sensors in Experiment 2 (Sections 3 & 4).

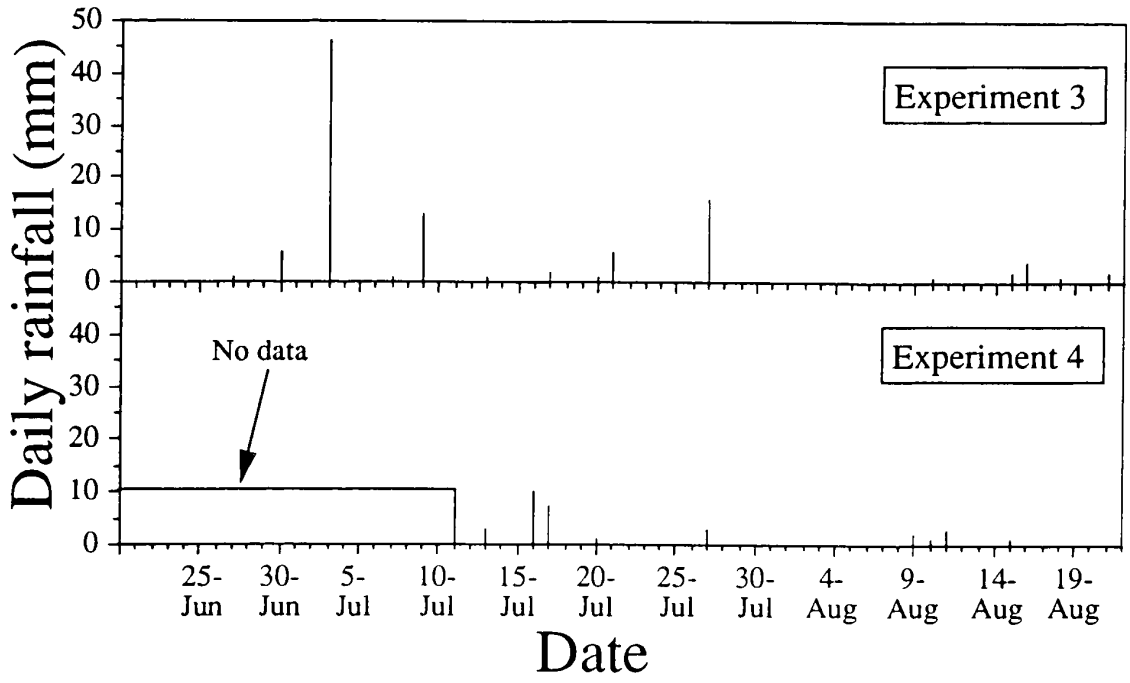

Figure 6.10. Daily total rainfall from June 21 to August 21 in Experiment 3 and from July 12 to August 15 in Experiment 4, Meadow Lake, 1990 (Sections 3 & 4).

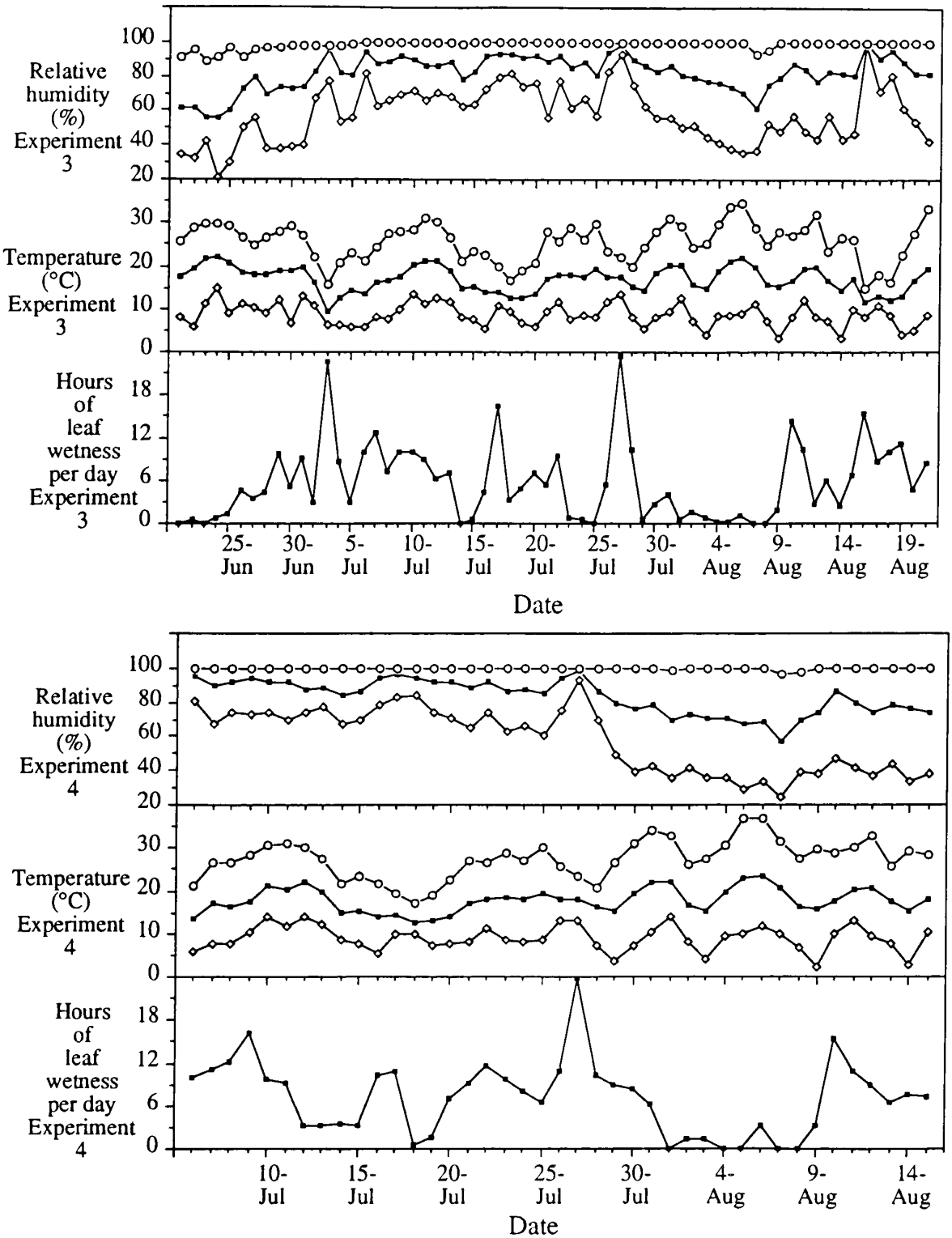

Figure 6.11. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature and daily leaf wetness duration from Experiment 3 June 21 to August 21 and Experiment 4 July 6 to August 15, Meadow Lake, 1990. Data for relative humidity, temperature and leaf wetness represent mean values from three sensors in Experiments 3 and 4 (Sections 3 & 4).

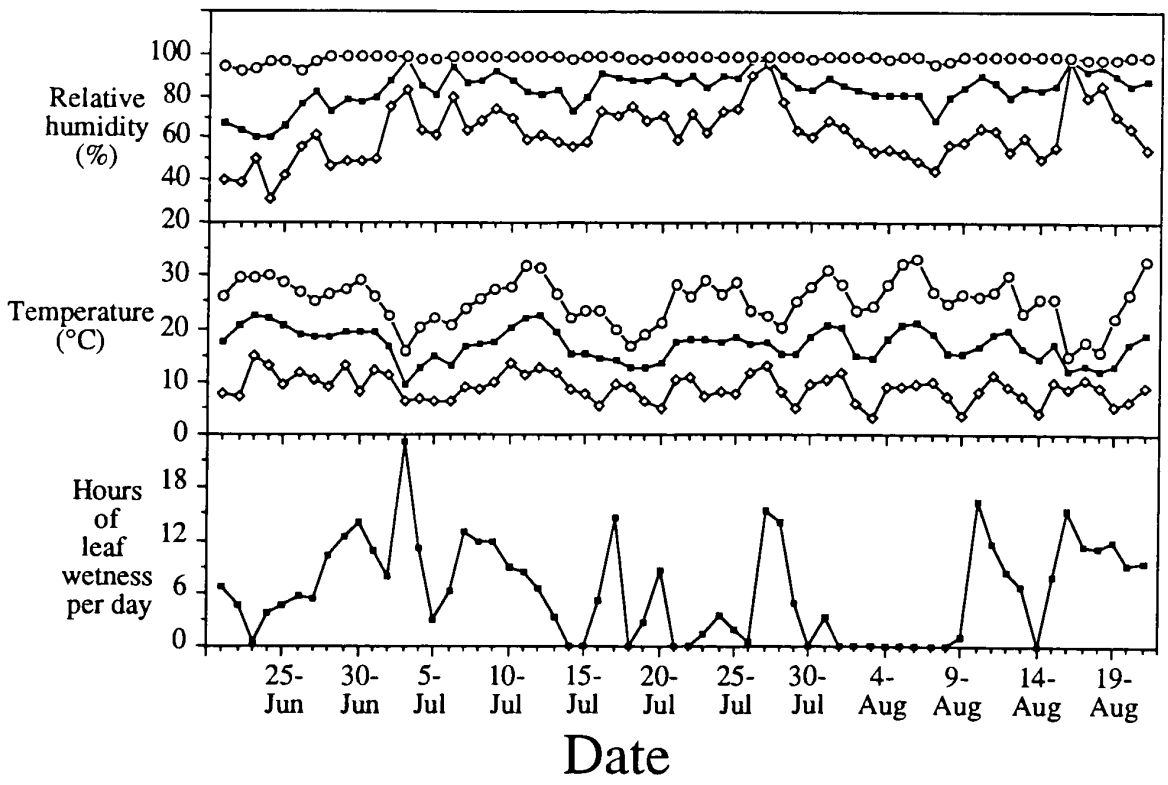

Figure 6.12. Mean (■), minimum (◊) and maximum (o) relative humidity and temperature, and daily leaf wetness duration from Experiment 5, Meadow Lake, 1990 (Sections 3 & 4).

Before evaluating multiple regression models for the data, TMDI for each year was plotted against each of the independent variables to reveal possible relationships. In all cases the scatter of points suggested that only linear relationships existed between TMDI and the respective independent variable. The overall null hypothesis tested was that none of the independent variables had a significant influence on, or helped to explain variation in TMDI. For example, the null and alternative hypotheses that were tested can be summarized using reduction notation (reduction in residual sums of squares) and partial regression coefficients:

$R(\beta_1, \beta_2)$ tests: Ho: $\beta_1 = \beta_2 = 0$ versus Ha: Not all β_i's are zero.

Where $R(\beta_1, \beta_2)$ represents the reduction in residual sums of squares due to fitting the regression model with both β_1 and β_2.

More specific analyses were also performed to test the significance of the respective partial regression coefficients. Appropriate sums of squares (SS) were derived for testing each individual coefficient after the effects of all other coefficients were accounted for (SAS Institute 1985). A series of F-tests were then performed using the error mean square from the overall multiple regression analysis. For example, using reduction notation and partial regression coefficients the respective null and alternative hypotheses tested for β_1 can be summarized as follows:

$R(\beta_1/\beta_2)$ tests Ho: $\beta_1=0$ versus Ha: $\beta_1\neq0$.

Where $R(\beta_1/\beta_2)$ represents the reduction in residual sums of squares due to fitting the regression model with β_1 after accounting for the influence of β_2.

For model selection the independent variable with the lowest partial F value was eliminated and the resulting reduced model was fitted to the collected data. This process was followed until all remaining variables were significant at $p<0.10$.

In 1987, TMDI appeared to be most closely related to MPPI at full and late bloom (Fig. 6.13). A multiple regression model with MPPI at full and late bloom was then evaluated. In the resulting model, the regression SS was highly significant and accounted for 98% of the variation in TMDI (Table 6.4). Tests of partial regression coefficients indicated that MPPI at full and late bloom were significant, with slope values of 0.25 and 0.21, respectively.

Scatter plots for Outlook in 1988 suggested that TMDI was most closely related to MPPI at full bloom (Fig. 6.14). In addition, TMDI also appeared to be related to MHT (Fig. 6.14). A multiple regression model with MPPI at full bloom and MHT was significant and explained 75% of the variation in TMDI (Table 6.5). However, only the partial regression coefficient for MHT was significant. A reduced model with MHT was found to be highly significant and explained approximately 70% of the variation in TMDI (Table 6.6).

At Meadow Lake in 1988 TMDI appeared to be most closely related to MPPI at early, full and late bloom, MHT and MPLP (Figs. 6.15, 6.16). The open box symbols in Figs. 6.15 and 6.16 indicate a probable outlier. This observation represents a crop where the sampling sites had been flooded in August. As a result, severe crop lodging occurred, followed by plant-to-plant disease spread, producing abnormally high disease levels. Thus, there was a good biological reason for removing the observation from the data set.

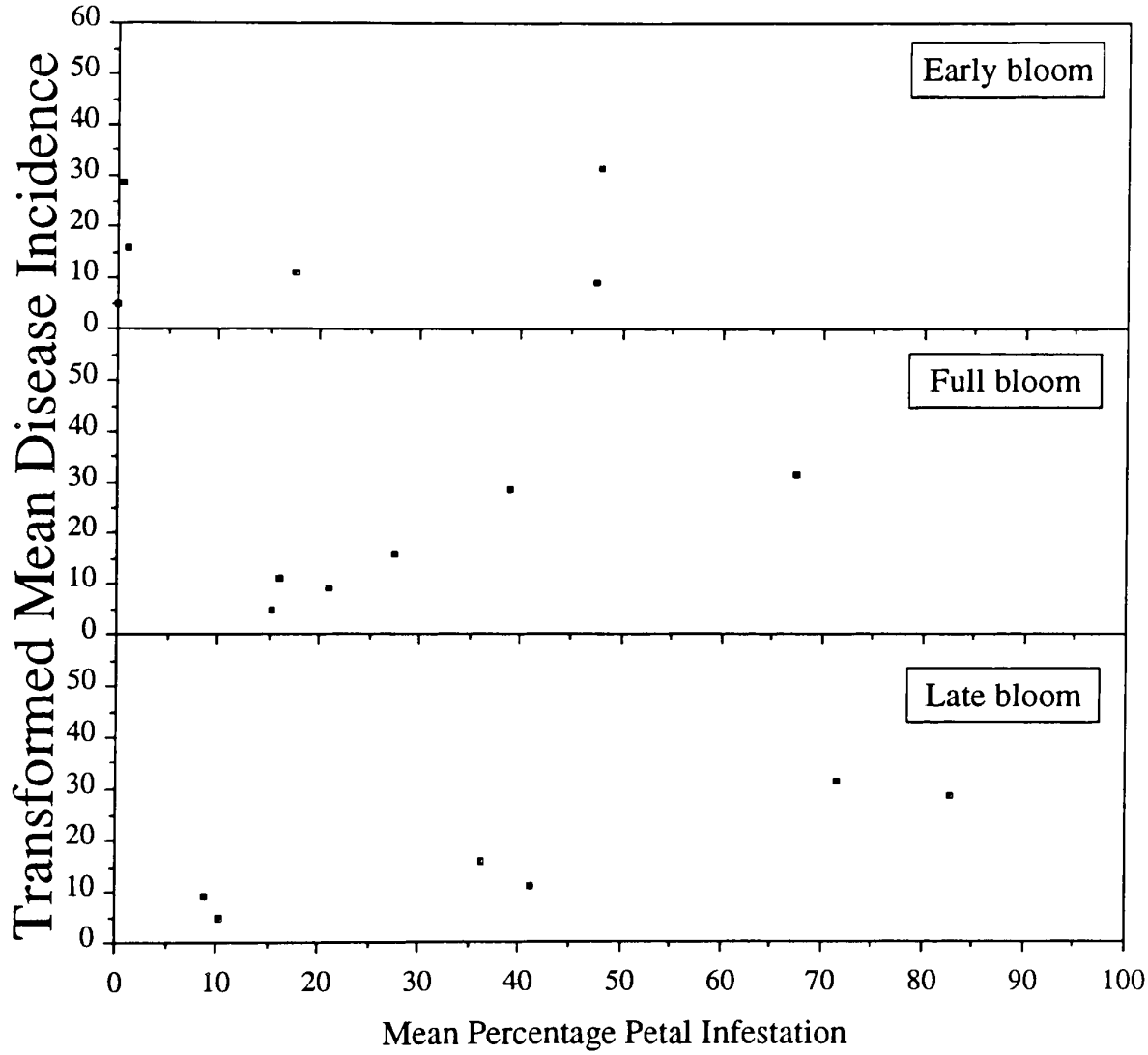

Figure 6.13. Scatter plots of transformed mean disease incidence versus mean percentage petal infestation at early, full and late bloom, Melfort, 1987.

Table 6.4. Analysis of variance for a proposed multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Melfort, 1987.

Source	df	SS	F
Model	2	576	83.2***
Error	3	10	
Total	5	586	
Partial regression coefficients†			
MPPIFB (β_1)	1	56	16.3**
MPPILB (β_2)	1	92	26.7**

Coefficient of determination: 98% Coefficient of variation: 11%

Parameter	Estimate	Standard Error
β_0 (Intercept)	0.14	1.5
β_1 (MPPIFB)	0.25	0.06
β_2 (MPPILB)	0.21	0.04

** Significant at p = 0.05.
*** Significant at p = 0.01.
† MPPIFB = Mean percentage petal infestation at full bloom, MPPILB = Mean percentage petal infestation at late bloom.

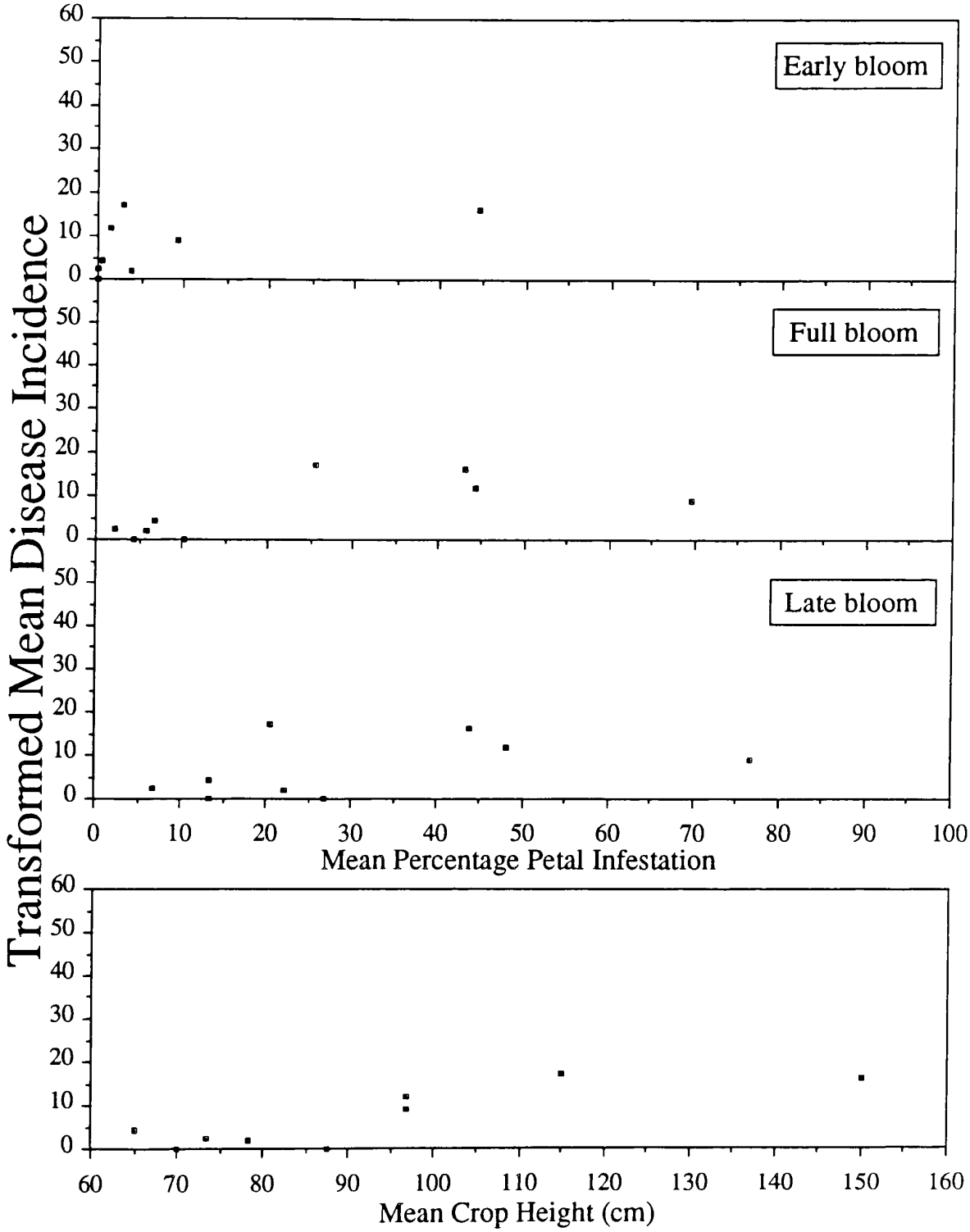

Figure 6.14. Scatter plots of transformed mean disease incidence versus mean percentage petal infestation at early, full and late bloom and mean crop height, Outlook, 1988.

Table 6.5. Analysis of variance for a proposed multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Outlook, 1988.

Source	df	SS	F
Model	2	275	9.0**
Error	6	92	
Total	8	367	
Partial regression coefficients†			
MPPIFB (β_1)	1	17	1.1
MHT (β_2)	1	113	7.4**

Coefficient of determination: 75% Coefficient of variation: 56%

Parameter	Estimate	Standard Error
β_0 (Intercept)	-10.8	5.3
β_1 (MPPIFB)	0.08	0.07
β_2 (MHT)	0.17	0.06

** Significant at p = 0.05.

† MPPIFB = Mean percentage petal infestation at full bloom, MHT = Mean crop height.

Table 6.6. Analysis of variance for a proposed reduced regression model to explain variation in arcsine-transformed mean disease incidence, Outlook, 1988.

Source	df	SS	F
Model	1	258	16.6***
Error	7	109	
Total	8	367	

Coefficient of determination: 70% Coefficient of variation: 56%

Parameter†	Estimate	Standard Error
β_0 (Intercept)	-12.7	5.0
β_2 (MHT)	0.21	0.05

*** Significant at p = 0.01.

† MHT = Mean crop height.

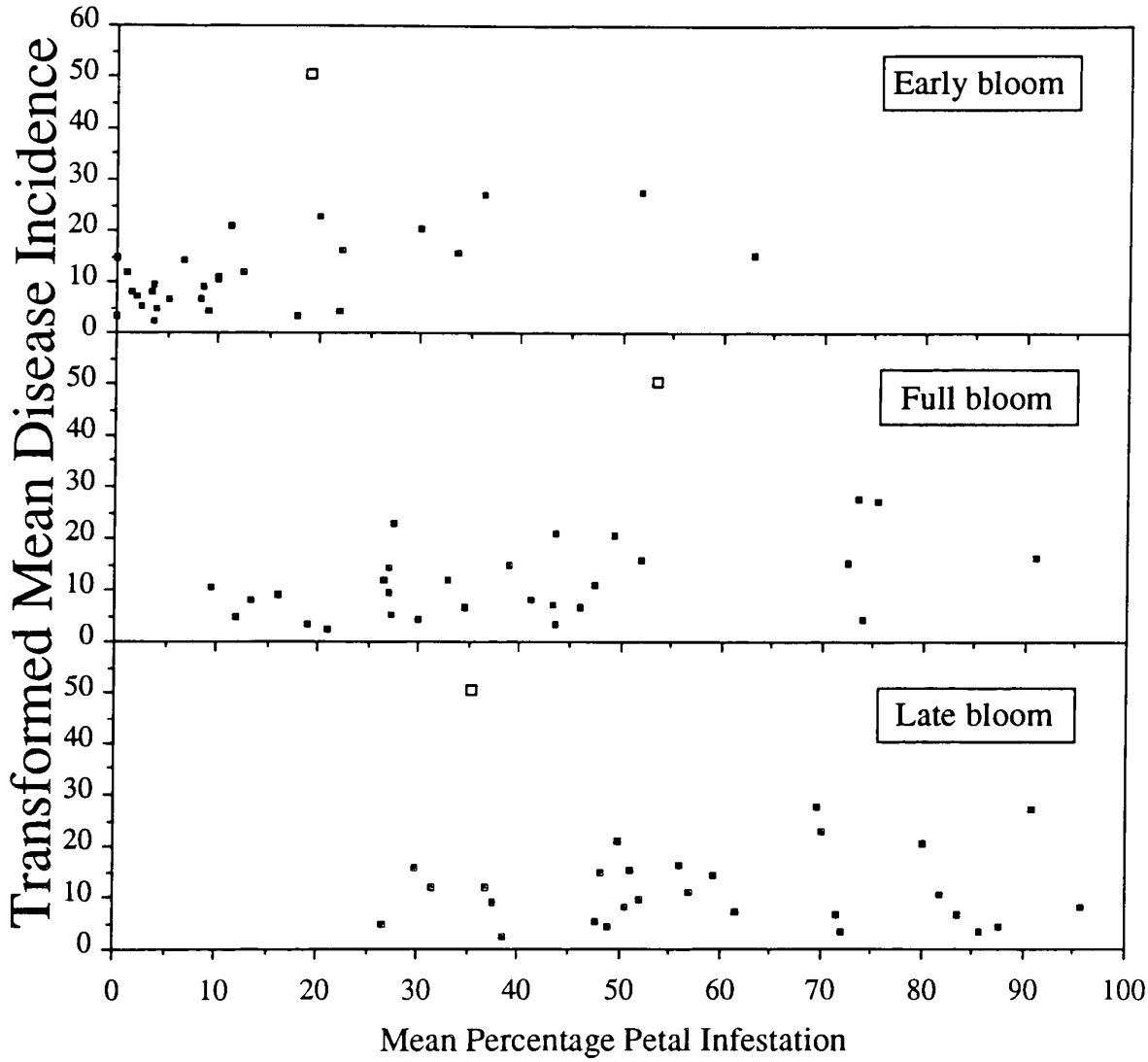

Figure 6.15. Scatter plots of transformed mean disease incidence versus mean percentage petal infestation at early, full and late bloom, Meadow Lake, 1988. The open box symbol in each plot indicates a possible outlier (See text for explanation).

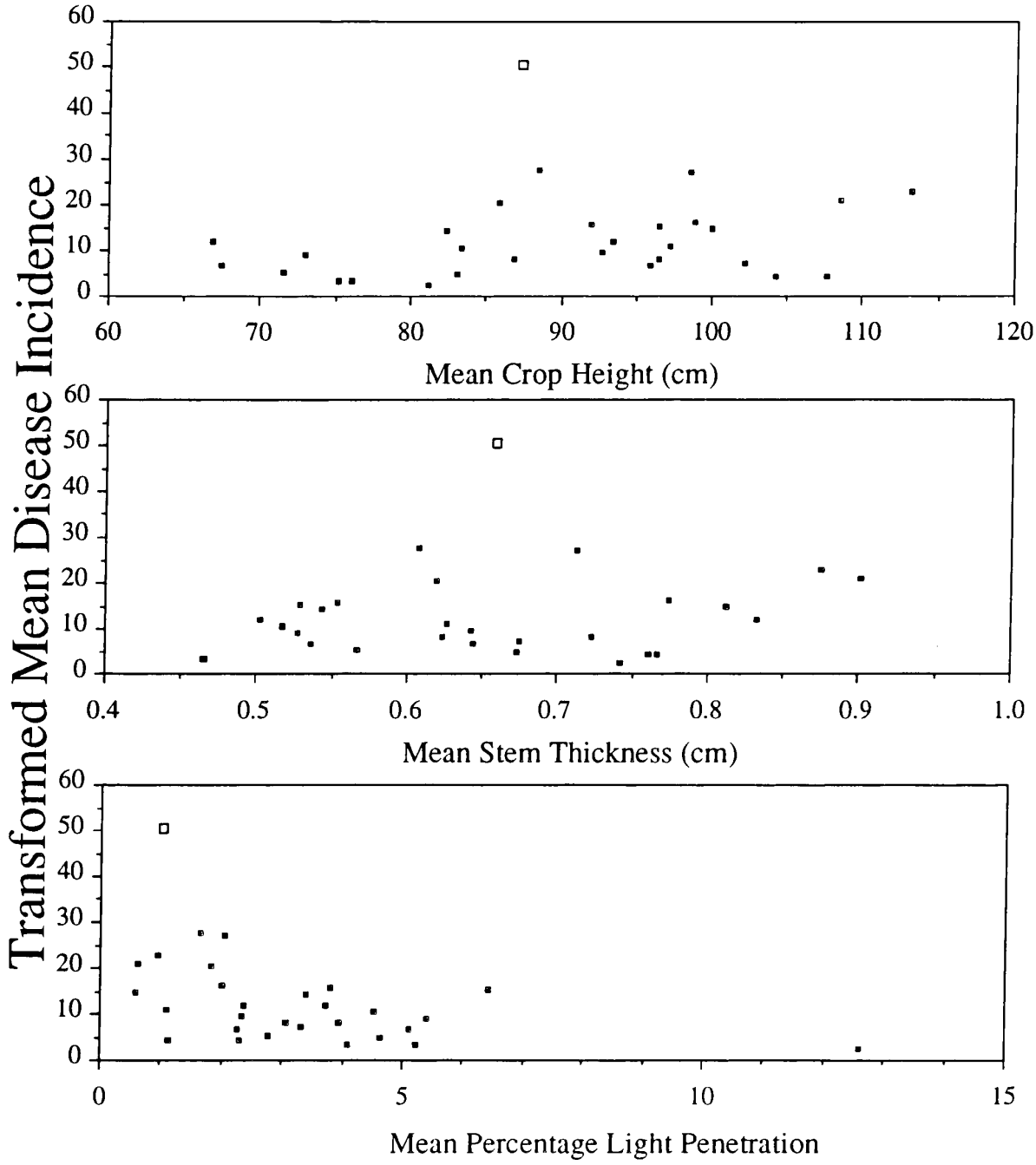

Figure 6.16. Scatter plots of transformed mean disease incidence versus mean crop height, mean stem thickness and mean percentage light penetration, Meadow Lake, 1988. The open box symbol in each plot indicates a possible outlier (See text for explanation).

A regression model with MPPI at early, full and late bloom, MHT, and MPLP was then tested (Table 6.7). The model SS was highly significant and accounted for 58% of the variation in TMDI. From the appropriate SS for the partial regression coefficients only MPPI at early bloom and MPLP were significant. A reduced model with MPPI at early bloom and MPLP was highly significant and explained 56% of the variation in TMDI (Table 6.8). Tests for the partial regression coefficients indicated that MPPI at early bloom was highly significant with a slope value of 0.27, while the value for MPLP was negative and also highly significant.

From scatter plots for Meadow Lake in 1989 TMDI appeared to be most closely related to MPPI at early bloom, MHT, MST and MPLP (Figs. 6.17, 6.18). The open box symbols in Figs. 6.17 and 6.18 represent four late crops in which early bloom did not occur until after July 11. Disease incidence in these crops was low even though MPPI at early and full bloom was relatively high. Because the amount and frequency of rainfall was extremely low during their entire flowering period, data from these crops were considered outliers and excluded from the regression analysis. A multiple regression model with MPPI at early bloom, MHT, MST and MPLP was significant and accounted for 71% of the variation in TMDI (Table 6.9). Appropriate SS for the partial regression coefficients indicated that only MPPI at early bloom and MPLP were significant. A reduced model with MPPI at early bloom and MPLP was highly significant ($p<0.01$) and explained 70% of the variation in TMDI (Table 6.10). Tests for the partial regression coefficients indicated that MPPI at early bloom was highly significant with a slope value of 0.33, while the value for MPLP was negative and highly significant.

In 1990, TMDI appeared to be related to MPPI at early and full bloom, MHT and MLAI (Figs. 6.19, 6.20). The open box symbols in Figs. 6.19 and 6.20 represent a crop which was almost two weeks later in development than most other crops. Because of its late development it was not included in the analysis. A model with MPPI at early and full

Table 6.7. Analysis of variance for a proposed multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1988.

Source	df	SS	F
Model	5	799	6.1***
Error	22	580	
Total	27	1379	
Partial regression coefficients†			
MPPIEB (β_1)	1	308	11.7***
MPPIFB (β_2)	1	2	0.08
MPPILB (β_3)	1	13	0.48
MHT (β_4)	1	11	0.42
MPLP (β_5)	1	183	7.0**

Coefficient of determination: 58% Coefficient of variation: 44%

Parameter	Estimate	Standard Error
β_0 (Intercept)	9.4	9.2
β_1 (MPPIEB)	0.28	0.08
β_2 (MPPIFB)	-0.02	0.07
β_3 (MPPILB)	-0.04	0.05
β_4 (MHT)	0.06	0.09
β_5 (MPLP)	-1.3	0.48

** Significant at p = 0.05.
*** Significant at p = 0.01.
† MPPIEB = Mean percentage petal infestation at early bloom, MPPIFB = Mean percentage petal infestation at full bloom, MPPILB = Mean percentage petal infestation at late bloom, MHT = Mean crop height, MPLP = Mean percentage light penetration.

Table 6.8. Analysis of variance for a proposed reduced multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1988.

Source	df	SS	F
Model	2	774	16.0***
Error	25	605	
Total	27	1379	
Partial regression coefficients†			
MPPIEB ($ß_1$)	1	489	20.2***
MPLP ($ß_5$)	1	248	10.3***

Coefficient of determination: 56% Coefficient of variation: 43%

Parameter	Estimate	Standard Error
$ß_0$ (Intercept)	12.0	1.9
$ß_1$ (MPPIEB)	0.27	0.06
$ß_5$ (MPLP)	-1.3	0.40

*** Significant at p = 0.01.

† MPPIEB = Mean percentage petal infestation at early bloom, MPLP = Mean percentage light penetration.

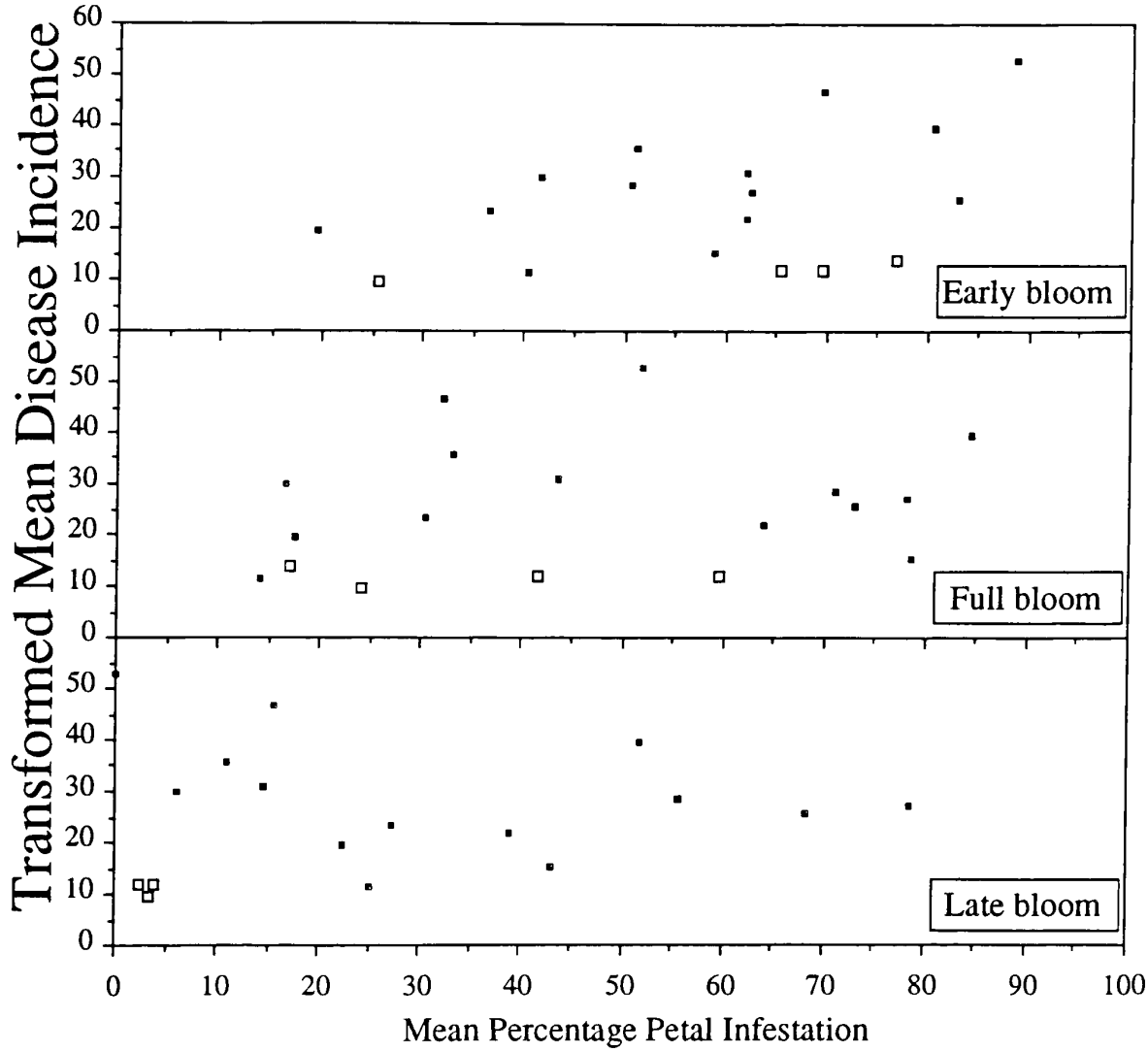

Figure 6.17. Scatter plots of transformed mean disease incidence versus mean percentage petal infestation at early, full and late bloom, Meadow Lake, 1989. The open box symbols in each plot indicate possible outliers (See text for explanation).

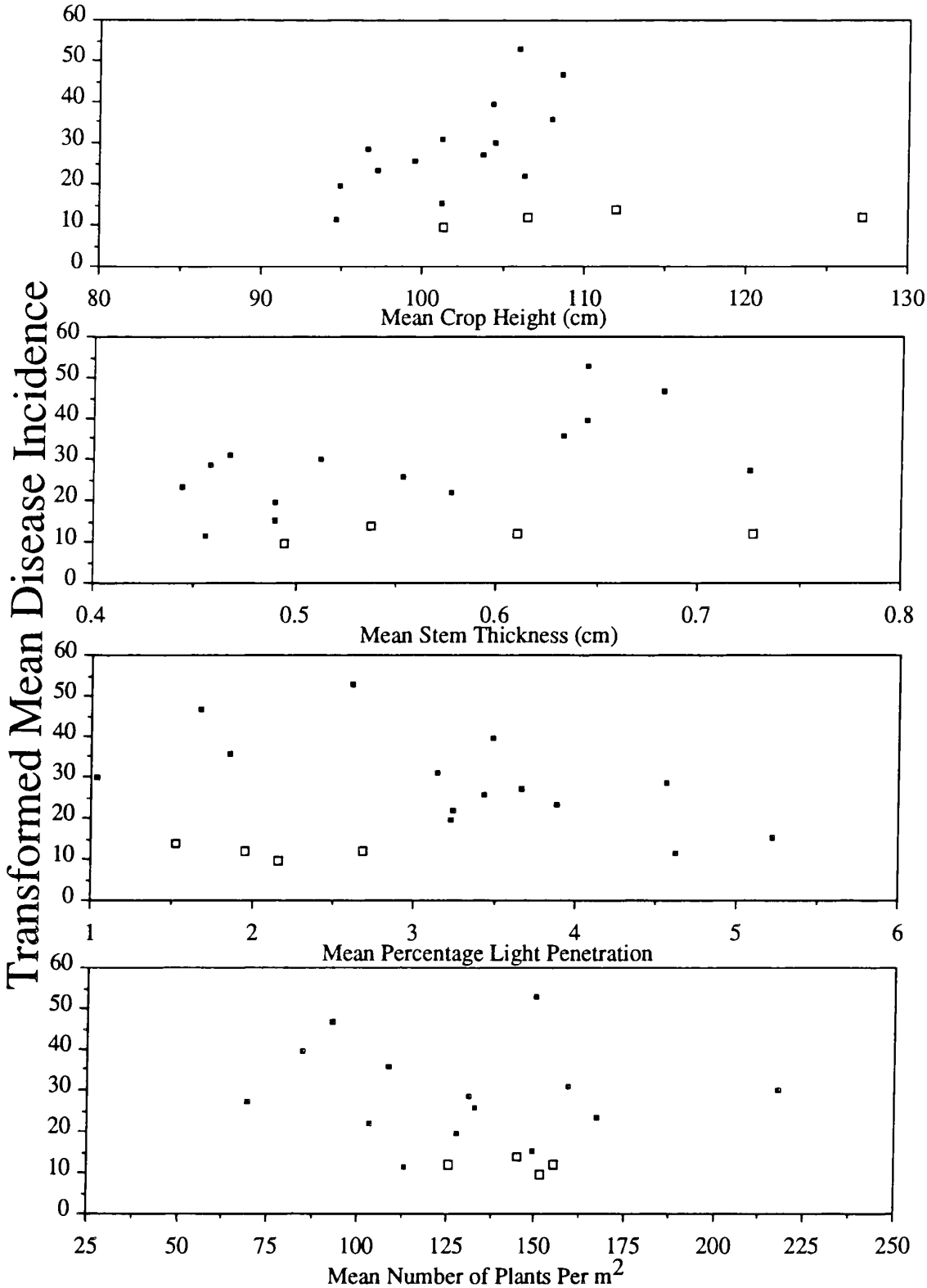

Figure 6.18. Scatter plots of transformed mean disease incidence versus mean crop height, mean stem thickness, mean percentage light penetration and mean number of plants per m^2, Meadow Lake, 1989. The open box symbols in each plot indicate possible outliers (See text for explanation).

Table 6.9. Analysis of variance for a proposed multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1989.

Source	df	SS	F
Model	4	1205	5.4**
Error	9	500	
Total	13	1705	
Partial regression coefficients†			
MPPIEB (β_1)	1	254	4.6*
MHT (β_2)	1	6	0.11
MST (β_3)	1	15	0.27
MPLP (β_4)	1	264	4.7*

Coefficient of determination: 71% Coefficient of variation: 26%

Parameter	Estimate	Standard Error
β_0 (Intercept)	50.0	86.4
β_1 (MPPIEB)	0.32	0.15
β_2 (MHT)	-0.30	0.91
β_3 (MST)	18.6	35.9
β_4 (MPLP)	-5.7	2.6

* Significant at p = 0.10.
** Significant at p = 0.05.
† MPPIEB = Mean percentage petal infestation at early bloom, MHT = Mean crop height, MST = Mean stem thickness, MPLP = Mean percentage light penetration.

Table 6.10. Analysis of variance for a proposed reduced multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1989.

Source	df	SS	F
Model	2	1190	12.7***
Error	11	515	
Total	13	1705	
Partial regression coefficients†			
MPPIEB (β_1)	1	543	11.6***
MPLP (β_4)	1	547	11.7***

Coefficient of determination: 70% Coefficient of variation: 23%

Parameter	Estimate	Standard Error
β_0 (Intercept)	27.9	8.3
β_1 (MPPIEB)	0.33	0.1
β_4 (MPLP)	-5.5	1.6

*** Significant at p = 0.01.

† MPPIEB = Mean percentage petal infestation at early bloom, MPLP = Mean percentage light penetration.

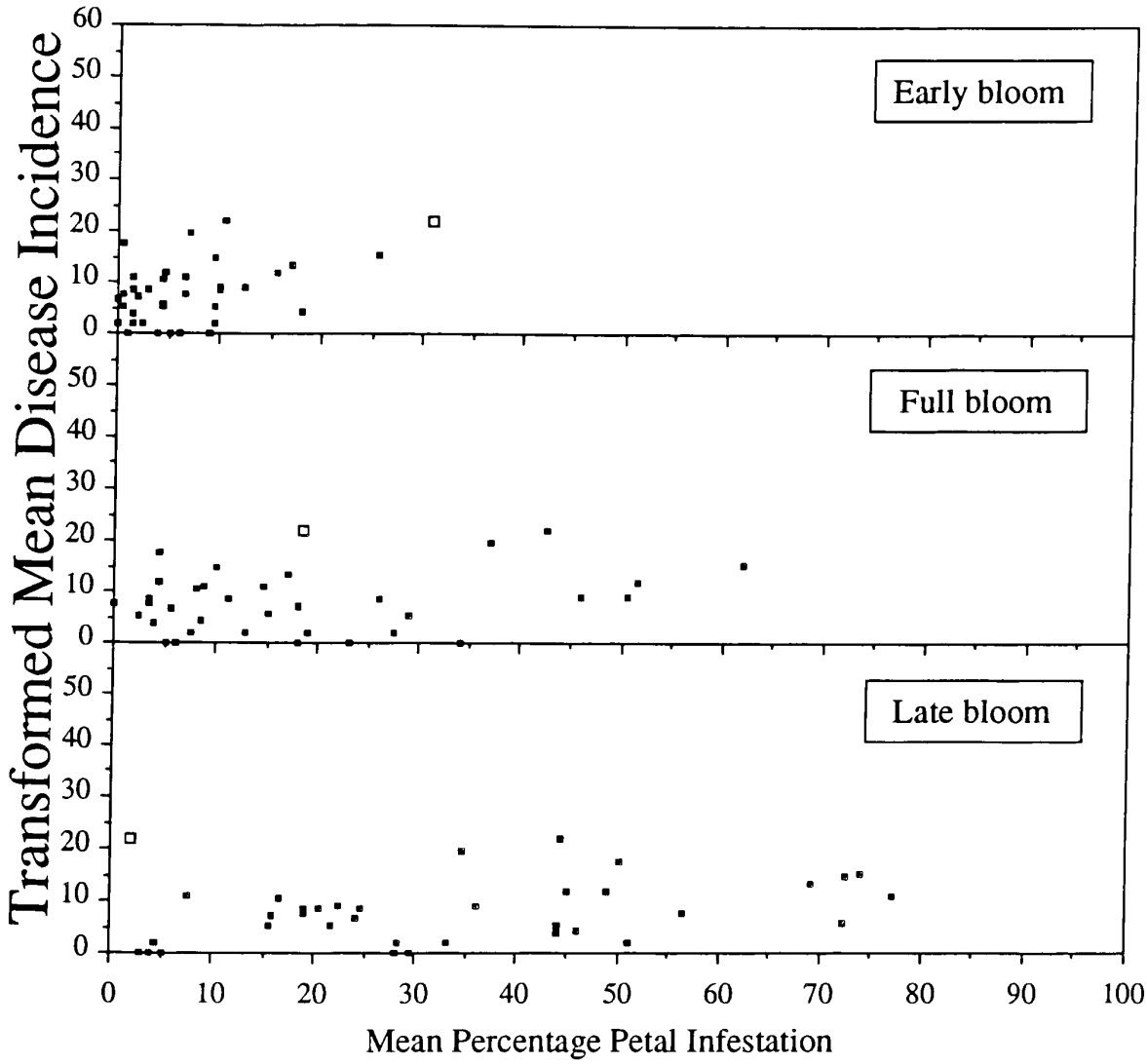

Figure 6.19. Scatter plots of transformed mean disease incidence versus mean percentage petal infestation at early, full and late bloom, Meadow Lake, 1990. The open box symbol in each plot indicates a possible outlier (See text for explanation).

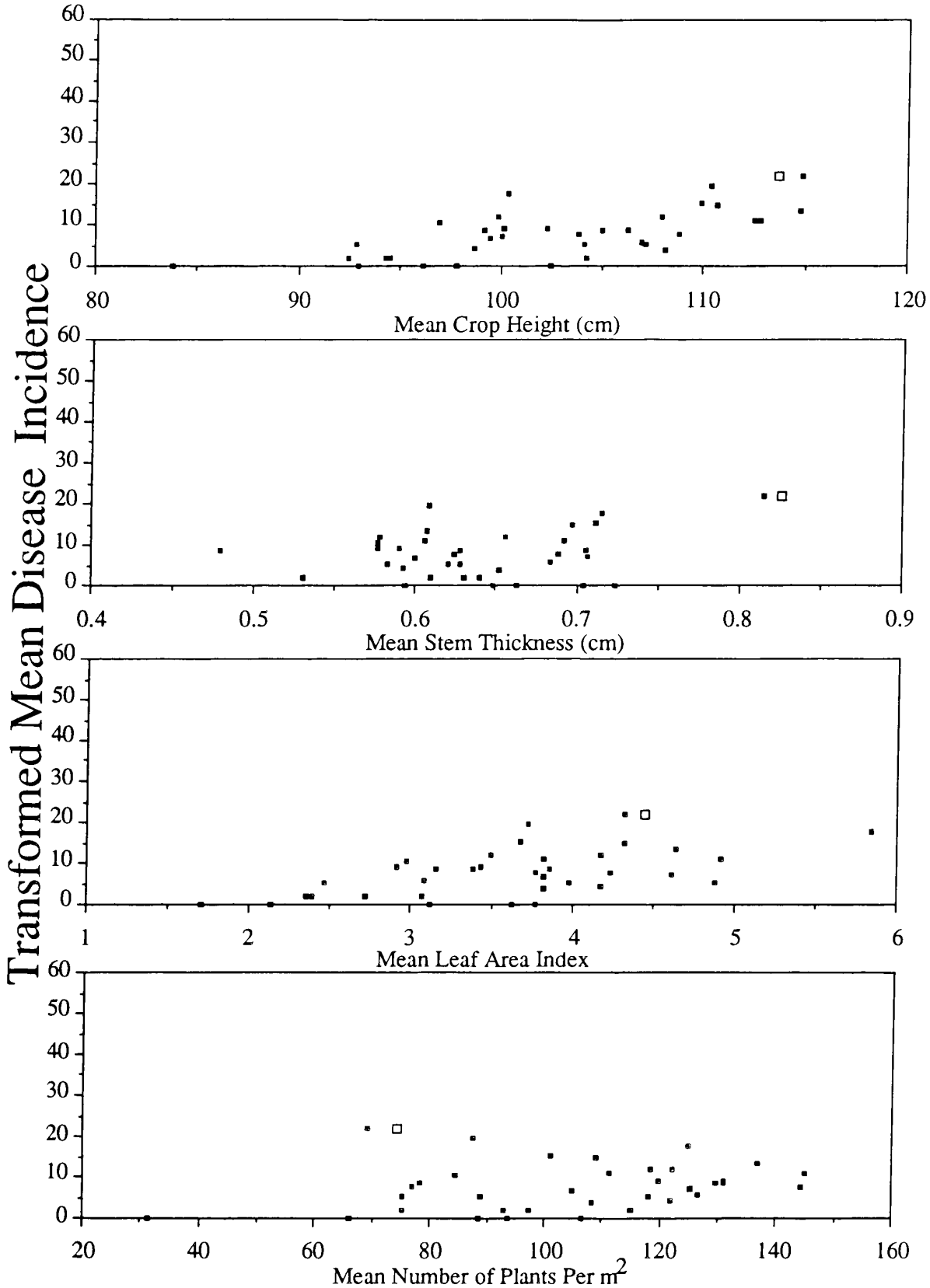

Figure 6.20. Scatter plots of transformed mean disease incidence versus mean crop height, mean stem thickness, mean leaf area index and mean number of plants per m^2, Meadow Lake, 1990. The open box symbol in each plot indicates a possible outlier (See text for explanation).

bloom, MHT and MLAI was then tested. The regression SS was highly significant and accounted for 55% of the variation in TMDI (Table 6.11). Tests for the partial regression coefficients indicated that MHT was significant at p = 0.01, MLAI was significant at p = 0.05, while MPPI at full bloom was significant at p = 0.10. A reduced model with MHT, MLAI and MPPI at full bloom was tested and found to be highly significant; it accounted for 55% of the variation in TMDI (Table 6.12). The partial regression coefficient for MPPI at full bloom was significant with a slope value of 0.10. The slope value for MLAI was positive and significant at p = 0.05, while the value for MHT was positive and highly significant.

6.4. Discussion

Disease levels reflected average MPPI from 1987 to 1990 (Table 6.1). The lowest average TMDI and MPPI were observed at Outlook in 1988 and Meadow Lake in 1990. Slightly higher TMDI and MPPI were observed at Melfort in 1987 and Meadow Lake in 1988. The highest TMDI was observed at Meadow Lake in 1989, which also had the highest average MPPI. However, the importance of MPPI at early, full and late bloom varied from year to year. In general, MPPI at a particular flowering stage was significantly related to TMDI if the presence of inoculum coincided with favorable moisture conditions. These conditions typically resulted from an increased frequency of rainfall rather than the total amount recorded. For example, approximately average levels of rainfall occurred in July at Melfort in 1987 and at Meadow Lake in 1988 and 1989 (Table 6.3). However, in 1990 well above average rainfall was recorded for July, but MDI and MPPI remained low. The difference in MDI and MPPI from 1987 to 1990 may partly reflect variation in June rainfall which influenced sclerotial germination and ascospore production. Nevertheless, the pattern and frequency of rainfall during the flowering and infection period was probably

Table 6.11. Analysis of variance for a proposed multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1990.

Source	df	SS	F
Model	4	628	9.2***
Error	30	509	
Total	34	1138	
Partial regression coefficients†			
MPPIEB (β_1)	1	0.3	0.02
MPPIFB (β_2)	1	57	3.4*
MHT (β_3)	1	135	7.9***
MLAI (β_4)	1	73	4.3**

Coefficient of determination: 55% Coefficient of variation: 54%

Parameter	Estimate	Standard Error
β_0 (Intercept)	-37.9	11.0
β_1 (MPPIEB)	-0.02	0.16
β_2 (MPPIFB)	0.10	0.06
β_3 (MHT)	0.35	0.12
β_4 (MLAI)	2.1	1.0

* Significant at p = 0.10.
** Significant at p = 0.05.
*** Significant at p = 0.01.
† MPPIEB = Mean percentage petal infestation at early bloom, MPPIFB = Mean percentage petal infestation at full bloom, MHT = Mean crop height, MLAI = Mean leaf area index.

Table 6.12. Analysis of variance for a proposed reduced multiple regression model to explain variation in arcsine-transformed mean disease incidence with appropriate tests for the partial regression coefficients, Meadow Lake, 1990.

Source	df	SS	F
Model	3	628	12.7***
Error	31	510	
Total	34	1138	
Partial regression coefficients†			
MPPIFB (β_2)	1	85	5.2**
MHT (β_3)	1	137	8.4***
MLAI (β_4)	1	72	4.4**

Coefficient of determination: 55% Coefficient of variation: 53%

Parameter	Estimate	Standard Error
β_0 (Intercept)	-37.6	10.6
β_2 (MPPIFB)	0.10	0.04
β_3 (MHT)	0.35	0.12
β_4 (MLAI)	2.1	1.0

** Significant at p = 0.05.
*** Significant at p = 0.01.
† MPPIFB = Mean percentage petal infestation at full bloom, MHT = Mean crop height, MLAI = Mean leaf area index.

equally important for host infection. In 1990, a substantial amount of rainfall occurred on July 3 and 9 (Figs. 6.1, 6.10). However, these dates were followed by periods during which little or no rain fell and temperature (Figs. 6.11, 6.12) and sunshine (Fig. 6.7) conditions were conducive to high evapotranspiration. Thus, after both dates high moisture levels in the canopy persisted for only relatively short periods of time (Figs. 6.11, 6.12). In contrast, frequent showers during late June and July in 1987, 1988 and 1989 resulted in relatively high canopy moisture levels for longer periods of time than in 1990. This was evident from the RH data recorded by the microloggers, especially for Melfort, 1987, and Meadow Lake 1988, where the frequency with which daily mean RH values were close to the daily maximum was greater than in 1990 (Figs. 6.2, 6.3, 6.5, 6.6, 6.8, 6.9, 6.11, 6.12).

In 1987, lack of rainfall during most of June restricted ascospore production until the second week of July when most crops were in full or late bloom (Figs. 6.1-6.3). Only after rainfall on June 30 did conditions favorable for sclerotial germination occur. As a result substantial ascospore production was delayed until the second week of July when most crops were at full-late bloom. Multiple regression analysis demonstrated a significant relationship between TMDI and MPPI at full and late bloom (Table 6.4). These variables were significant because the presence of inoculum at these flowering stages coincided with the occurrence of rainfall which produced favorable moisture conditions for host infection from infested petals.

In 1988 at Outlook, MPPI increased as the crop progressed from early to late bloom (Table 6.1). All crops at Outlook were under overhead irrigation so moisture should not have been a limiting factor for sclerotial germination. However, high temperatures, long periods of sunshine and lack of substantial rainfall during most of June would have limited any influence that irrigation may have had (Fig. 6.4). Evapotranspirational water loss from crops during the second half of June may have been high enough to restrict soil moisture levels despite irrigation, especially since crops may not have completely covered the soil

surface at that growth stage. However, rainfall after June 28 (Fig. 6.4) in conjunction with further crop development and irrigation may have been sufficient to produce favorable moisture conditions for sclerotial germination. As a result increased ascospore production occurred 1-2 weeks later, leading to increased MPPI when crops were at full-late bloom.

Disease levels at Outlook appeared to most closely reflect MPPI at full bloom (Fig. 6.14). Most crops were at full bloom from July 8 to 15 and during this period several small showers occurred which may have been associated with cooler more favorable conditions for host infection. Higher temperatures and reduced rainfall after July 19 probably restricted host infection from infested petals. During this period all crops were at late bloom. Multiple regression analysis indicated that TMDI was not significantly related to MPPI at any flowering stage (Tables 6.5, 6.6).

Overall, the lowest TMDI of all locations and years occurred at Outlook (Table 6.1). Even though all crops at Outlook were under irrigation and moisture was probably not a limiting factor for crop growth, MPPI and TMDI still remained low. At Outlook in 1988, a study investigating the influence of irrigation on sclerotinia stem rot of canola (B.K. Teo et al. unpublished) showed that MPPI remained less than 30% and MDI ranged from 1 to 10% (mean = 4%) for several irrigation regimes. Thus, irrigation probably did not have a major effect on TMDI or MPPI during 1988. Irrigation, especially during sunshine, probably does not increase the duration of high RH and leaf wetness compared with rainfall, since evapotranspiration of water is higher (B.K. Teo et al. unpublished).

In 1988 at Meadow Lake, lack of substantial rainfall in June (Fig. 6.1) prevented significant ascospore production until the second week of July when most crops were at full or late bloom. Most crops were at early bloom from the last week of June to the first week of July. During this period frequent showers produced a substantial amount of rainfall, which would have created conditions favorable for host infection. The majority of crops were at full bloom from July 6 to 11, a period when virtually no rainfall was recorded. Showers occurred from July 12 to 14, but during the rest of the month the

amount and frequency of rainfall was limited. In general increased MPPI at full and late bloom did not coincide with as favorable moisture conditions for infection as at early bloom. Multiple regression analysis demonstrated a significant relationship between TMDI and MPPI at early bloom, but MDI remained fairly low (Tables 6.7, 6.8).

In 1989, frequent showers, especially during late June (Figs. 6.1, 6.8), probably promoted sclerotial germination and ascospore production so that MPPI was relatively high at early and full bloom (Table 6.1). However, moisture conditions became less favorable after July 11 resulting in a decrease in MPPI at late bloom. The presence of relatively high MPPI at early bloom coincided with the occurrence of favorable moisture conditions for infection resulting in relatively high TMDI. Multiple regression analysis demonstrated a significant relationship between TMDI and MPPI at early bloom (Tables 6.9, 6.10). Moisture conditions were less favorable at full and late bloom and no significant relationship with TMDI was demonstrated.

In 1990, lack of rainfall during most of June (Figs 6.1, 6.10) restricted ascospore production early in July. However, rainfall from June 30 to July 9 probably initiated sclerotial germination with ascospore production occurring 1-2 weeks later, as evidenced by increased MPPI at full and late bloom (Table 6.1). Most crops were at early bloom between July 5 and 9 and average MPPI at this stage was <10%; however, by late bloom average MPPI had increased to >30%. Transformed disease incidence appeared to be most closely related to MPPI at early and full bloom (Fig. 6.19). The analyses of data from 1990 indicated that TMDI was significantly related to MPPI at full bloom (Tables 6.11, 6.12). Petal infestation at full bloom may have been important, since over 50% of the crops were at full bloom by July 11-12, and moisture conditions shortly before July 18 appeared to be relatively favorable for host infection. Most crops were at late bloom by July 18-25, a period with little rainfall and increased levels of sunshine. Furthermore, results from the canopy density experiments (Section 4) suggested that MLAI may have been highest during full bloom; a high MLAI would have promoted more favorable

microenvironmental conditions at full bloom.

For those regressions that were significant the slope of the relationship between TMDI and MPPI ranged from 0.10 to 0.33 (Tables 6.4-6.12). The differences in slope may partly reflect variation in the pattern, frequency and amount of rainfall in June and July each year. In addition, the differences may have resulted from variation due to crop growth stage. In 1987, the slope of the relationship between TMDI and MPPI decreased slightly from full to late bloom. A slightly higher slope was observed for MPPI at early bloom at Meadow Lake in 1988, a location which had similar MPPI and TMDI to that in 1987. As canola crops progress from full to late bloom, leaves begin to abscise or have already abscised and the number of petals available for infestation is rapidly decreasing. Thus, the potential for infection is limited by a shortage of petals and infection sites. Also, as leaves begin abscising late in the flowering period, the microenvironment around the canola plant becomes less conducive for disease development. All these factors may contribute to a decrease in the slope of the relationship between TMDI and MPPI as crops progress from early to late bloom. Therefore, even with increased MPPI during full-late bloom, plant infection may be reduced due to lack of petals and infection sites and to unfavorable microenvironmental conditions. However, the results of 1987 and of Rude (1989) demonstrate that significant levels of disease can sometimes develop even if sufficient inoculum and conducive moisture conditions do not occur until later in the flowering period. This may be related to cool, moist environmental conditions prolonging flowering and preventing excessive leaf abscission, which increase the period when petals and infection sites are available.

Crop canopy density has been shown to have a significant influence on the development of white mold of dry edible bean (Section 2.2.4). From 1988 to 1989 TMDI was significantly related to MPLP. In general, MPLP provided a more effective estimate of the influence of canopy density than MST or MHT, since MPLP was probably more closely related to the amount of plant material present in a crop. Thus, as MPLP decreased

crop canopy density and TMDI increased. Denser crop canopies would be expected to restrict the loss of moisture from the crop, thus enhancing and prolonging conditions favorable for host infection from infested petals. However, as crop canopy density decreased the loss of moisture from the microenvironment would be expected to increase. Therefore, less dense crop canopies probably did not promote and maintain as favorable moisture conditions for infection as denser canopies. In 1990, TMDI was also significantly related to MLAI, a similar measurement to MPLP; crop canopy density and TMDI increased as MLAI increased.

At Outlook in 1988, and Meadow Lake in 1990, a significant positive relationship was found between TMDI and MHT. Both locations also had the lowest MDI of all years. These results may be an indication of unfavorable conditions for crop canopy development. Perhaps increased leaf abscission meant that crop height became a more important factor influencing the microenvironment and disease development. Indeed, in 1990 MHT was significant at $p = 0.01$, while MLAI was only significant at $p = 0.05$ (Table 6.12). Taller crops would tend to restrict the loss of moisture from the microenvironment to a greater extent than shorter canopies. Furthermore, taller crops may develop at locations that have received more moisture either as rainfall or irrigation. From 1989 to 1990 TMDI was never significantly related to MNPS. Gugel and Morrall (1986) were also unable to demonstrate a significant relationship between the incidence of stem rot and MNPS. In 1989, MNPS was slightly higher than in 1990 (Table 6.1). This difference may have resulted from more favorable moisture conditions for seedling establishment and survival in 1989 than 1990. Average values for MNPS in 1989 and 1990 were comparable to those reported in the Canola Growers Manual (Thomas 1984) and by Gugel (1985).

7. GENERAL DISCUSSION

7.1. Introduction

The management of diseases caused by S. sclerotiorum has largely focused on the use of cultural control practices and foliar-applied fungicides. However, because of the pathogen's longevity and capacity for long range dispersal, cultural control measures such as crop rotation and sanitation are relatively ineffective (Adams & Ayers 1979, Morrall & Dueck 1982, Schwartz & Steadman 1978, Williams & Stelfox 1979, 1980a, 1980b). Furthermore, practices such as irrigation management and canopy modification may counteract attempts to maximize yields (Steadman 1979). Because of the wide host range of S. sclerotiorum, disease management with host resistance has also been difficult, especially in canola (Krüger 1980, Morrall & Dueck 1982, Steadman 1983).

Currently, foliar-applied fungicides are one of the most effective management tools for the control of several sclerotinia diseases. For example, in snap beans control of white mold was achieved using a single application of benomyl, that adequately covered blossoms, 3-5 days before full bloom (Hunter et al. 1978). Mwiindilila & Hall (1989a) also found that foliar application of benomyl gave effective control of white mold of snap bean, especially when applied at the time of emergence of apothecia. Grau (1988) achieved effective control of white mold of soybean with a single application of benomyl at early flower. Morton & Hall (1982, 1989) found that benomyl controlled white mold of white bean, although results varied depending on the time of application and the number of sprays used. Tu (1983) showed that several fungicides, including benomyl and iprodione, also controlled white mold of white bean, using two applications of fungicide starting at the early blossom stage.

A large amount of data also exists concerning the potential for effective control of sclerotinia stem rot of canola/rapeseed using foliar-applied fungicides (Davies 1986, Dueck

et al. 1983, Krüger 1973, Morrall et al. 1983, 1984b, 1985, 1989, Rude et al. 1987, Rude 1989, Thomson et al. 1984, Verma et al. 1983, 1985, 1986, 1987). For example, Dueck et al. (1983) found that ground and aerial application of fungicide at early bloom (GS 4.1-4.2) provided effective control of stem rot. Ground application of fungicide was effective at later flowering stages (Morrall et al. 1985, 1989, Rude et al. 1987, Rude 1989).

Effective control of S. sclerotiorum with fungicides has not always been achieved. Hunter et al. (1978) demonstrated that white mold in snap bean was not controlled without proper coverage of the crop canopy, especially the blossoms. Steadman (1979, 1983) also attributed lack of control in dry edible bean to inefficient coverage of blossoms. He suggested that protecting the flowers of indeterminate dry edible bean cultivars may be difficult, since fungicide residues were present for only about two weeks from the date of application, while flowers were present for at least four weeks. The more consistent control observed by Hunter et al. (1978) may relate to better protection of the blossoms, since snap beans have a determinate growth habit and flowers are only present for about two weeks (Steadman 1983). Ineffective disease control may also result from aerial application of fungicide (Morrall et al. 1983, 1985, Steadman 1983). In canola less effective control with aerial than with ground application was ascribed to poor penetration of the canopy because of reduced spray volumes compared with ground application (Morrall et al. 1985, Thomas 1984).

Improvements in spray technology may mean that improper application is no longer a critical factor influencing the efficiency of control with fungicides, especially with ground application (Morrall et al. 1985, 1989, Morton & Hall 1989). Much more critical is the influence of improper timing and failure to recognize whether a disease risk exists. Krüger (1973) concluded that control of stem rot of rapeseed was the result of fungicide being applied at the "correct time", that is application coincided with ascospore release. However, Krüger (1973) suggested that proper timing may be "difficult to determine". Steadman (1979, 1983) also suggested that effective control of white mold of bean resulted

from "timely blossom coverage", and indicated that the timing of application would have a crucial influence on control efficiency. Morton & Hall (1989) also suggested that the "effect of spray timing" would be influenced by the time of infection of bean blossoms.

For effective management of diseases caused by S. sclerotiorum suitable forecasting systems must be available to provide guidance for the use of fungicides (Dueck et al. 1983, Steadman 1983). However, an adequate forecasting system requires knowledge of the important host, pathogen and environment factors that influence disease development (Boland & Hall 1987, Fry 1982, Zadoks & Schein 1979).

7.2. Factors influencing a petal-based forecasting system for sclerotinia stem rot of canola

7.2.1. Host

Because suitable sources of host resistance do not exist in canola the major influence of the host is through modification of the microenvironment and the production of flowers which serve as a foodbase for infection (Kapoor et al. 1983, Krüger 1975b, Morrall & Dueck 1982). Modification of the microenvironment starts soon after host emergence (Section 2.2.1). In the case of canola and of bean the extent of modification is greatest when the plant canopy covers the soil surface (Abawi & Grogan 1979, Morrall & Dueck 1982, Schwartz & Steadman 1978). This not only creates favorable conditions for sclerotial germination, but also for host infection; so the host has the potential to have a major impact on disease development. For bean this influence has been reported in numerous papers (Section 2.2.4).

In canola, Morrall & Dueck (1982) found that canopy closure was associated with the appearance of apothecia, while flowering was associated with the occurrence of disease. In white bean, Boland & Hall (1987) found that the appearance of apothecia and

disease were associated with the development of a closed canopy and the presence of flowers. Mwiindilila & Hall (1988, 1989b) also found that the incidence of white mold of white bean was associated with canopy density and suggested that it would be an important factor to include in a spray management program.

In the present study, canopy density was found to have a significant influence on the development of sclerotinia stem rot of canola. Denser crop canopies probably helped to promote microenvironmental conditions that were more favorable for host infection than conditions within lighter crop canopies. This difference was probably through an influence on the penetration of radiation into the canopy and the magnitude of turbulent transfer between the macro and microenvironment (Section 2.2). In general, the more plant material present in a crop the less light and wind penetration, permitting longer periods of conducive microenvironmental conditions to persist. Results from the canopy density experiments suggested that denser crops tended to have slightly higher mean and minimum RH's and longer periods of leaf wetness than lighter crops.

In general, MPLP and MLAI provided a more effective estimate of the influence of canopy density than MST, MHT and MNPS, since they were probably more closely related to the amount of plant material in the crop. However, at Meadow Lake in 1990, TMDI was also significantly related to MHT. This may have been the result of differences in moisture where taller crops and increased disease occurred in fields where rainfall had been more abundant. Estimates of MLAI and MPLP are related since both are based on measurements of radiation interception by the canopy, although the wavelength of radiation measured by each instrument is different; MPLP is based on wavelengths between 400-700 nm, while MLAI is based on wavelengths < 490 nm.

The relationship between disease and MPLP varied from 1988 to 1989. The slope value for TMDI was -1.3 in 1988 (Table 6.8), but in 1989 it was - 5.5 (Table 6.10). Similar slope values of -2.9 and -4.9 were also observed for the covariate MPLP in canopy density Experiments 1 and 2, respectively (Section 4). The difference between 1988 and

1989 may reflect higher overall disease incidence in 1989.

Both the canopy density and long-term sampling studies illustrated the usefulness of measuring MPLP and MLAI as objective methods of assessing canopy density and disease risk. Crops with low MPLP and increased MLAI tend to develop more stem rot than crops where MPLP is relatively high and MLAI low. Because canopy density influences disease incidence it must be accounted for in disease risk assessment. However, it must be stressed that a risk will only exist when a source of inoculum (infested petals) and conducive environmental conditions are available.

7.2.2. Pathogen

The pathogen is one component of the disease tetrahedron (Zadoks & Schein 1979) that disease forecasting may be based on, using an inoculum density-disease incidence relationship (Johnson 1987). For example, systems developed by Backman et al. (1981) and Adams (1979, 1981) utilize sclerotial populations in the soil to forecast the risk of sclerotium rot of sugar beet, and white rot of onion, respectively (Section 2.1.3.1.2). Attempts have also been made to relate inoculum density and disease incidence for diseases caused by S. sclerotiorum.

In dry edible bean, Schwartz and Steadman (1978) found no correlation between soil populations of sclerotia and the severity of white mold. They did however, suggest that a substantial level of canopy infection (46%) could be produced even when the soil population of sclerotia was low (0.2 sclerotia / kg soil). In white bean, Boland & Hall (1988) were able to demonstrate significant correlations between apothecial numbers and the incidence of white mold. Correlation coefficients ranged from 0.28 to 0.95 depending on the size of sampling area. However, there was a substantial difference between two years in the quantitative relationship between the incidence of white mold and the frequency

of apothecia, and this was attributed to variation in moisture conditions between the two years (Boland & Hall 1988). Mwiindilila & Hall (1988, 1989b) also found that the incidence of white mold of white bean was correlated with numbers of apothecia.

In rapeseed, Krüger (1973) suggested that at least 3 apothecia per m^2 were required for an epidemic of sclerotinia stem rot to occur. In a subsequent paper, Krüger (1987) was unable to correlate the level of stem rot to soil populations of sclerotia. In western Canada, Morrall & Dueck (1982) could not demonstrate a consistent relationship between the numbers of apothecia and disease progress and incidence. They found that substantial levels of disease developed in crops where apothecia were nonexistent or at very low levels and suggested that apothecia located outside the field in question may serve as important sources of inoculum. In Japan, Suzui & Kobayashi (1972a) reported dispersal of ascospores for distances up to 25 m and suggested dispersal may take place over several hundred meters (Suzui & Kobayashi 1972b). Ben-Yephet & Bitton (1985) also found that ascospore dispersal may take place over distances up to 400 m. In western Canada, Williams and Stelfox (1979) reported dispersal of ascospores up to 150 m.

For sclerotinia stem rot of canola, clear inoculum density-disease incidence relationships have been difficult to demonstrate (Gugel & Morrall 1986). Although the frequency of apothecia has been related to the incidence of white mold of white bean (Boland & Hall 1988), Gugel & Morrall (1986) suggested that the extent of sampling required would make it difficult to utilize apothecia to forecast on a commercial scale in canola. They conducted a series of studies to determine if the incidence of stem rot was more closely related to ascospore infestation of various parts of the canola plant than the number of germinated sclerotia. They demonstrated a positive, linear relationship between the percentage of live or dead petals infested with S. sclerotiorum and disease incidence. Significant slope values over the two years of the study ranged from 0.003 to 0.01 (based on arcsine and multiple infection transformed data); coefficients of determination ranged from 0.14 to 0.70. Although a similar relationship of disease to germinated sclerotia was

found, both petal infestation and disease occurred in the absence of apothecia. Based on their results Gugel & Morrall (1986) suggested that the relationship between DI and petal infestation could be exploited and used as a quantitative forecasting system that accounts for extrinsically produced inoculum.

Subsequent studies by Turkington (1988) also demonstrated a significant positive relationship between MDI and MPPI at early bloom with slope values of 0.10-0.30. However, the strength of the relationship varied, with coefficients of determination ranging from 0.18 to 0.63. In the present study, significant positive relationships were demonstrated between TMDI and MPPI at various flowering stages. Petal infestation at a single flowering stage was not consistently significant and differences between years may have been related to varying moisture conditions (Section 6). Significant slope values ranged from 0.10 to 0.33.

Slope values from the present study also suggested that the relationship between TMDI and MPPI may change as crops progress from early to late bloom. The relationship would be expected to change, given that increased leaf abscission and decreased petal production occur at the later flowering stages. The result would be a reduction in the absolute quantity of infested petals and number of potential infection sites, which would contribute to a decrease in the slope of the relationship between TMDI and MPPI as crops progress into late bloom. In addition, leaf abscission from full to late bloom would cause the development of less favorable microenvironmental conditions and further influence the relationship between TMDI and MPPI. Thus, if MPPI is low at early bloom, but increases to relatively high levels by full-late bloom, the apparent increased risk of disease may not be translated into increased host infection.

Diurnal and long-term fluctuations in MPPI were observed from 1987 to 1990. Gugel (1985) also observed changes in PPI over several days in a small number of crops. Similar changes in aerial ascospore concentrations of S. sclerotiorum were observed by Ben-Yephet & Bitton (1985) and Hartill (1980). In the present study, variation in MPPI

during the flowering period was probably the result of variation in rainfall which influenced carpogenic germination and ascospore production. Hartill (1980) related variation in ascospore production over a period of 2-3 months to variation in apothecial production and rainfall. He observed no apothecia and trapped no ascospores during extended dry periods. Morrall & Dueck (1982) also found that "flushes of apothecia" were separated by fairly dry conditions. In Germany, Krüger (1974) found that extended dry periods caused dehydration of apothecia and reduced ascospore production. Boland & Hall (1987) also observed changes in carpogenic germination of sclerotia which were probably the result of variation in rainfall. They found that dry weather for approximately 7 days caused dehydration of apothecia, but subsequent rainfall permitted >55% of the apothecia to rehydrate and resume ascospore production.

Because MPPI can change substantially during the flowering period in canola, disease risk will change. However, the importance of this change will be determined by host and environmental factors. For disease to develop the presence of infested petals must coincide with the occurrence of favorable environmental and host conditions for infection. For example, in 1989, four late crops had relatively high MPPI at early bloom, which occurred around July 11. However, little or no rainfall occurred at Meadow Lake after July 11 (Figs. 6.1, 6.8). In addition, the daily hours of sunshine (Fig. 6.7) were relatively high for July 12-16 and 18-24. There was also a general decrease in mean and minimum RH and an increase in mean, minimum and maximum temperatures after July 11 (Fig. 6.9). Leaf wetness duration also decreased to very low levels from July 12 to 19 and remained relatively low after this period (Fig. 6.9). All these factors combined to produce conditions that were less favorable for host infection from infested petals in these four crops than in the earlier-seeded crops. Although disease risk, as indicated by MPPI, was relatively high for these crops it was not translated into substantial host infection because of the influence of the environment.

One aspect of the relationship between MDI and MPPI not investigated during the

current study was inoculum potential. Gugel (1985) suggested that the probability of host infection may increase as the number of infested petals per leaf axil or base increases. Lamarque (1983) indicated that symptoms of stem rot of rapeseed appeared to occur at locations where a large number of petals had been deposited. She also found that surface disinfected petals gave the greatest amount of infection. Based on these observations Lamarque (1983) suggested that, as the number of infested petals per infection site increases, the "inoculum pressure of S. sclerotiorum" increases giving it a competitive advantage over other organisms that may be present on the petal.

Boland & Hunter (1988) also found evidence of a similar competitive phenomenon with white mold of white bean. They observed that the number and size of white mold lesions were decreased when sterilized bean blossoms infested with both S. sclerotiorum and two other fungi (Alternaria alternata and Cladosporium cladosporioides) were used as inoculum, compared with blossoms infested with only S. sclerotiorum. They suggested that this difference was the result of nutrient competition "rather than" a direct influence through parasitism or antibiosis. Inglis & Boland (1990) obtained similar results. Sterilized field-collected bean blossoms inoculated with ascospores of S. sclerotiorum initiated more and larger lesions on the primary leaves of bean seedlings than field-collected nonsterilized blossoms that were inoculated with S. sclerotiorum.

Work by Suzui & Kobayashi (1972c) also suggested that the number of ascospores per petal may be important. They found that the probability of successful colonization of kidney bean petals increased as the concentration of ascospores on them increased. However, it was possible for a single ascospore to successfully colonize a petal. Because direct evidence of the importance of inoculum potential for the development of sclerotinia stem rot of canola is lacking, especially under field conditions, this may be an area of research that merits further investigation.

7.2.3. Environment

The environment has a substantial impact on diseases caused by S. sclerotiorum. Temperature and moisture are among the most important factors that influence the disease cycle. Both factors influence carpogenic germination of sclerotia, which occurs optimally at temperatures of 10-15°C and soil water potentials of 0 to - 7.5 bars (Abawi & Grogan 1975, Grogan & Abawi 1975, Krüger 1975a, 1975b, Morrall 1977, Teo & Morrall 1985a, 1985b). Ascospore production also requires humid conditions and can occur at temperatures of 4-30°C, although 20°C is optimal (Krüger 1975b, Newton & Sequeira 1972). Ascospore germination and host infection are also influenced by temperature and moisture. Temperatures of 20-25°C were found to be the most favorable for ascospore germination, host infection and lesion development (Abawi & Grogan 1975). Both ascospore germination and host infection were also found to occur at temperatures as low as 10°C (Abawi & Grogan 1975, Weiss et al. 1980b). Ascospore germination and host infection required the presence of free water for 39-72 hours (Abawi & Grogan 1975, Boland & Hall 1987), but also occurred at RH's ≥ 90% (Brün et al. 1983, Le Coz 1982).

In the present study, moisture appeared to be the most important environmental factor limiting disease development. From 1987 to 1990 canopy temperatures during July rarely exceeded 30°C with mean daily values mostly from 10 to 25°C, which is well within the range favorable for carpogenic germination, ascospore production, host infection and lesion development. However, temperatures > 25°C often occurred in June before canopy closure and in late July and August following leaf abscission, and also during extended dry periods. Variation in the presence and persistence of moisture (liquid or vapour) was observed from 1987 to 1990. The frequency and distribution of rainfall appeared to be more critical for disease than the total amount recorded. This was especially evident for 1990, where precipitation on July 3 and 9 produced well above average rainfall for July (Table 6.3, Fig. 6.1). However, the persistence of moisture was probably limited, since

little or no rainfall was recorded after these dates and relatively clear, sunny conditions enhanced evapotranspirational water loss. In contrast, in 1987, frequent showers throughout July helped to maintain relatively high moisture levels within crops.

From 1987 to 1990 daily mean relative humidity within crop canopies in July was usually above 80%. However, mean and minimum RH <80% often occurred in June before canopy closure and in late July and August following leaf abscission, and also during extended dry periods. In July of 1987 and 1988, the longest periods of continuous leaf wetness ranged from 44 to 79 hours and would have been sufficient to permit host infection from infested petals (Abawi & Grogan 1975). However, in 1989 and 1990 the maximum periods of leaf wetness ranged from 18 to 41 hours. Interrupted periods of leaf wetness may also allow host infection from infested petals. Boland and Hall (1987) found that host infection from senescent infested bean blossoms did occur after two periods of interrupted leaf wetness which lasted about 15 hours each. Blad et al. (1978) reported the development of white mold of dry edible bean with interrupted periods of leaf wetness of up to 12 hours. In the present study, interrupted periods of leaf wetness of approximately 14-16 hours over four days were observed in early July of 1989 and were probably sufficient to permit host infection.

Extended periods of RH ≥ 90% may permit host infection from infested petals (Brün et al. 1983, Le Coz 1982); however, the fluctuations in RH that occurred in the present study may not have been conducive for host infection. H. Brün, (personal communication) studied the influence of variable daily periods of RH at saturation on infection of rapeseed under controlled conditions. She found that when RH was at saturation for only 8 hours per day, stem rot symptoms never developed. Furthermore, when RH was reduced to 80% for only 4 hours per day symptom development was delayed by 2 days. In another study Brün et al. (1983) found that stem rot symptoms failed to develop even after 62 hours of continuous leaf wetness when the subsequent mean RH was approximately 70%.

Although leaf wetness duration and RH are certainly important for the development of diseases caused by S. sclerotiorum, one factor affecting host infection from infested petals that needs to be considered is the influence of water droplets in leaf axils and bases. Royle & Butler (1986) have suggested that the "significance to the infection process of different patterns of water distribution on leaves is largely unknown.". This is indeed true for sclerotinia stem rot of canola. In canola large droplets of water are often observed in leaf axils and bases, locations where substantial numbers of petals tend to collect. Water droplets will also persist for longer periods than a continuous film of water (Brain & Butler 1985, Royle & Butler 1986) and therefore could have a substantial impact on host infection from infested petals. Leaf axil position within the canola canopy also has an impact on droplet persistence (Gugel 1985). The importance of water droplets to infection of canola by S. sclerotiorum merits further investigation.

In the present study, the environmental data were mostly used for indicating general trends that occurred in each year. Nevertheless, differences in rainfall and microenvironmental conditions occurred among crops that were sampled. Multiple regression analyses with several independent variables, derived from the host and pathogen, explained 55-98% of the variation in TMDI from 1987 to 1990. However, in some years a considerable proportion of the variation in TMDI was not explained by the multiple regression analyses. This additional variation was probably the result of variability among crops in rainfall and microenvironmental conditions.

7.3. Implications of the present study for practical on-farm disease forecasting

Turkington (1988) concluded that factors in addition to PPI at early bloom determined disease risk and incidence. The occurrence of short-term and long-term fluctuations in MPPI were thought to be important. Data from the present study suggest

that long-term changes in MPPI may be more important in determining disease incidence than short-term diurnal or weather-mediated changes. The increases in MPPI during the day were usually small compared with long-term changes. Long-term changes could be accounted for in a stem rot forecasting system based on MPPI, by sampling petals several times during the flowering period. Although not as critical, diurnal fluctuations in MPPI may be of some interest, since relatively large changes from morning to afternoon occasionally occurred. Thus, as a precaution against underestimating MPPI, petals should be sampled in the afternoon and sampling should be avoided during, or soon after substantial rainfall or heavy dew.

Long-term changes in MPPI during the flowering period can result in substantial changes in disease risk. However, the utility of recognizing a high disease risk later in the flowering period would depend on whether chemical control was still effective. Studies by Morrall et al. (1985, 1989) and Rude (1989) have demonstrated that effective control is possible when increased MPPI and conducive environmental conditions do not occur until full or late bloom. However, the influence of increased leaf abscission and decreased petal production at late bloom will need to be considered in order to achieve economic control. In addition, Rude (1989), under controlled conditions, demonstrated that yield losses were significantly higher when canola plants were infected at early bloom than at late bloom. Thus, yield increases achieved by fungicide application at late bloom may not be high enough to provide economic control. Nevertheless, Rude (1989) did demonstrate that yield losses with late bloom-infected canola can be relatively high. Results from 1987 of the current study also indicated that significant levels of disease can develop when inoculum and environmental conditions are not conducive until full or late bloom.

Both the influence of the host and of the environment also need to be recognized when using petal infestation to forecast disease risk. However, for the farmer, assessing the influence of these factors may be difficult. Farmers do not have access to the type of equipment used in the current study to assess canopy density. The typical canola grower

would also probably not be able to justify the cost of in-crop environmental monitoring equipment; moreover, it is future environmental conditions that are of major interest. Nevertheless, the frequency of rainfall might be used to crudely assess the influence of the environment. Frequent showers and overcast conditions would indicate a higher risk than a large amount of rainfall on a single day, which was followed by several days of relatively sunny, warm conditions. To account for the influence of canopy density, perhaps yield potential could be estimated by farmers in place of measurements of MPLP and MLAI. Disease risk is higher in a crop with a yield potential of >2000 kg/ha than a crop with a potential yield of < 1400 kg/ha.

Recent control strategies for stem rot developed by Morrall et al. (1985, 1990) and Rude (1989) could have the potential of providing a means of reducing the risk of variable DI and uneconomical control that is associated with varying host and environmental conditions. Petal testing could be used to indicate when the pathogen is present and at what levels. Control strategies could then be tailored to accommodate the influence of the host and future weather conditions. For example, a petal test at early bloom may indicate high disease risk, but weather conditions for the previous three days have been characterized by variation in air masses, infrequent rainfall, broad temperature ranges and relatively sunny conditions. In this situation a farmer may decide to use an application of fungicide at 1/4 or 1/2 the recommended rate if the crop yield potential was >2000 kg/ha. The farmer could also decide to wait until the results from a second petal test at full bloom were available. If one application had been made at early bloom and by full-late bloom MPPI had remained relatively high and environmental conditions had become more favorable the farmer could decide to make another application of fungicide at either 1/4 or 1/2 the recommended rate. Moreover, at this stage a farmer whose crop was expected to yield < 2000 kg/ha might consider a single application at 1/4-1/2 the recommended rate. Thus, options such as split applications and reduced rates of fungicide may allow farmers to achieve economical control by tailoring their control practices to the disease risk indicated by MPPI, crop yield

potential and environmental conditions. However, a petal-based system of forecasting, even with the modifications for the influence of the host and environment, will never be able to account for the influence of unfavorable environmental conditions after forecasts are produced. This situation is illustrated by the four late crops in 1989, where unfavorable environmental conditions for infection resulted in low levels of disease even though MPPI and MPLP indicated that a substantial disease risk existed.

Although the influence of unfavorable environmental conditions is a limitation of the current forecasting system, it is also a shortcoming associated with other systems for sclerotinia stem rot, such as the sclerotinia checklist (Thomas 1984) and the Danish system (Buchwaldt 1986, 1989). The checklist is a risk assessment scheme based on a series of mainly qualitative questions about host, pathogen and environment factors thought to influence disease development. The Danish system is based mainly on monitoring carpogenic germination of sclerotia in depots established throughout the country. Both these systems provide qualitative disease forecasts; the checklist does this on an individual crop basis, while the Danish system issues forecasts on a regional basis. In western Canada a system based on assessing MPPI may be more useful since it provides a quantitative forecast of disease risk on an individual crop basis. This will allow the farmer to consider more effectively the potential yield loss and benefit that might result from fungicide application. Furthermore, petal testing will allow the farmer to more adequately account for ascospores dispersed from apothecia located outside the field in question.

The possibility exists of incorporating synoptic weather forecasts into the current system to account for the influence of future environmental conditions. Attempts have been made to incorporate weather forecasts into systems for potato late blight (Royer et al. 1989) and Botrytis leaf blight of onion (Vincelli & Lorbeer 1988). However, Campbell & Madden (1990) have suggested that the present accuracy of weather forecasts, especially for precipitation, is probably not high enough to be an effective part of disease forecasting.

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APPENDIX A. Tests of hypotheses for canopy density experiments 1989

The following null and alternative hypotheses were tested for Experiments 1 and 2 before covariates were added to the analyses:

(1) Seeding rate

Ho: No significant differences in TMDI exist among the seeding rates.
Ha: Significant differences in TMDI exist among the seeding rates.

(2) Cultivar

Ho: No significant differences in TMDI exist between the cultivars.
Ha: Significant differences in TMDI exist between the cultivars.

(3) Seeding rate * cultivar

Ho: The interaction of seeding rate and cultivar has no significant effect on TMDI.
Ha: The interaction of seeding rate and cultivar has a significant effect on TMDI.

Variation in TMDI due to seeding rate was further partitioned into linear, quadratic, and cubic components and the following null and alternative hypotheses were tested:

(4) Cubic effects

Ho: No cubic relationship exists between seeding rate and TMDI, therefore a simpler relationship must exist.
Ha: A cubic relationship exists between seeding rate and TMDI.

(5) Quadratic effects

Ho: No quadratic relationship exists between seeding rate and TMDI, therefore a simpler relationship must exist.
Ha: A quadratic relationship exists between seeding rate and TMDI.

(6) Linear effects

Ho: No linear relationship exists between seeding rate and TMDI.
Ha: A linear relationship exists between seeding rate and TMDI.

When the covariate MPLP was added to the analyses appropriate SS were derived for testing each individual source of variation after the effects of all other sources were

accounted for (SAS Institute 1985). For example, using reduction notation (reduction in residual SS) the respective null and alternative hypotheses tested for cultivar can be expressed as:

$R(C/B, SR, SR*C, \beta_1)$ which tests

Ho: $C = 0$ versus Ha: $C \neq 0$.

Where:

R = reduction in residual SS due to cultivar effect after accounting for the effects of all other sources of variation.
C = cultivar effect
B = block effect
SR = Seeding rate effect
SR*C = effect of the interaction of seeding rate and cultivar
β_1 = coefficient for covariate 1 (MPLP).

APPENDIX B. Mean TMDI and corresponding standard errors for all seeding rates in Experiments 1 and 2, Meadow Lake, 1989.

	Experiment 1		Experiment 2	
SR†	TMDI	Standard error	TMDI	Standard error
1.5	27.0	7.5	10.9	4.6
4.0	28.5	7.5	15.5	6.2
6.5	29.8	8.2	16.5	3.9
9.0	26.4	5.2	18.6	6.0
11.5	35.7	9.3	17.6	3.5
14.0	29.1	7.3	20.3	8.2

† Seeding rate (kg/ha).