ESTIMATION OF PHENOLOGICAL DEVELOPMENT AND FRACTIONAL LEAF AREA OF CANOLA (*BRASSICA NAPUS* L.) FROM TEMPERATURE

By

JANNA L. WILSON

A Thesis Submitted to the Faculty of
Graduate Studies in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF ARTS

Department of Geography
University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

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Argentine Canola (*Brassica napus* L.) is an economically successful crop on the Canadian Prairies. The 1999 growing season had a record area seeded of 5,598,700 hectares, declining slightly to 4,894,600 hectares in 2000. Since 1997, canola has been ranked as Manitoba's most valuable agricultural commodity. Although canola is an important contributor to the Canadian economy, little research has been conducted at the field level to determine how crop phenological stage and ground cover respond to weather variables such as temperature. Such basic agronomic knowledge is essential for successful agrometeorological modeling. The objectives of this project were to develop a methodology for estimating phenological development and fractional leaf area of canola using temperature, and to further evaluate the accuracy of top-zone (10 cm depth) soil moisture modeled from a Canola Phenology and Water-Use Model. Five test sites within Agro-Manitoba were used during the 1999 growing season, while three test sites were used in 2000. Weekly field observations were conducted during the growing season to determine the phenological stage of the crop, the amount of ground cover, and near surface soil moisture. Daily maximum and minimum temperatures and rainfall data were obtained from the nearest Environment Canada weather station.

The fungal infection Sclerotinia (*Sclerotinia sclerotiorum* (Lib.) de Bary) costs prairie canola producers approximately $260 million annually as a result of yield loss and management techniques requiring expensive fungicide applications. The current model for predicting sclerotinia stem rot on the Canadian Prairies estimates the risk of infection based on crop phenological stage and soil moisture estimates derived from the Raddatz model. However, the current model is regional in nature and is limited because crop stage is estimated using a simple growing degree-day (GDD) above 5°C, while soil moisture is modeled using a coupled atmosphere-crop-soil agrometeorological model, which utilizes the simple GDD relationship to estimate fractional leaf area. This study determined that a GDD above 5°C was an inadequate estimator of crop phenology and that the P-Days system, utilizing base, optimal, and maximum temperature thresholds of 5, 17, and 30°C, respectively was an overall better estimator of crop phenology. Further results indicated that fractional leaf area was better estimated from $P\text{-}Days_{(5,17,30)}$ than from GDD used in the original model. Observed and modeled top-zone soil moisture values were compared. The relatively low R^2 of 0.60 suggests that poor estimates of soil moisture was linked to the use of off-site precipitation data and perhaps linked to the inaccurate estimation of fractional leaf area from GDD above 5°C.

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TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

Table **Page**

LIST OF FIGURES

Figure **Page**

Figure **Page**

1.0 INTRODUCTION

Since 1995, canola (*Brassica napus* L.) has been the second most successful cash crop in Canada. The 1999 growing season had a record area seeded of 5,598,700 hectares, declining slightly to 4,894,600 hectares in 2000 (Statistics Canada 2001). Although canola is an important contributor to the Canadian economy, little research has been conducted at the field level to determine how crop phenological stage and ground cover respond to weather variables such as temperature. The fungal infection Sclerotinia (*Sclerotinia sclerotiorum* (Lib.) de Bary) is a serious disease of canola in western Canada. The current model for predicting Sclerotinia disease for the Canadian Prairies predicts the risk of infection based on crop stage and top-zone soil moisture estimates from a Canola Phenology and Water-Use Model (Raddatz 1993, Raddatz et al. 1996). Crop stage and fractional leaf area are estimated using accumulated growing degree-days above 5°C and utilized in the estimation of top-zone soil.

The accurate estimation of ground cover is an important component of determining sclerotinia risk. The amount of canopy cover influences the relative humidity of the environment of the disease organism. If there is little or no canopy cover, air near the soil surface can mix with the air above, thereby lowering the relative humidity near the soil surface, regardless of the surface soil moisture content. If there is complete ground cover, air near the soil surface is prevented from mixing with the air above, and thus relative humidity in the canopy is strongly influenced by surface soil moisture (Oke 1987). Thus, knowledge of the fractional leaf area is vital in accurately assessing disease risk.

1.1 Objectives

The overall aim of this project was to improve the current method for estimating the risk of Sclerotinia infection on the Canadian Prairies. Presently, Sclerotinia risk is based on soil moisture and growth stage information derived from a Canola Phenology and Water-Use Model (Raddatz 1993). However, this model is limited because it uses a simple heat unit to estimate phenological stage and percent ground cover. The accumulated growing degree-days (GDD) above 5°C is a crude predictor of canola phenology because it assumes a linear plant-development- temperature relationship. The specific project objectives are to:

(1) Develop a heat unit specific for canola. A non-linear heat unit system such as the P-Days system used to predict potato phenology will be adapted to reflect the cardinal temperatures of canola and determine if this improves estimates of canola phenology.

(2) Determine the relationship between fractional leaf area and a heat unit developed specifically for canola.

(3) Evaluate the accuracy of top-zone soil moisture estimated from the Canola Phenology and Water-Use Model (Raddatz 1993; Raddatz et al. 1996).

2.0 LITERATURE REVIEW

2.1 Canola

Canola (*Brassica napus* L.) is an economically successful crop on the Canadian Prairies. The majority of Canadian canola is grown on the Prairies; Manitoba accounts for 18% of Prairie production, behind Alberta (33%), and Saskatchewan (48%) (Manitoba Agriculture 2000a). In 1999, canola totaled 22.6% of the area of crops planted in Manitoba, ranking second to wheat at 29.0% (Manitoba Agriculture 1999). The harvested area of canola in Manitoba during the 1999-growing season totaled 995,500 hectares while the harvested area of wheat was 1,272,700 hectares (Manitoba Agriculture 1999). Since 1997, canola has been designated as Manitoba's most valuable agricultural commodity (Manitoba Agriculture 2000a). Agricultural production in its entirety in Manitoba is estimated at $2,867.2 million with $1,543.4 million attributed to crop production (Manitoba Agriculture 1999). In terms of farm gate value, canola was the number one crop in 1999, with production estimates of $401.3 million (Manitoba Agriculture 1999).

Despite the important economic contribution of canola to the agricultural sector in Manitoba, basic agronomic knowledge is inadequate (Vigil et al. 1997). Limited field research has been conducted to determine how crop phenological stage responds to environmental variables such as temperature and photoperiod (Morrison 1988). Further, environmental factors that affect canola phenology have yet to be studied in detail (Hodgson 1978a). Tracking crop phenology is a fundamental component in yield estimation and disease modeling. The ability to accurately estimate the various life

stages of plant development from agrometeorological information has proven to be a useful crop management tool and is essential for the prediction and control of the fungal infection sclerotinia stem rot.

2.1.1 Sclerotinia

Sclerotinia stem rot is the most devastating disease of canola on the Canadian Prairies and afflicts all canola-growing areas of Canada. All canola varieties are susceptible to this fungal infection, and it is estimated that sclerotinia stem rot costs Prairie canola producers $260 million annually as a result of yield loss and management techniques requiring expensive fungicide applications (G.B.H. Ash, personal communication, Canadian Wheat Board, Winnipeg, MB). Percentage yield losses are approximately equal to 0.5 times the percentage infection (Thomas 1995). In 1999, the mean percent of canola fields infected (prevalence) in Manitoba was 60%, which was substantially lower than the provincial mean of 82% in 1998 (McLaren and Platford 2000). The mean provincial disease incidence of infected crops (percent plants infected in a field) was 8% in 1999 and is estimated to have resulted in approximately a 4 % yield loss (McLaren and Platford 2000).

The development, propagation, and management of this fungal infection is greatly influences by weather conditions and the developmental stage of the crop. A study by Morall and Dueck (1982) found there was an inconsistent correlation with disease incidence (percent plants infected per crop) and the relative abundance of apothecia. Therefore, although the inoculum is usually present, the differences in disease severity indicate that weather microclimate, including the conditions induced by plant phenology, are the primary variables controlling disease severity.

Variations in disease incidence (percent plants infected per crop) is related to several factors (Thomas 1995):

(1) Quantity of spores,
(2) Plant population,
(3) Crop height and vigour (creating favourable micro-climate conditions),
(4) Rainfall or irrigation,
(5) Soil Moisture,
(6) Temperature.

After infection takes place, the severity of the disease and its effect on yield is variable and is a function of several factors including (Thomas 1995):

(1) Temperature,
(2) Rainfall,
(3) Crop density,
(4) Stage of crop at time of infection .

2.1.1.1 Biology

Sclerotinia sclerotiorum (Lib.) de Bary is the soil-borne fungus responsible for causing sclerotinia stem rot. *S. sclerotiorum* over-winters in the soil, in seed, and in stubble as irregular-shaped resting bodies called sclerotia that can remain viable, buried in the soil, for several years (Thomas 1995). The sclerotia germinate in the summer when environmental conditions are favourable producing either mycelium (microscopic filaments), or apothecia, tiny mushroom like structures that release millions of wind-borne spores (ascospores) (Thomas 1995). Although mycelium can infect plants directly, the primary inoculum for epidemics in canola is a result of ascospore infection produced by the apothecia (Thomas 1995). The surface soil moisture must be at or near field capacity for a prolonged period (approximately ten days) with moderate temperatures in

order for the sclerotia to produce apothecia (Thomas 1995). A single sclerotium can produce up to 15 apothecia (Thomas 1995).

Sun and Yang (1997) conducted an experiment on sclerotia collected in Iowa to quantify the effects of temperature and moisture on apothecium production. Apothecia production was greatest when the soil was at full field capacity and high field capacity when the temperatures were at 18°C and 25°C. These conditions occurred in canola fields after the crop canopy closed over and shaded the soil surface, usually during the late rosette stage (Thomas 1995). Since there is a ten-day delay from the onset of moist soil conditions for sclerotia to germinate, the apothecia begin to appear while the canola is susceptible to infection at the early to full bloom stage (Thomas 1995). Apothecia release millions of ascospores that land on the petals of the flowering canola. Once the petals drop from the flower, they land in the leaf canopy below, lodging and adhering to the leaves and stems of the plant. The spores utilize the dead petals as a food source, and provided that the conditions remain moist enough for two to three consecutive days, the spores germinate, penetrate the leaves and stems of the plant, thereby disrupting the vascular system and destroying plant tissue. The stem of the canola plant is weakened and vital quantities of nutrients are prevented from reaching the developing pods. Black sclerotes remain in the weakened stem and are returned to the soil surface during swathing and combining. The sclerotes ensure that the disease cycle will continue the following season provided that the environmental conditions are conducive to sclerotia germination.

2.1.1.2 Management

Sclerotinia is particularly prevalent in dense, vigorous canola crops because the crop canopy helps to create a suitable microclimate that promotes sclerotia germination. Although sclerotinia stem rot damage can be somewhat controlled with the appropriate use of fungicides, they must be applied before the disease is visibly evident in the crop at the 20 – 30% bloom stage and prior to significant petal drop. At this time, it must be determined whether spraying fungicide is economically and environmentally justifiable. Once sclerotinia is visible in the field, fungicide application will not reduce or control the propagation of the infection. The sporadic outbreaks of sclerotinia in both time and space make the disease difficult and often cost ineffective to manage with the application of foliar fungicide (Bom and Boland 2000).

The "window of opportunity" to utilize foliar fungicide is extremely short and needs to be accurately identified. The objective of spraying the crop is to cover the greatest number of petals so that when they drop from the inflorescence, they will be sufficiently covered with fungicide to prevent the germination of the ascospores. The optimal time for fungicide application is at the 20–30% bloom stage because this ensures the maximum number of petals are covered, thus providing the optimal amount of fungicide control.

Disease risk assessment is essential for controlling sclerotinia in an efficient, economical, and environmental responsible manner. Crop rotation is ineffective because ascospores can be blown from adjacent fields, the dormant sclerotia remain viable for several years buried in the soil, and the fungus has a host range of greater than 350 species from the broad-leaf plant family which include many weed hosts (Thomas 1995).

Several products are available to assist producers with management decisions: sclerotinia check-lists, in-field diagnostic kits, petal test-kits, and disease forecasts using real-time agrometeorological data. Petal test kits will give the percentage of petals infested by *S. sclerotiorum*, but the delay of several days to grow the fungus from infested petals on culture plates containing a nutrient medium, and the difficulty in identification of colonies from cultural characteristics are disadvantages (Bom and Boland 2000). Environmental conditions conducive to disease development between petal sampling and the completion of the diagnostic petal assay can occur within the three-day period from sampling. Fungicide must be applied when spores are present but before infection has occurred (Bom and Boland 2000).

Manitoba Agriculture has developed a Sclerotinia Risk Forecast Program for Canola (operated by the Agrometeorological Centre of Excellence (ACE) since 2000). This program uses top-zone soil moisture (percent of capacity) and growing degree-days above 5°C modeled from a Canola Phenology and Water-Use Model (Raddatz 1993) and is provided biweekly for approximately forty-two real-time Environment Canada weather stations in the form of a bulletin. This information is interpolated using a Geographic Information System (GIS) to produce two separate maps depicting (1) soil moisture as a percent of capacity for example (Figure 2.1), and (2) crop stage for example (Figure 2.2). Sclerotinia disease pressure in the agricultural regions of the Canadian Prairies are then determined by combining the two maps in a GIS. The maps are regional in nature and are intended to inform producers when environmental conditions are favorable for the development of the disease. Disease pressure is expressed using three broad risk categories, low, moderate, and high. The sclerotinia risk forecast program warns

producers when there is a risk of infection and further promotes the efficient application of fungicide based on disease pressure (Figure 2.3).

The Sclerotinia Risk Forecast Program and the Canola Phenology and Water-Use Model use a growing degree-day above 5°C to track phenological development (Table 2.1). Although the "simple" growing degree-day method is used extensively in agrometeorological modeling, a heat unit specific for estimating canola phenology that accounts for the non-linear plant-development-temperature response, and includes the base, optimum, and maximum temperature thresholds, has not yet been developed. The current method for estimating sclerotinia risk utilizes a very broad estimate of heat units required for flowering (518-776 GDD). The regional nature of the Sclerotinia Risk Forecast Program utilizes a broad-window for crop stage estimation in order to capture the spatial variability around the modeled points. In addition, the interpolation of the data using a limited number of Environment Canada weather stations reduces the accuracy of the program by creating generalized regional maps; improved crop stage modeling accuracy would likely have little impact on the current regional risk assessment. However, if in the future, on-site meteorological and planting date data were available, it could lead to substantial improvements. Thus, a heat unit that could more accurately predict key growth stages in canola would enhance the Sclerotinia Risk Forecast Program at the local level by improving the method by which phenology is predicted, and possibly improve the soil moisture data simulated from the Canola Phenology and Water-Use Model (Raddatz 1993; Raddatz et al. 1996).

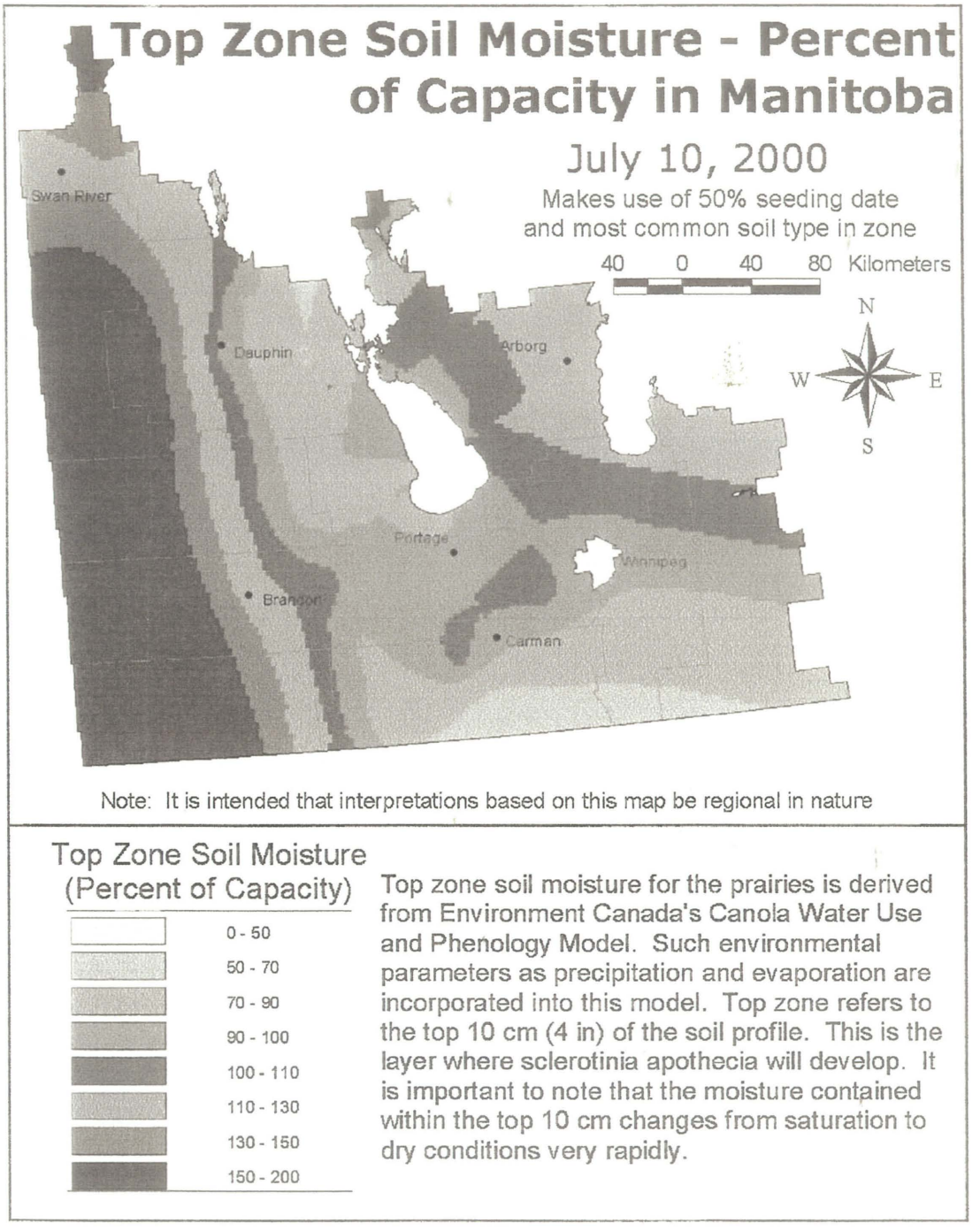


Figure 2.1 Top-zone soil moisture as a percent of capacity in Manitoba, July 10, 2000 (Map provided by the Agrometeorological Centre of Excellence, Carman, MB).

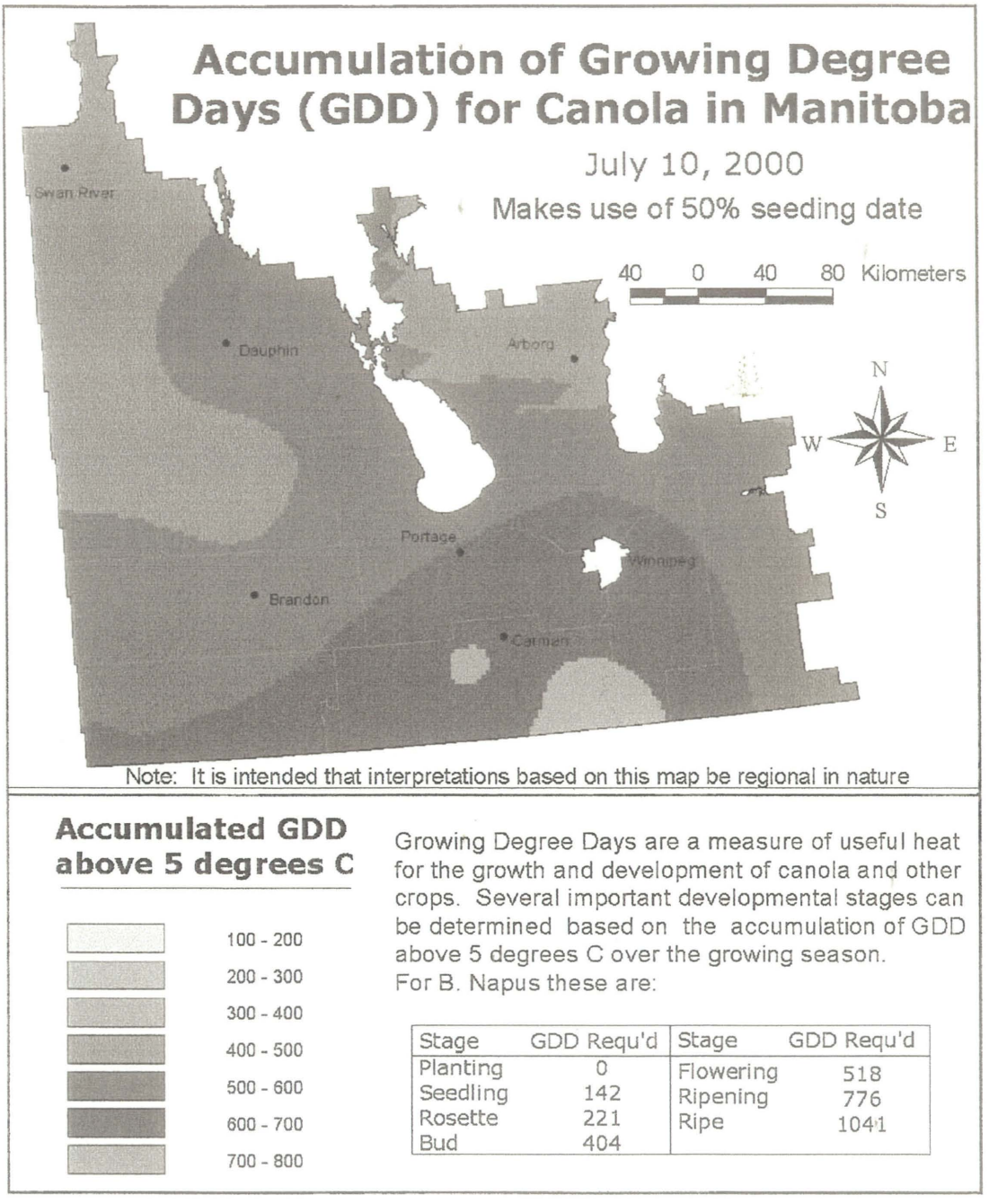


Figure 2.2 Growing degree-days (GDD) above 5°C for canola in Manitoba, July 10, 2000 (Map provided by the Agrometeorological Centre of Excellence, Carman, MB).

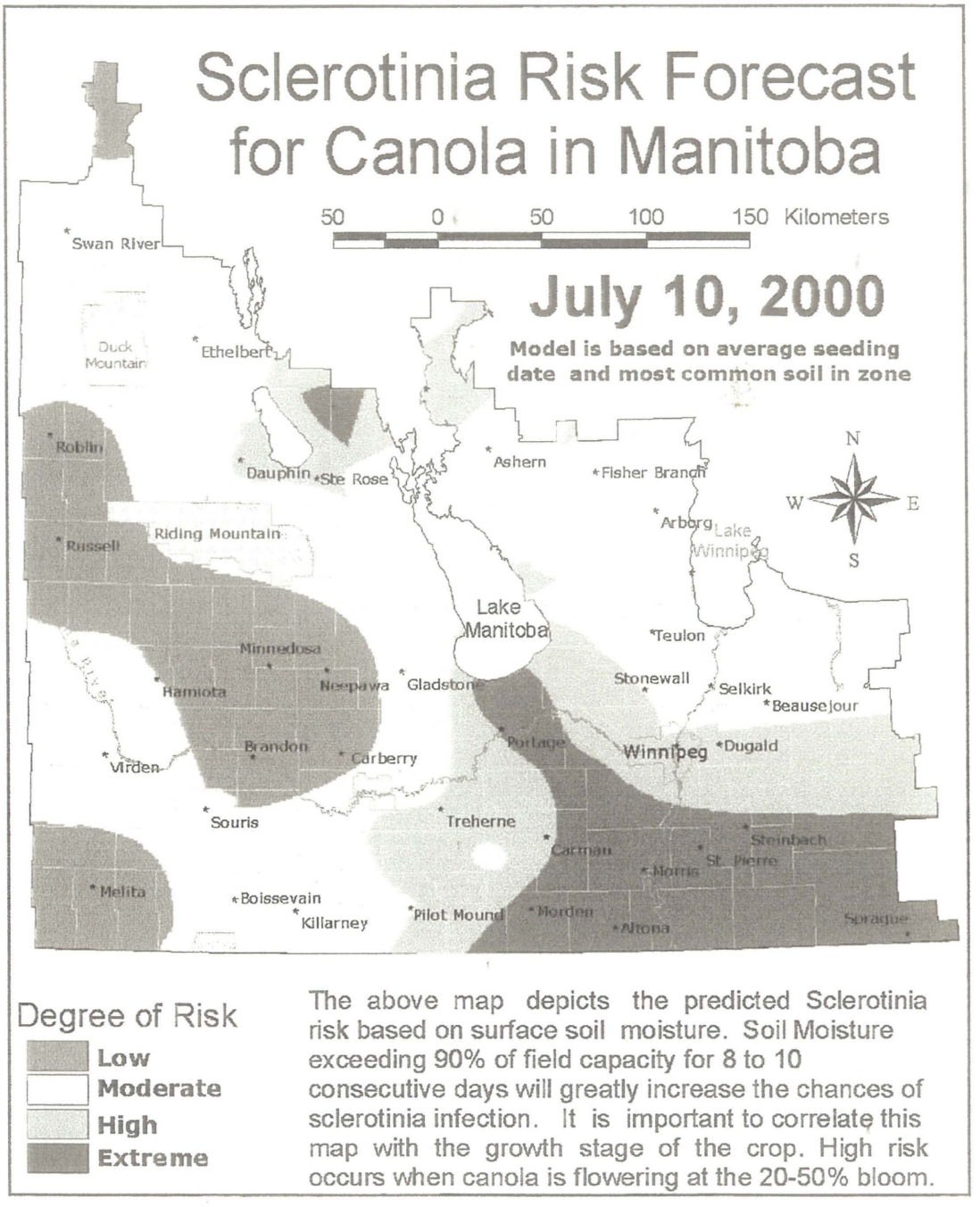


Figure 2.3 Sclerotinia Risk Forecast for canola in Manitoba, July 10, 2000 (Map provided by the Agrometeorological Centre of Excellence, Carman, MB).

Table 2.1 Growing degree-days and phenological developmental stage of canola used in the Sclerotinia Risk Forecast Program.

Crop Stage	Growing Degree-Days above 5°C
Planting to Seedling	0 – 142
Seedling to Rosette	142 - 221
Rosette to Budding	221 - 404
Budding to Flowering	404 - 518
Flower to Ripening	518 - 776
Ripening to Maturity	776 – 1041

Original work is published in Morrison et al. (1989) and has been slightly modified by Raddatz and Shaykewich based on 1988 - 1992 data from prairie wide canola field trials (personal communication, Environment Canada, Winnipeg, MB).

2.2 Basic Concepts In Crop Production

Knowledge of the growth and development process of agricultural crops is of immense value to the agricultural community. The current trend of increasing agricultural intensification and crop productivity require that effective crop management decisions be derived from scientific knowledge of growth and development processes. This knowledge will allow producers to continue to have increasingly successful harvests.

2.2.1 Growth Versus Development

Growth refers to an irreversible increase in size (Gepts 1987). Hodges (1991b) describes growth as the accumulation of biomass in the plant as a whole or in a specific

organ. Although growth and development are highly interrelated, phenology deals specifically with plant development. Predicting dry matter accumulation (growth) and phenological development stages are key components of understanding growth and development processes. Although both growth and development have been successfully modeled, the physiological control processes of crop phenology are not as well understood as those relating to dry matter accumulation (Gepts 1997). While producers are greatly concerned with crop growth and yield, crop phenology is a fundamental component of agrometeorological modeling and a key consideration for many crop management decisions.

2.2.2 Phenology

In a general sense, phenology refers to a specific life stage of a crop. Hodges (1991a) refers to phenology as the "development, differentiation, and initiation of organs." Lieth (1974) used a more refined definition from the US/IBP Phenology Committee which states:

> Phenology is the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species.

Development refers to the "physiological age" or "life stage" of the crop (phenology). Development is therefore characterized by the appearance of new types of morphological structures (such as flowers) and or the transition from one major physiological state to the next (Gepts 1987).

Plant phenology can be described by a development scale. This is a description of the successive morphological events that occur in an individual plant's life cycle or an entire plant community (Gepts 1987). Development scales are used to describe important

biological events and while there has been an attempt to create a universal scale (Lancashire et al. 1991), the majority of development scales are crop specific, particularly when secondary stages are included. Development scales are set up in a numerical fashion based on the ontogenetic appearance in organs (Lancashire et al. 1991). These scales are ordinal in nature and although the stages are ordered numerically, plant development between scale points is undefined and therefore a linear relationship from one stage to the next does not necessarily exist (Lancashire et al. 1991). Caution should be exercised when utilizing growth stage scales such as the one used in this study because a numeric code is used to describe each stage. For example, canola can be divided into several growth stages based on significant biological events (Table 2.2). Life stages of plants are described qualitatively and determined with a certain degree of observer subjectivity. Variation in the criteria used to judge phenological stage and the resolution with which plant development is observed creates challenges among researchers when attempting to standardize phenological stage observations. In the phenological development scale used by the Canola Council of Canada (Thomas 1995), six primary growth stages are used; pre-emergence, seedling, rosette, bud, flower, and ripening (Figure 2.4). These stages are further divided into more specific secondary categories. This development scale is modeled after the scale developed by Harper and Berkenkamp (1975).

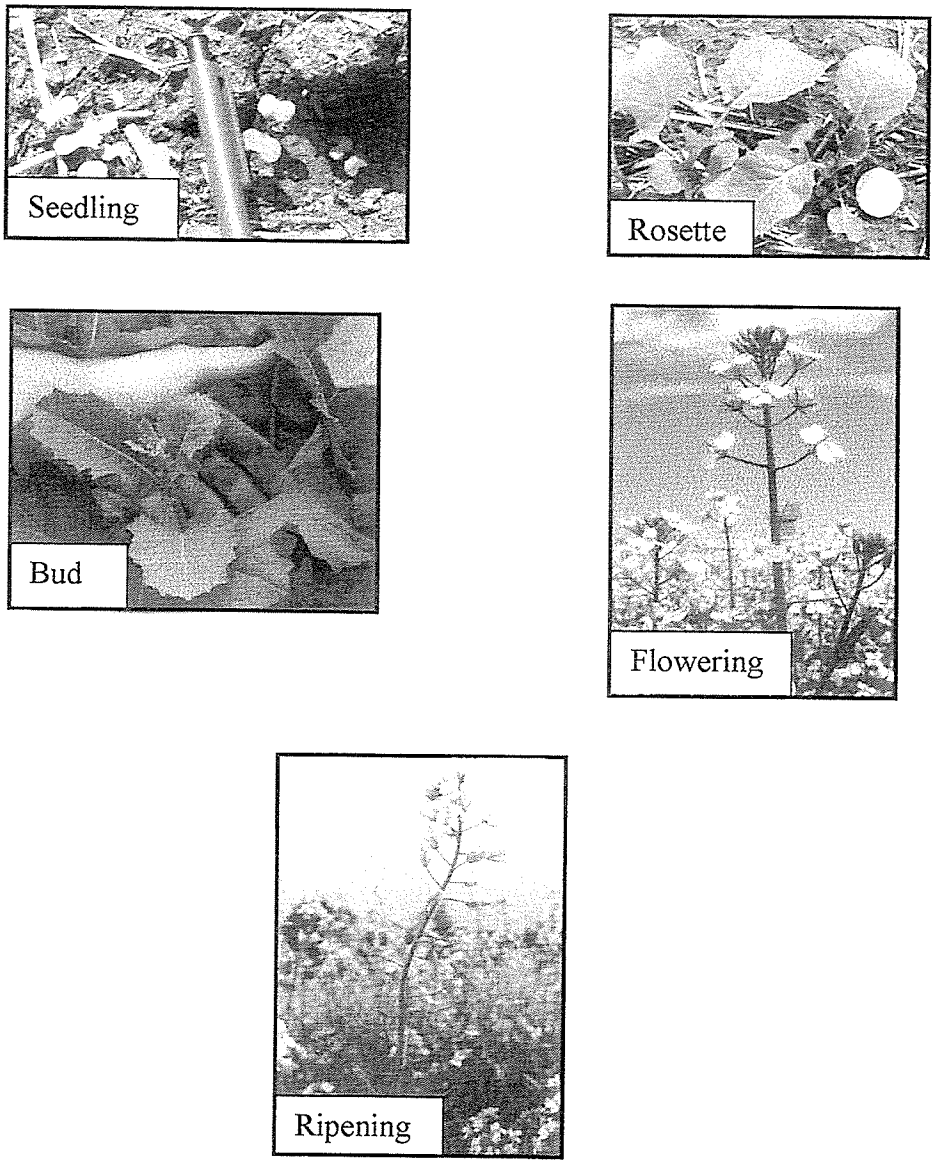


Figure 2.4 Primary phenological stages of *Brassica napus* L.

Table 2.2 Summary of Canola Growth Stages (Thomas 1995).

Stage	Description of Main Raceme
0	**Pre-emergence**
1	**Seedling**
2	**Rosette**
2.1	1st true leaf expanded
2.2	2nd true leaf expanded
2.3	etc. for each additional leaf
3	**Bud**
3.1	Flower cluster visible at center of rosette
3.2	Flower cluster raised above level of rosette
3.3	Lower buds yellowing
4	**Flower**
4.1	1st flower open
4.2	Many flowers opened, lower pods elongating
4.3	Lower pods starting to fill
4.4	Flowering complete, seed enlarging in lower pods
5	**Ripening**
5.1	Seeds in lower pods full size, translucent
5.2	Seeds in lower pods green
5.3 [z]	Seeds in lower pods green-brown or green-yellow, mottled
5.4	Seeds in lower pods yellow or brown
5.5	Seeds in all pods brown, plant dead

[z]Physiological Maturity

Although it is useful to simply identify stages of phenological development using a universal format, the quantification of phenological development scales allows this information to be utilized in a practical and utilitarian manner by including this knowledge in models that simulate growth and development.

2.2.3 Factors Influencing Crop Phenology

The factors influencing phenological development can be divided into two broad categories: (1) genetic constitution, and (2) environmental variables. The genetic constitution of a plant is as essential to plant growth and development as is the complex set of interdependent environmental factors (Meyer et al. 1960). All crops have a

maximum genetic potential with respect to growth and development. Provided all the environmental conditions are favorable and non-limiting, theoretically the plant will grow and develop at its optimum based on genetic potential. The genetic constitution sets a definite limit as to the maximum growth and development potential regardless of the environmental conditions. The interrelationships among the numerous environmental factors complicates the growth and development response because the change of magnitude or duration of one factor rarely occurs without giving rise to subsidiary changes in other factors.

The genetic component is becoming increasingly important in agriculture, as genetically modified organisms (GMOs) are perfected to thrive in specific environmental conditions. Historically, crop selection was largely based on the climate and soils. The development of hybrids and agricultural crops with environmentally specific genetically altered traits have allowed producers to select crops from an enormous pool of varieties and has further promoted the diversification of crops. The development of GMOs, particularly in canola, has resulted in high variety turnover rate, making scientific investigation of any one of these varieties of limited value because they may remain in production for only a limited number of years. Thus, variety specific information is often unavailable and a great deal of information must be implied from knowledge of other varieties. Further, many varieties have been genetically modified to suit specific environments, e.g. faster emerging and maturing varieties, yet this information can not be included in agro-meteorological models because it is unavailable. Thus, much of the basic information required to successfully model phenological development must be

derived from other varieties for which the information exists, despite the fact that this information is cultivar specific.

2.2.4 Environmental Factors

There are innumerable interrelated environmental variables that affect plant growth and development. They can be divided into climatic, edaphic, and biological. Table 2.3 gives a list of some of the common variables affecting plant development.

Table 2.3 Environmental factors affecting phenological development.

Climate	Temperature	▪ Day and night ▪ Heat/cold Stress
	Light	▪ Photoperiod ▪ Light Intensity
	Precipitation	▪ Available Water ▪ Soil Water Content
	Hazards	▪ Hail ▪ Wind ▪ Water Stress (drought/flood)
Edaphic (Soil)	Fertility	▪ Nutrients
	Physical Properties	▪ Texture ▪ Aeration ▪ Bulk Density ▪ Soil Water Content
Biological	Pathogens	▪ S. sclerotiorum, *Alternaria brassicae* and *A. raphani*
	Pests	Flea Beatles (*Phyllotreta crucifera* (Goeze) and *Psylliodes punctulatus* (Melsheimer)
	Weeds	▪ Wild mustard, Shepard's Purse
	Herbivores	
	Human	▪ Stand density ▪ Seed quality

The majority of environmental variables are interrelated and rarely act autonomously. For example, soil water content depends on the amount of precipitation or irrigation input into the plant-soil system, but the retention of this water and the amount available to plants is highly correlated with the physical properties of the soil as well as the plant's

ability to extract this water. The success of germination and early seedling development is dependent on temperature, light, and moisture (Murray et al. 1984, in Nykiforuk and Johnson-Flanagan 1994). Despite the myriad of possible variables, phenological development can be estimated with reasonable accuracy using a few simple variables, temperature and photoperiod being the most common (Shaykewich 1995). Although it is impossible to mathematically express the complex interaction of all the above variables and their affect on phenological development, temperature indices are often a sufficient estimator of crop phenology and are currently used with a great degree of confidence for many agricultural crops.

Temperature is the single most important factor influencing phenological development (Gepts 1987, Hodges 1991b, Johnson and Thornley 1985, Shaykewich 1995, Wielgolaski 1974, Morrison et al. 1989). Although there is a lack of literature with regard to the influence of temperature on phenological development rates of canola, Morrison et al. (1989) determined that temperature was the most important regulating factor. Squire et al. (1997) determined that oilseed rape (canola) is heavily influenced by temperature with respect to non-germination (categorical trait) and time to germination (quantitative trait).

2.3 Phenological Modeling

Phenological modeling refers to the mathematical equations that express the rate of change in life stages, as a function of environmental variables such as temperature, humidity, photoperiod, and radiation (Shaykewich 1995). Phenological modeling attempts to quantify biological processes (phenological development) and further correlate these processes with environmental variables such as temperature (Hodges 1991b). These mathematical equations are based on the fundamental relationships between the rate of plant development and environmental parameters (Shaykewich 1995). Phenological models are concerned with the "physiological age" of the organism as it relates to the integration of environmental variables over time. The agricultural phenologist examines the effect of environmental parameters such as climate and soil on the timing of biological events in commercial agricultural crops (Wielgolaski 1974).

Predicting crop phenology is a useful tool and is widely used in the agricultural community from the broad regional level to local scale situation. The accuracy of crop simulation models is heavily influenced by the reliability of predicting crop phenological stage (French and Hodges 1985, Hodges 1991b). At the regional level, phenology models are important components of agrometeorological models such as yield predictions because the influence of meteorological conditions on crop vitality depends upon growth stage (French and Hodges 1985). Crop insurance companies benefit from phenological modeling, particularly when the stage of crop is important in determining damage and the regeneration potential of a crop after environmental injury. For example, canola can recover from hail injury in the early flowering stage when buds and flowers are severed from a portion of the inflorescence and even when the stems of a portion of the

inflorescence are partially severed (McGregor 1987). Water-use models such as the Canola Phenology and Water-Use Model (Raddatz 1993) require phenological relationships . Phenological modeling reduces the number of in field measurements required for the majority of regional agrometeorological models.

The use of "heat-units" to characterize plant development has become an increasingly common practice in the field of agriculture. The heat unit concept provides a way of assessing the total accumulated heat that is "useful" for a particular crop and further correlating this "effective heat" to a life stage or phenological development stage of a plant. Many methods have been devised to quantify the amount of heat useful for plant development. These methods are crop specific and therefore must be tailored to reflect the crop's cardinal temperatures and the temperature-development relationship. Many heat units assume a linear response of development to temperature. This is valid between a limited range of temperatures, but frequently, the actual development response outside this limited range is overlooked. Heat units that are crop specific are superior to calendar days for predicting plant development.

2.3.1 Plant Growth Temperature Response

Morrison et al. (1989) determined that temperature was the single most important factor controlling phenological development in canola and accounted for 99 % of the total variation. Hodgson (1978b) concluded that the duration of developmental phases in *B. campestris* and *B. napus* are heavily influenced by temperature.

Plant growth rates have been found to progressively increase with an increase in temperature up to an optimal threshold temperature above which the rate of growth begins to decline. This relationship between plant growth and development with

temperature is so typical that many experiments measuring different growth and development aspects all produce similar curves (Johnson and Thornley 1985). Figure 2.5 shows a schematic graph of a typical plant growth and development curve. Development curves are obtained by growing plants at constant temperatures (in growth chambers) and measuring a particular aspect of development at each temperature regime. The plant-development-temperature response curve can be divided into sections based on the different rates of development. Section 1 shows an accelerating increase from the base temperature. The second section is an approximately linear response within a limited range of temperatures. Section 3 shows an increase in development at a decreasing rate up to an optimum temperature. Section 4 shows a rapid fall off from the optimum temperature until a maximum temperature at which growth and development cease. This plant-development curve illustrates the inappropriateness of utilizing a linear relationship, particularly outside the linear portion of the plant-development-temperature curve. Plant-development is therefore curvilinear and a climate in which the temperatures frequently fall outside this limited range cannot be accurately characterized by a heat unit system which assumes that plant-development rate is a linear function of temperature.

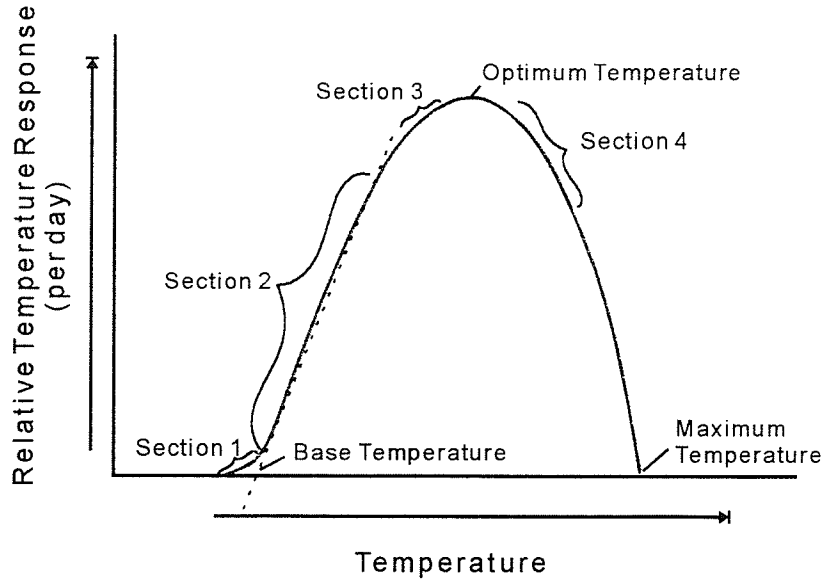


Figure 2.5 Schematic of the plant-development-temperature response.

Figure 2.5 shows a distinct nonlinear response to temperature, particularly near the base temperature and at the optimum temperature. Shaykewich (1995) concluded that the development rate of most plant species is a sigmoidal function of temperature. In addition, the above growth curves illustrate two important concepts. (1) The physiological development of organisms is driven by the accumulation of thermal energy (heat) which is more important than the accumulation of time. (2) Many organisms slow or stop their growth and development when temperatures are above or below threshold levels. These are referred to as cardinal temperatures, i.e. minimum, optimum, and maximum temperature thresholds.

The various biological processes occurring within a plant all respond differently to temperatures (Johnson and Thornley 1985). There exists a minimum, optimum and maximum temperature for each individual process. The effect of temperature on the various physiological, and chemical processes of plants are interrelated and therefore, the

optimum temperature for one process may not be the optimum temperature for another process. Whatever the individual effects on specific plant physiological responses, the cumulative effect of temperature produces a typical bell shape curve when development rate measures are plotted as a function of temperature, e.g. Figure. 2.5.

The plant growth temperature relationship may be well defined for individual plants in a controlled environment, but it is less well defined in a field setting. Although leaf temperature would more accurately reflect the amount of heat a plant experiences in the field, it is difficult to measure. Air temperature is more readily available and has historically been used in the calculation of useful heat. Air temperature may not always be representative of the temperature at the photosynthetic site.

2.3.2 Cardinal Temperatures for Canola

The cardinal temperatures for plant development are key considerations when attempting to quantify the plant-development-temperature response. Canola is often described qualitatively as a cool season crop. Much of the basic agromonic information, such as cardinal temperatures are unavailable for the majority of *B. napus* cultivars. In addition, environmental factors that affect canola phenology have received inadequate investigation (Hodgson 1978a, Morrison 1988).

2.3.2.1 Baseline Temperature

All calculations of "useful accumulated heat," are derived from a common basic assumption that every organism has a baseline temperature threshold (T_{base}) below which growth is absent or negligible.

Baseline temperatures differ between plant species, cultivars, and with crop stage (Hodges 1991b). Controlled growth chamber experiments are conducted to analyze the

growth of various plant species. The plant temperature growth relationship curve is often extrapolated in order to determine the baseline temperature and is further verified using field data. Various methods for determining the base temperature from laboratory data have been reviewed and refined by Gbur, Thomas and Miller (1979). Figure 2.5 shows a schematic representation of the relative temperature response as a function of temperature. Extrapolation of this line to nil rate leads to the baseline or threshold temperatures (Guyot 1998). Hodgson (1978b) determined the baseline temperature for successive stages of *B. napus* L. cv. Midas using temperature development rate responses measured in the field at Tamworth, New South Wales. Baseline temperatures were determined using a linear rate temperature development using the x-intercept method developed by Arnold (1959).

Table 2.4 Baseline temperatures for *B. napus* L. cv. Midas (Hodgson 1978b).

Growth Phase	Baseline Temperature (°C)
Planting to bolting	0.45
Bolting to first flower	1.44
First flower to pod fill	6.07
Pod fill to maturity	1.14

Using the x-intercept method described by Arnold (1959), Morrison et al. (1989) determined an overall baseline temperature of 5°C for canola for the entire growth/development period. Morrison (1988) plotted development rate versus the $\log_{10}$ of mean growth cabinet temperature while Hodgson (1978b) used a simple linear regression without a transformation.

An overall estimated base temperature for emergence of canola determined by Vigil et al. (1997) for five different cultivars was 0.9°C. Using data from Morrison et al. (1989) and Blackshaw (1991) and assuming a linear relationship between development rate and temperature, Vigil et al. (1997) derived base temperatures of 2.3°C (Morrison's data) and 1.6°C (Blackshaw's data).

Nykiforuk and Johnson-Flanagan (1994) determined that low temperature has an injurious effect on germination of canola. Emergence consists of germination and early seedling development. Soil temperatures for seeding canola should be between 15 and 20°C (Anonymous, in Nykiforuk and Johnson-Flannagan 1994). Canola will germinate in temperatures ranging from 2 to 25°C (Thomas 1995), but temperatures below 10°C resulted in slow germination rates. Blackshaw (1991) concluded that temperatures between 10 and 25°C resulted in greater than 90% emergence and that temperatures of 5 and 30°C resulted in only slightly lower germination. This was in disagreement with Nykiforuk and Johnson-Flannagan (1994). Based on the limited amount of information of baseline temperatures for canola, it would appear that the 5°C baseline proposed by Morrison et al. (1989) would be the most appropriate to this study since it is representative of the entire life cycle of canola.

2.3.2.2 Optimum Temperature

The optimum temperature is that temperature at which the development rate is greatest. Since a plant-development-temperature response curve for canola has not yet been determined, the optimum temperature can be approximated using previous studies. Angadi et al. (2000) used 20°C/15°C (day/night temperatures) as the optimal growing temperature for their study with *Brassica* species and suggested that the optimal

temperature for *B. napus* was somewhat lower that that for *B. Juncea* and *B. rapa*. Nykiforuk and Johnson-Flanagan (1994) used 22°C as the optimum temperature for canola germination and Blackshaw (1991) determined that canola seedling emergence was greater than 90% between 10 and 25°C. Although the precise optimum temperature for canola development has not yet been determined, based on the above literature it would be reasonable to assume that the optimum temperature would be below 20°C.

2.3.2.3 Maximum Threshold Temperature

The maximum temperature threshold (T_{hi}) refers to that temperature in which any further increase in temperature would be detrimental to the growth and development of the organism. Morrison (1988) was unable to obtain a maximum temperature threshold. The growth cabinets with mean temperatures of 22 and 25°C resulted in plant sterility and Morrison (1988) further suggests that in order to obtain a maximum temperature threshold, *B. napus* would have to be grown in growth chambers in which temperature was constant between 25 and 30°C. Further studies conducted by Morrison (1993) determined that the canola stages most sensitive to heat stress occurred from late bud development through early seed formation. Morrison (1993) determined that canola was sterile in controlled growth cabinet experiments when the maximum temperatures exceeded 27°C. Angadi et al. (2000) determined that moderate temperature stresses of 28/15°C (day/night temperatures) did not result in a reduction in dry matter production but temperatures of 35/15°C (day /night temperatures) were injurious to reproductive organs at various developmental stages and decreased dry matter production by 19% overall (Angadi et al. 2000). In addition, dry matter production was reduced by 21% during early flowering and by 8% during early pod development (Angadi et al. 2000).

Polowick and Sawhney (1988) concluded that 32/26°C (day/night temperatures) resulted in male and female sterility in the flowers of *B. napus* L. cv. Westar, but at 28/23°C, fertility was not impaired. Hodgson (1978a) found that the temperature response curve for some phases of canola become asymptotic (i.e. near zero development rate) to the temperature axis at high temperatures (around 25°C). Richards and Thurling (1978) observed that leaf tissue was disrupted at 42°C in all cultivars. Although the above literature does not pin point an exact maximum temperature, it can be inferred that plant development begins to slow between 28 - 35°C and that the maximum threshold temperature must be between 35 - 42°C.

2.3.3 Heat Unit Systems

Common to all heat unit systems is the general assumption that development rate is some function (*f*) of temperature (Allen 1976).

$$\frac{da}{dt} = f(\mathrm{T}(t)) \qquad \textbf{(2.1)}$$

Where

a is age,
T(t) is temperature at time t.

The accumulated physiological age or development from 0 to time τ is then

$$\Delta a = \int_0^{\tau} f(\mathrm{T}(t))dt, \qquad f(\mathrm{T}(t)) \geq 0 \qquad \textbf{(2.2)}$$

The above equation illustrates two fundamental concepts;

(1) Organisms integrate temperature effects according to some function that is species specific,

(2) Developmental rate cannot be negative.

Therefore, if f in equation 2.1 is assumed to be a linear function, then the plant development rate is proportional to temperature and hence, the organism will age in step with the accumulation of area under the diurnal temperature curve (Figure 2.6).

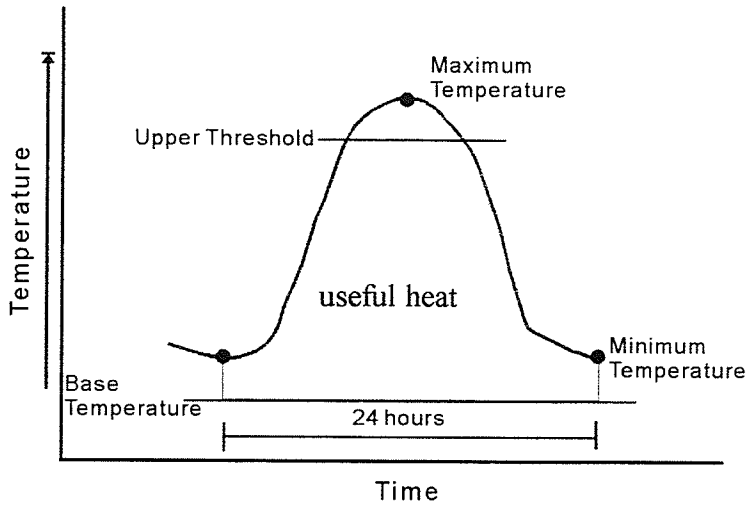


Figure 2.6 Schematic of "useful" heat represented by the accumulation of area under the diurnal temperature curve.

The quantification of the plant development temperature response allows modelers to determine the amount of useful heat experienced by a plant to progress from one stage of development to the next. Theoretically, this amount of "useful" heat should be constant. Although it is obvious that the plant development temperature curve is distinctly non-linear, many attempts to describe development using a linear temperature function have been relatively successful because daily temperatures usually fall within the linear portion of the response curve.

Linear heat unit calculations are based on calculating the area under the diurnal temperature curve above the base temperature. Figure 2.6 shows an idealized diurnal

temperature curve and the shaded area under the curve represents the amount of heat "useful" for plant development.

While this may be a simple calculation in the growth chamber studies, it is more difficult under field conditions. Daily temperature curves are often irregular and often do not follow a simple curve pattern such as that seen in Figure. 2.6. In order to calculate the "actual" amount of useful heat, one would have to obtain a continuous set of temperatures over time and then calculate the area under the diurnal temperature curve. Approximations such as the "simple" growing degree-day have been derived to determine the area under the graph and approximate the "actual" amount of accumulated heat for a given set of daily temperature extremes.

2.3.3.1 Growing Degree-Days

The "simple" growing degree-day method has been widely accepted because it is simple and only requires the daily maximum and minimum temperatures. Growing degree-days are calculated using the following equation:

$$GDD = \sum_{S_1}^{S_2} \frac{(T_{MAX}) + (T_{MIN})}{2} - T_{base} \qquad \textbf{(2.3)}$$

Where

GDD is growing degree-day,
T_{MAX} is the maximum daily temperature (°C),
T_{MIN} is the minimum daily temperature (°C),
T_{base} is the base temperature threshold (°C),
S_1 is stage 1,
S_2 is stage 2.

This method uses a rectangular area to approximate the area under the diurnal temperature curve (Figure 2.7). This rough estimate has gained wide acceptance because it requires a limited amount of data (maximum and minimum daily temperatures), and the degree of accuracy has been sufficient for many agrometeorological models. If one

assumes a sine function for the day, areas that are overestimated in the earlier and later part of the diurnal temperature curve, are compensated by the underestimation that occurs during midday (Figure 2.7).

Many variations of the simple growing degree-day have been developed to reflect the six possible situations that exist between the daily temperature cycle and the upper and lower temperature thresholds when the daily maximum and daily minimum diurnal temperature combinations go above and below the upper and lower temperature thresholds (University of California Statewide IPM Project 1998). The relation between temperature and development rate is not in fact linear and during a typical day, temperatures fall outside the linear portion of the plant-development-temperature response. Therefore, any improvement in estimating the actual area under the diurnal temperature curve will not result in an improvement in predicting the actual amount of heat useful for plant development.

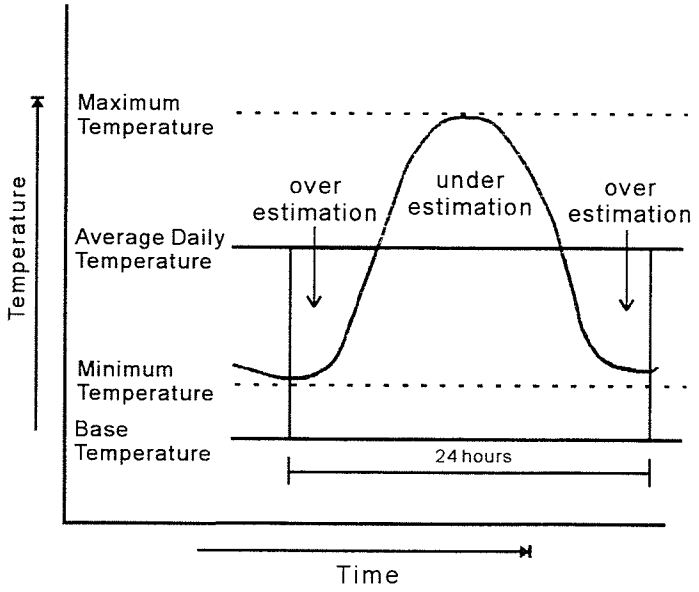


Figure 2.7 Schematic of the area estimated by a simple growing degree-day under the diurnal temperature curve.

2.3.3.2 P-Days

Sands et al. (1979) developed a methodology for determining the physiological age of potatoes from, p-time (P) with units P-Days. This method has gained wide acceptance in the potato industry because it is simple and allows for the use of the cardinal temperatures: baseline (T_{base}), optimum (T_{opt}), maximum temperature (T_{hi}), thresholds, and therefore considers the plant development temperature relationship as non-linear.

The cardinal temperatures used for potatoes, T_{base}, T_{opt}, and T_{hi} are 7, 21, and 30°C, respectively. The model uses daily minimum (T_{MIN}) and maximum temperatures (T_{MAX}), recognizing that a greater portion of the diurnal temperature variation is spent closer to the daily minimum temperature than to the daily maximum.

P-Days are calculated from the following equation

$$P-Days = \frac{1}{24} * \left(5 * P(T_1) + 8 * P(T_2) + 8 * P(T_3) + 3 * P(T_4)\right) \quad \textbf{(2. 1)}$$

Where

$$T_1 = T_{MIN}$$

$$T_2 = \frac{(2 * T_{MIN}) + T_{MAX}}{3}$$

$$T_3 = \frac{T_{MIN} + (2 * T_{MAX})}{3}$$

$$T_4 = T_{MAX}$$

The accumulation of heat is calculated from a function of temperature, P(T), where the temperatures T_1 through T_4 are used to define the value of P by the following formula:

$$P = 0 \qquad \text{When: } T < 7$$

$$P = k * \left(1 - \left((T - 21)^2 / (21 - 7)^2\right)\right) \qquad \text{When: } 7 \le T < 21$$

$$P = k * \left(1 - \left((T - 21)^2 / (30 - 21)^2\right)\right) \qquad \text{When: } 21 \le T < 30$$

$$P = 0 \qquad \text{When: } T \ge 30$$

Where

k is a scale factor set to a value of 10,
7, 21, and 30 are the lower, optimum, and maximum threshold temperatures, respectively.

Figure 2.8 graphically shows the relationship between temperature and the accumulation of P-Days.

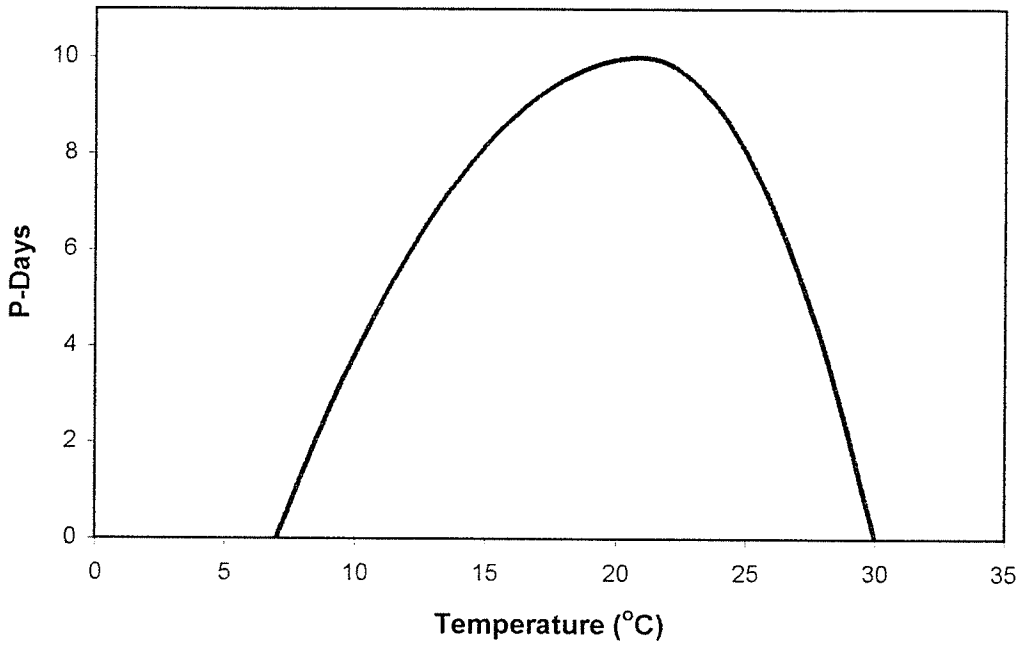


Figure 2.8 P-Days as a function of temperature.

2.3.4 Photoperiod Response

Although temperature is one of the most important factors affecting phenological development in crops, photoperiod also plays a significant role. Major (1980) determined that photoperiod and temperature were the main factors influencing flowering of plants. Hodgson (1978a) found that phase duration in *B. napus* annual cultivars grown in northern New South Wales was largely accounted for by correlation with temperature and photoperiod. Major (1980) developed a systematic classification scheme for photoperiod response in plants. Plants can be categorized into three classes:

(1) Short-Day – plant flowers more rapidly as photoperiod decreases.

(2) Long-Day – plant flowers more rapidly as photoperiod increases.

(3) Day-Neutral – photoperiod has no effect.

Figure 2.9 shows the response of a long-day plant to photoperiod. The optimal photoperiod is defined as that photoperiod in which flowering occurs in the shortest time (Major 1980). Canola is classified as a quantitative long-day plant (Major 1980, King and Kondra 1986). As the photoperiod increases, the plant flowers more rapidly, thus the plant flowers in the least amount of days. The number of days to flowering is also an estimate of the basic vegetative stage (BVP). The basic vegetative stage is the period of juvenility before the plant flowers and the plant must pass through this stage before it can respond to photoperiod stimulus. The length of the BVP will vary according to the photoperiod. A long-day plant such as canola will have a shorter BVP as photoperiod increases up to the minimal optimal photoperiod (MOP). At this photoperiod (and longer), the basic vegetative phase is at its minimum (MBVP). The non-optimal

photoperiod is that photoperiod for which there is a delay in flowering and is described as the photoperiod-induced-phase (PIP) (Major 1980). The PIP is expressed as the delay in days/hour decrease in photoperiod (or increase in the case of short-day plants). The critical photoperiod is that photoperiod at or below which flowering would not occur. Time to flowering remains constant between the minimum optimal and maximum photoperiod.

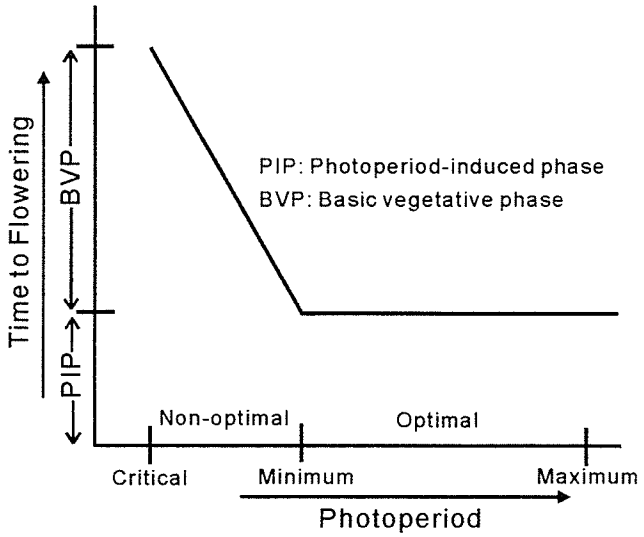


Figure 2.9 Long-day plant-development response to photoperiod (Major 1980).

Major (1980) determined that the cultivars *B. napus* L. cv. Zephyr and Tower had minimal optimal photoperiods of 18.0 and 18.8 hours, respectively. The photoperiod sensitivity of these two cultivars was 5.09 and 4.97 days delay in flowering per hour decrease in photoperiod (Major 1980). King and Kondra (1986) determined a slightly different minimal optimal photoperiod for *B. napus* using different cultivars (Table 2.5).

Table 2.5 Minimal optimal photoperiod (MOP), minimal basic vegetative stage (MBVP) and photoperiod sensitivity (B_1) for several cultivars of *B. napus*.

CULTIVAR	MOP	MBVP (DAYS)	B_1 (DAYS/H)
Zephyr[z]	18.0	32.5	-5.09
Tower[z]	18.8	32.8	-4.967
Altex[y]	17.0	30.9	-3.50
Regent[y]	16.7	30.9	-4.24
Midas[y]	17.4	29.8	-2.80
Oro[y]	16.7	32.6	-4.69
74G-1382[y]	17.2	26.9	-1.81
75G-908[y]	16.9	27.8	-2.50
81-68410[y]	17.3	28.5	-2.08

[z] (Major 1980)
[y](King and Kondra 1986)

King and Kondra (1986) suggested that the minimal optimal photoperiod may not be reached in canola growing areas of Canada. Based on Major's (1980) research, Morrison concluded that time to flowering for *B. napus* is relatively insensitive to photoperiods greater than 12 hours and since the photoperiod during the canola growing season on the Canadian prairies exceeds this, the influence of photoperiod would be insignificant. Morrison (1988) further suggested that the growing degree-day method was not entirely accurate and any refinements to the model might possibly include photoperiod and light intensity.

2.3.5 Fractional Leaf Area

The Canola Phenology and Water-Use Model (Raddatz 1993) simulates fractional leaf area (L_A) from an accumulated "simple" growing degree-day above 5°C. Previous research involving ground cover has focused primarily on the leaf area index (LAI),

which is a measure of the surface area of one side of the leaves per unit of ground area (m^2/m^2). This differs from the fractional leaf area (L_A) which is an estimate of the fraction of the ground covered by actively transpiring vegetation. The maximum value for L_A is 1.0, which represents a closed canopy. The leaf area index does not theoretically have an upper limit since it is based on the area of leaf per unit area of ground. Since crop canopies can have many layers, the leaf area covering the ground can be considerably greater than the ground surface area, hence values greater than 1 are expected. In fact, values of 5 or more are common.

Since an empirical relationship for L_A was not available, Raddatz (1993) employed the following relationships using GDD above 5°C (Figure 2.10).

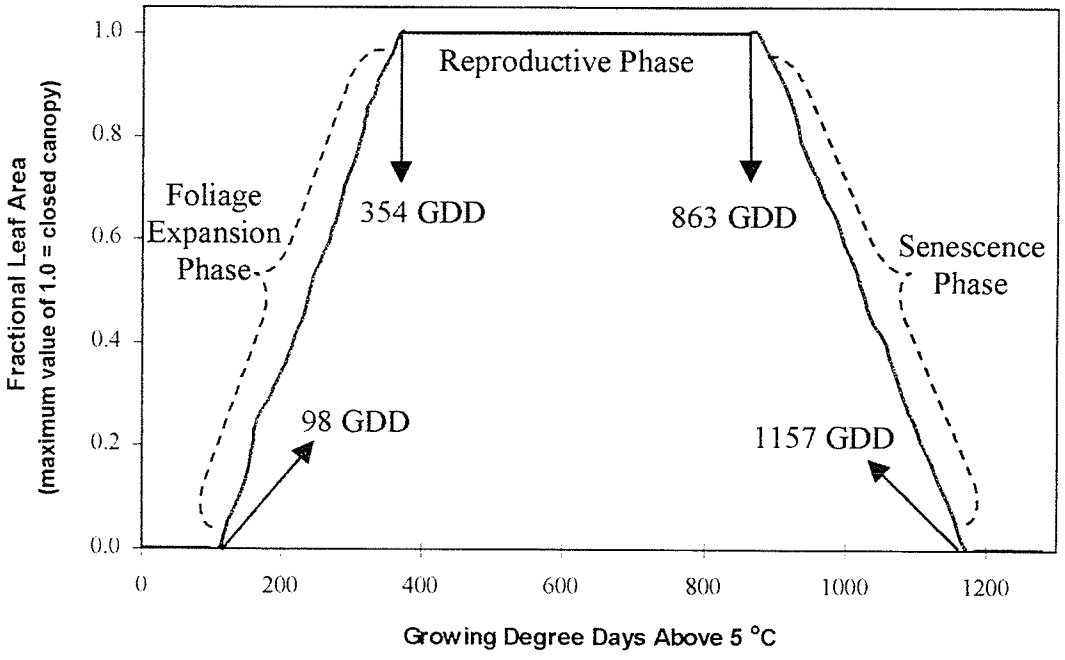


Figure 2.10 Relationship between fractional leaf area and growing degree-day above 5°C used in the Canola Phenology and Water-Use Model (Raddatz 1993).

In the Raddatz (1993) model, L_A represents the amount of actively transpiring vegetation (primarily leaves) in the crop canopy. L_A increases linearly from 93 to 354 GDD above 5°C. At 354 GDD above 5°C, which represents full canopy in the Raddatz (1993) model, a fractional leaf area of 1.0 is maintained until 863 GDD above 5°C is reached, representing flowering complete or the beginning of ripening (stages 4.3 –5.1). Although the LAI of the canopy may vary between 354 and 863 GDD above 5°C, a fractional leaf area of 1.0 is maintained. A linear relationship describes the senescence of the leaves between 863 to 1157 GDD above 5°C.

Canola is a determinate crop in which the pods ripen and the leaves senesce. Although different vegetative components such as pods and stems may cover the ground in addition to leaves, the model requires estimates of actively transpiring vegetation. Therefore, although stems and pods and beaks all possess stomata, and in the early stages of ripening contribute to photosynthetic activity, (Allen et al. 1971, Allen and Morgan 1975, Tayo and Morgan 1975, Thurling 1974), the stage of the crop is important when determining actively transpiring. As the pods continue to ripen, photosynthetic activity declines substantially and therefore, even though the ground may be covered by vegetation, it is not actively transpiring and therefore should not be included in the estimates of L_A.

Since most agronomic studies focus on leaf area index (LAI), information with respect to L_A can only be approximated. A LAI of 1.0 would represent an even ratio of plant area to ground area, although it would not necessarily represent full canopy cover since there would most likely be vegetative layering within the crop canopy. Thomas (1995) indicates that full canopy cover occurs during the late rosette stage (stages $2.4 \leq 3.1$). Rapid leaf development occurs during the rosette stage and maximum leaf area is

reached near the start of flowering (stage 4.1). Morrison (1988) determined that a LAI of 1.0 would occur between stages 2.1 and 3.1. Clarke and Simpson (1978), Thomas (1995), Allen and Morgan (1975) also determined that maximum LAI would occur at the of start of flowering. Thomas (1995) indicated that rapid development and growth of large leaf area was maintained well beyond start of flowering. Allen and Morgan (1975) determined that LAI remained high during flowering to early pod growth, but began to decline rapidly during the ripening stage. As the crops began to senesce (stages 5.1 –5.3) a LAI of less than 1.0 began to occur (Morrison 1988).

Thus, using the above information, a L_A of 1.0 is expected to occur in the late rosette stage as utilized in the Raddatz (1993) model, and estimated to occur at 354 GDD above 5°C, according to Morrison (1988). A L_A of less than 1.0 occurs around stage 5.2, which occurs at approximately 863 GDD above 5°C in the Raddatz model using Morrison's (1988) development scale. If the L_A represents actively transpiring vegetation, then the inclusion of pods, beaks, and stems would be appropriate up until the beginning of the ripening stage (stage 5.2). Thus, use of crop stage for determining actively transpiring leaf area is essential to appropriately estimate this crop growth parameter.

3.0 CANOLA PHENOLOGY AND WATER-USE MODEL

The soil moisture and growing degree-day data utilized in the Sclerotinia Risk Forecast program is derived from a Canola Phenology and Water-Use Model (Raddatz 1993). This model estimates soil moisture in the top-zone and root-zone, and actual evapotranspiration or crop water-use. This information is provided in the form of a daily bulletin in which the root-zone and top-zone soil moisture is given in millimeters and as a percentage of available water holding capacity. In addition, precipitation, relative humidity (of the thin air layer adjacent to the soil surface) expressed as a percentage, growing degree-days above 5°C, and fractional leaf area are also included in the daily output.

The estimation of potential evapotranspiration is a key component for many water use models. Potential evapotranspiration is defined as the upper limit of water that can be evaporated from plant and/or soil surfaces. Rosenberg (1983) defines potential evapotranspiration as "the evaporation from an extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water." Therefore, the crop will demand an amount of water equivalent to potential evapotranspiration when there is 100 percent ground cover. When the percent ground cover is less than 100 percent, then the actual amount of evapotranspiration is some fraction (as determined from crop stage) of the potential evapotranspiration. Therefore, the ratio of crop water demand to potential evapotranspiration increases with increasing ground cover, and reaches a maximum value

of 1.0 at full ground cover and then declines as the crop matures and senesces. The degree to which atmospheric demand (potential evapotranspiration) is attained is dependent on the conditions of the evaporating surface, in particular, the amount of soil water available for evaporation. Therefore, actual evapotranspiration is supply-limited.

This coupled model simulates the interaction of the atmospheric boundary layer which is governed by surface generated turbulence that changes as a result of the typical daily cycle of changing thermal stability and the evolution of the crop-soil boundary layer throughout the growing season. This model was derived from fundamental climatological principles and has been described in detail elsewhere (Raddatz et al. 1996, Raddatz 1993).

A schematic representation of the growing-season phase of the Canola Phenology and Water-Use Model (Figure 3.1) will be used to highlight the role of phenological relationships within the model. This model requires phenological relationships for fractional leaf area, and rooting depth.

3.1 Atmospheric/Planetary Boundary Layer (PBL)

Atmospheric boundary layer profiles of wind, potential temperature, and water vapour (mixing ratio) are generated for selected climatological sites twice daily (1200 and 0000 UTC) and coupled with the overnight low and maximum temperatures. These vertical profiles are generated from:

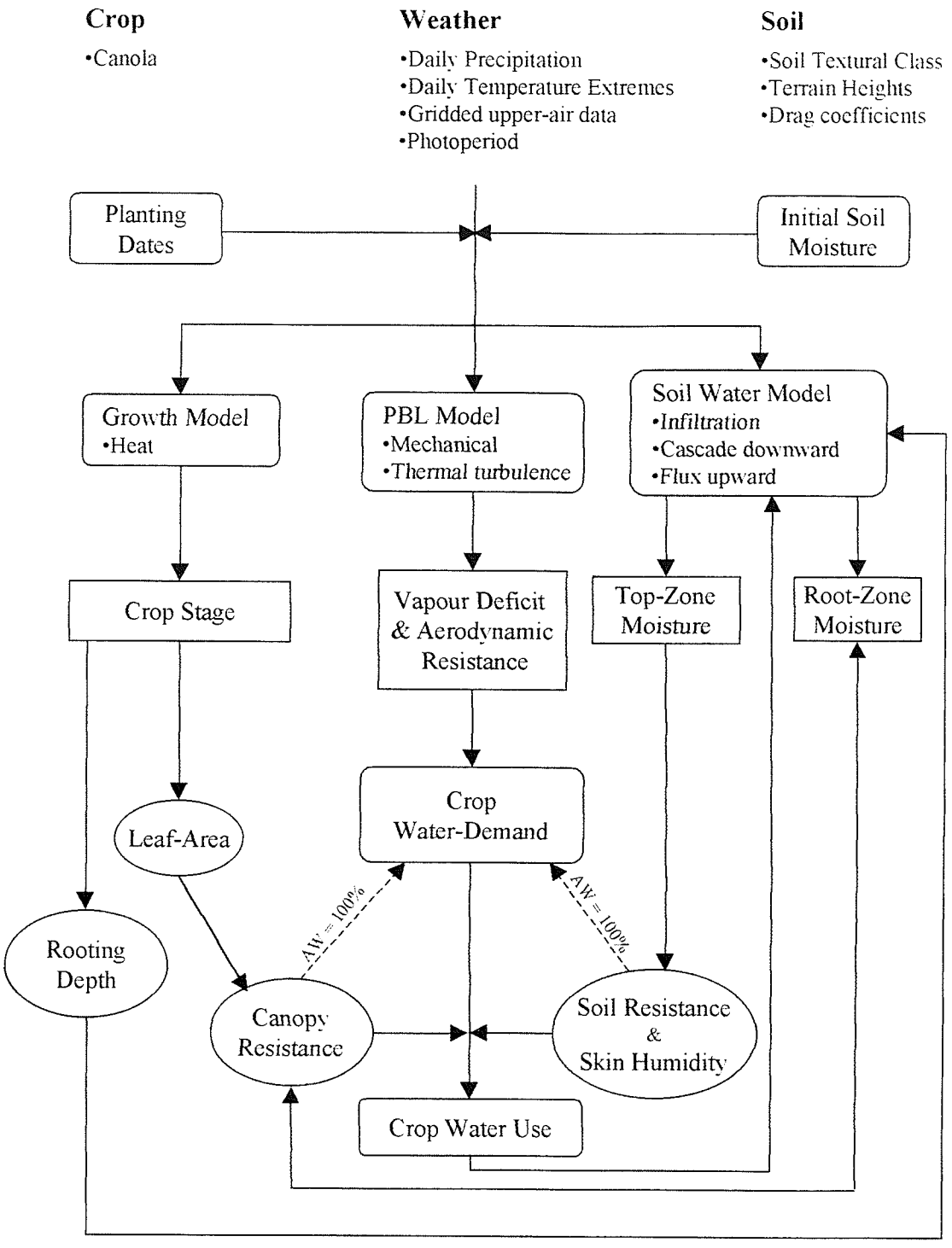


Figure 3.1 Schematic representation of the growing-season phase of the Second-Generation Prairie Agrometeorological Model (modified from Raddatz et al. 1998).

(1) Standard level (100, 85, 75, 50 kPa) upper-air observational data (temperature, dewpoint temperature and geopotential height values) analyzed to grid-points (25 km x 25 km), and then interpolated to the site of interest;

(2) Daily surface climatological observations (maximum temperature, overnight minimum temperature, and total precipitation); and

(3) Surface characteristics (roughness length, drag coefficient, soil textural class, and crop type and stage).

3.2 Crop-Soil Boundary Layer

The crop-soil boundary layer is composed of the developing crop and the top 120 cm of the soil (root plus sub-zones) (Raddatz et al. 1996). The depth of the root-zone is contingent on the type and stage of the crop and is determined from a heat accumulation relationship. As the root-zone grows, the sub-zone shrinks. The current model uses growing degree-days above 5°C to track phenological development of canola. A top-zone of 10 cm is designated based on the average depth of the penetration of the diurnal heat wave (Figure 3.2) (Deardorff 1972). The top 10 cm zone represents the maximum depth of direct atmospheric influence (atmosphere interface) while the root-zone represents the maximum depth of the soil-atmosphere exchange in which the maximum depth of the root and sub-zone is 120 cm. Bulk soil moisture in the top-zone and root/sub-zones is tracked using two separate water balances.

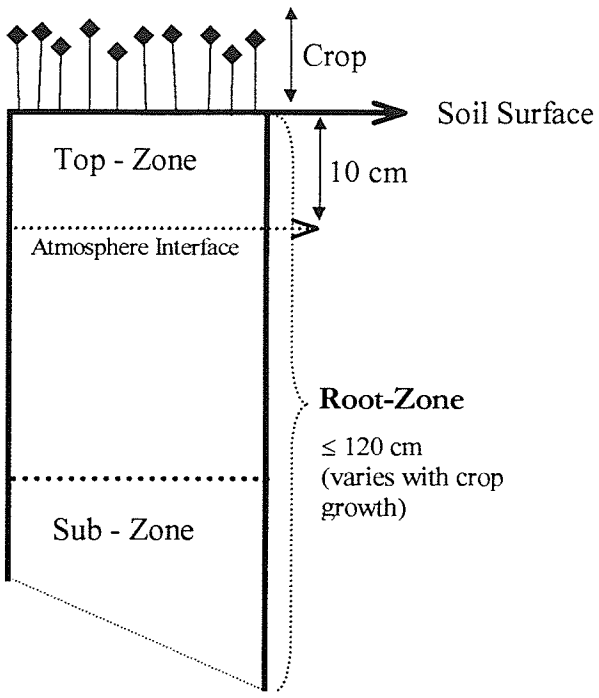


Figure 3.2 Schematic representation of the crop-soil boundary layer.

3.2.1 Soil Water Model

3.2.1.1 Water Balance Accounting for Tracking Water in the Root-Zone

Water balance accounting tracks the water content of the root/sub-zone, W, (millimeters of water) using a daily time-step, as follows:

$$W(JD) = \underbrace{W(JD\text{-}1)}_{\text{Term 1}} - \underbrace{(ET - P_I)}_{\text{Term 2}} - \underbrace{\theta_{sub}(Z_R(JD) - (Z_R(JD\text{-}1))}_{\text{Term 3}} \quad \textbf{(3.1)}$$

Term 1: Water content of root-zone on previous day (mm)

Term 2: Depletion due to evapotranspiration and addition due to infiltrating precipitation

Term 3: Root-zone increase in water due to root growth

With

$$\text{Permanent Wilting Percentage} \leq W(JD) \leq \text{Field Capacity}$$

Where

JD is the Julian Day,
ET is the evapotranspiration (mm),
P_I is the Infiltrating precipitation (mm),
θ_{sub} is the volumetric water content (cm^3*cm^{-3}) of the sub-zone,
Z_R is the root-zone depth (mm) – function of GDD.

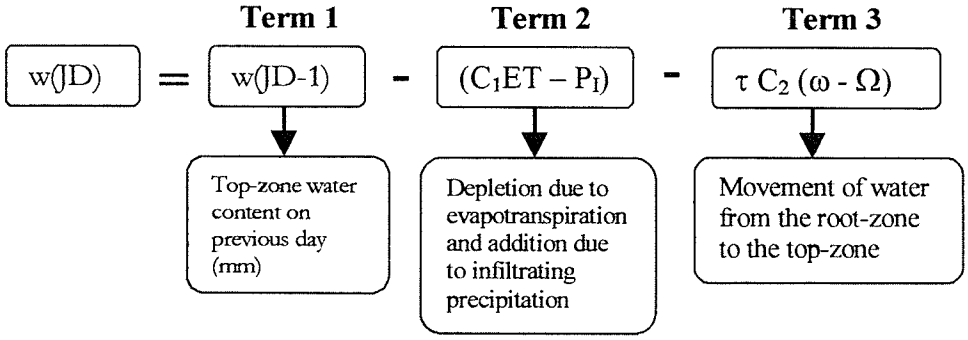
Water in excess of the root-zone's field capacity was assumed to infiltrate into the sub-zone, and water in excess of the sub-zone's field capacity contributed to deep drainage.

Term 3 in equation 3.1 represents water that becomes available as a result of root growth. The root-zone depth is a function of crop type and stage of development and is estimated using a "simple" growing degree-day approach. A dynamic root value is obtained from an equation patterned after Rasmussen and Hanks'(1978) equation for wheat, which assumes the maximum depth of root penetration occurs from flowering onward (576 GDD in equation 3.2). The root-zone is adjusted daily to reflect an increase in the root depth per day ($Z_R(JD) - (Z_R(JD-1))$.

$$Z_R = 5.0 + (115.0/(1.0 + \exp(5.0-(8.0 * (GDD * 10)/5760.0)))) \quad \textbf{(3.2)}$$

3.2.1.2 Water Balance Accounting for Tracking Water in the Top-Zone

The water content of the top-zone, w, (millimeters of water) is adjusted using a daily time-step using the following approach:



(3.3)

With 0.1 of PWP $\leq$ w(JD) $\leq$ saturation

Where

w(JD) represents the top-zones water content in millimeters,
C_1 is a function of fractional leaf area and represents the fraction of the evapotranspiration coming form the top-zone,
ET is evapotranspiration calculated from:
Evaporation (E_E) + Transpiration (E_T),
P_I is infiltrating precipitation (mm),
τ is the portion of each 24 hour period that is night,
C_2 is a function of root-zone water content (described later),
ω is volumetric water content of top-zone,
Ω is volumetric water content of root-zone,
PWP is permanent wilting percentage.

Term 2 in equation 3.3 accounts for the addition of moisture due to precipitation and the depletion due to evapotranspiration (ET). The top-zone experiences moisture depletion from evaporation and transpiration. Thus, C_1 (equation 3.3) sets the fraction of evapotranspiration that is attributed to the top-zone: C_1 is a function of the L_A:

$$C_1 = \cos\left(\frac{L_A \pi}{2.7}\right) \qquad \textbf{(3.4)}$$

With $1.0 \geq C_1 \geq 0.4$ for $0 \leq L_A \leq 1.0$

Where

L_A refers to the fractional leaf area and is a function of growing degree-days above 5°C using the following relationship for canola (Morrison et al 1989):

Planting to Emergence:
0 – 98 GDD: $L_A = 0$ **(3.5)**
Seedling to Full Canopy:
98 – 354 GDD: $L_A = (GDD - 98)/(354 - 98)$ **(3.6)**
5 Leaves to Flowering Complete:
354 – 863 GDD: $L_A = 1.0$ **(3.7)**
Seeds Translucent to all Seeds Brown:
863 – 1157 GDD: $L_A = 1.0 - [(GDD - 863)/(1157 - 863)]$ **(3.8)**

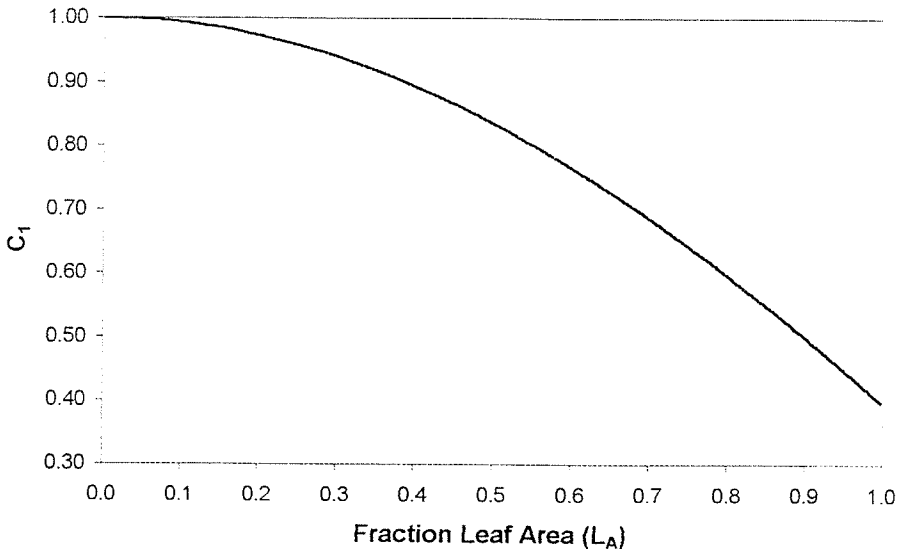


Figure 3.3 C_1, the portion of ET coming from the top-zone, as a function of fractional leaf area (L_A).

When $L_A = 0$, then all of ET (i.e. E_E) comes from the top-zone. When $L_A = 1$ (i.e. E_T), then 40% of ET comes from the top-zone.

Term 3, in equation 3.3 represents the equalization of water between the root-zone to the top-zone as the top-zone dries out. Thus, C_2 is the proportionality constant by which water content difference is multiplied to simulate the rate of upward movement of water. It is a function of hydraulic conductivity which in turn is a function of soil texture. The coefficient C_2 is a function of the root-zone water content (Ω), given by:

$$C_2 = \frac{C_{ref}\,\Omega}{(\Omega_S - \Omega + 0.0001)} \qquad \textbf{(3.9)}$$

Where

C_{ref} is a reference coefficient that is a function of soil textural class (Noilhan and Planton 1989),
Ω_S is volumetric root-zone soil moisture at saturation,
0.0001 is a numerical term used to limit the value of C_2 if the root-zone soil moisture is at or near saturation.

3.3 Evapotranspiration

Evapotranspiration, ET, may be defined as the upward flux of water through surface layers of the atmosphere. It is the combined loss of water through evaporation and transpiration. As described above, the proportion that each contributes to total evapotranspiration is contingent upon the amount of vegetative cover. In this model, the transpiration E_T from the crop and the evaporation flux, E_E, from bare soils are resolved separately and added to give total evapotranspiration (ET). Although the evapotranspiration rate is controlled by several factors, this model uses the vapour density deficit modulated by canopy resistance (r_c), atmospheric resistance (r_a), and soil resistance (r_g) as shown in equation 3.10.

Term 1 **Term 2**

$$\boxed{ET}\ \text{Evapotranspiration} = \underbrace{\frac{(L_A)[\rho(T_0) - \rho(Td_0)]}{(r_a + r_c)}}_{\text{Transpiration}} + \underbrace{\frac{(1 - L_A)[h\rho(T_0) - \rho(Td_0)]}{(r_a + r_g)}}_{\text{Evaporation}} \qquad \textbf{(3.10)}$$

Where

ET is evapotranspiration,
L_A is fractional leaf area (determined from crop type and stage),
$\rho(T_0)$ is saturated vapour density at current air temperature (T_0),
$\rho(Td_0)$ is actual vapour density of air, where Td_0 is the dew point temperature,
h is relative humidity of a laminar layer next to the soil (expressed as a fraction),
r_a is atmospheric resistance,
r_c is canopy resistance,
r_g is soil resistance.

Total evapotranspiration is a function of (1) atmospheric demand determined by weather variables which transport water vapour away from the crop by bulk air, and, (2) the amount of water available for transport (supply).

The fractional leaf area is used to partition evaporation ($1 - L_A$) and transpiration (L_A).

3.3.1 Transpiration

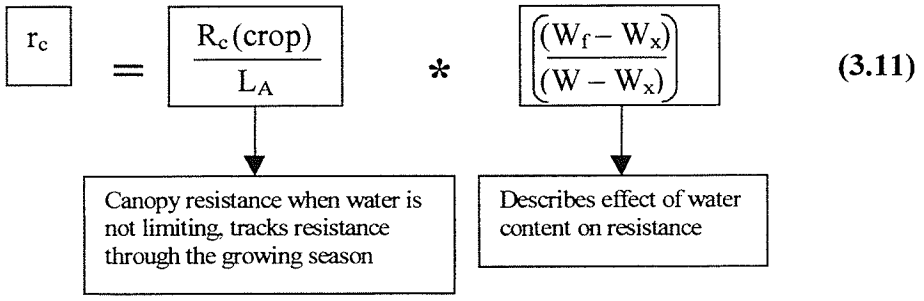
Transpiration accounts for the largest part of water loss to the atmosphere. Leaf stomata regulate the movement of water through the soil-plant-atmosphere continuum. Term 1 in equation 3.10 uses the vapour density deficit to simulate the drying power of the air relative to a saturated surface such as a leaf stomate (Oke 1987). It represents the amount of vapour necessary to achieve saturation if the temperature were held constant. The larger the deficit, the greater is the vapour density gradient to drive evapotranspiration (ET) at the surface (assuming the air and surface have approximately the same temperatures) (Oke 1987).

The expanding and then eroding proportion of the ground covered by vegetation L_A allows canopy resistance (r_c) to vary with crop stage. The greater the leaf area (L_A), the more stomata there are contributing to transpiration, and therefore the lower the canopy resistance (r_c).

The resistance to the flux of water through transpiration is limited by the combined atmospheric (r_a) and a bulk canopy resistance (r_c). Canopy resistance characterizes the physiological control of water loss by the entire plant community, rather than at the individual leaf level. An atmospheric resistance term (r_a) is used to modulate the vertical flux of water vapour into the atmospheric boundary layer. Atmospheric

resistance is dependent on the wind speed, surface roughness, and atmospheric stability (Oke, 1987). This model uses a stability adjusted aerodynamic resistance term.

Canopy resistance is at a minimum when the fractional leaf are equals 1.0 and the soil moisture is at field capacity. The resistance increases as the soil moisture decreases. The canopy resistance by soil moisture status is determined using the following relationship:



(3.11)

Where

r_c is canopy resistance,
W is water content of root-zone with subscripts f and x representing field capacity and permanent wilting percentage, respectively.

3.3.2 Evaporation

The evaporation term (term 2, equation 3.10) assumes that soil surface temperature is equal to air temperature. Modeling verification has only occurred when soils are cropped, therefore, information regarding bare soils is less certain. For evaporation, the vapour density difference between the air's actual value $\rho(Td_o)$ and the saturated value $\rho(T_o)$ at the air temperature is the driving force. The vapour density in the laminar layer will fall relative to that over a water surface when the water content in

the surface soil falls below field capacity (Phillip 1957). Relative vapour density is related to soil water potential by:

$$h = \exp(g\psi/R_w T_o) \quad \textbf{(3.12)}$$

Where

h is relative humidity fraction,
g is acceleration due to gravity (9.8 $m*s^{-2}$),
ψ is soil surface capillary potential (from Cosby et al. 1984),
R_w is the gas constant for water vapour (461.5 $J*kg^{-1}\ K^{-1}$),
T_o is air temperature ^oK.

The surface soil's water potential was approximated by the top-zone value give by:

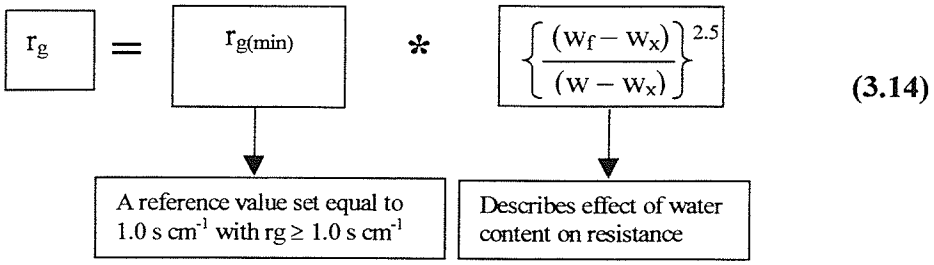
$$\psi = \psi_s (\omega_s/\ \omega)^b \quad \textbf{(3.13)}$$

Where

ψ is the current surface soil's water potential,
ψ_s is water potential at saturation,
ω_s is volumetric water content at saturation,
ω is volumetric water content, and
b is a soil texture dependent constant

Volumetric water contents at saturation (ω_s) for a number of soils have been determined by Wetzel and Chang (1987), and the power b, have been determined by Cosby et al. (1984) for eleven textural classes (Table 4.12).

A resistance to water movement through the soil (r_g) also occurs in the top-zone. This resistance is parameterized using a similar method to that of Wetzel and Chang (1987), in which evaporation rate is modulated by the water uptake:



(3.14)

With

r^g is r^g (min) when w (water content of the top-zone), was at field capacity with the subscripts f and x representing field capacity and permanent wilting percentage, respectively.

3.4 Role of Heat Units in the Canola Phenology and Water-Use Model

The development of a specific heat unit for predicting canola phenology is an important component of the Canola Phenology and Water-Use Model. Firstly, a heat unit accumulation – GDD above 5°C - is utilized to estimate the dynamic nature of the root-zone depth. Fractional leaf area (L_A) is also estimated from accumulated GDD above 5°C. L_A is an essential component of the model, because it partitions evaporation and transpiration flux in the soil-plant-atmosphere continuum (equations 3.3 and 3.11). L_A is a major factor in determining canopy resistance (equation 3.11) which in turn determines transpiration (equation 3.10). In addition, L_A (used via C_1 in equation 3.4) is employed in the top-zone water balance equation which models soil moisture and is used in assessing the risk of sclerotinia. In order to improve the estimate of L_A, a more accurate heat unit system for canola phenology needs be devised. An improvement in predicting phenology could improve the Canola Phenology and Water-Use Model. This would provide improved estimates of top-zone soil moisture, which is an integral component of the sclerotinia risk forecast model currently used on the Canadian Prairies.

4.0 MATERIALS AND METHODS

4.1 Project Design

The objective of this project was to develop a method of estimating phenological development and fractional leaf area of canola from air temperature measurement. To achieve the project's objectives, weekly field observations were made throughout the 1999 and 2000 growing season (approximately May 25 to October 1, 1999 and May 19 to September 20, 2000) to determine the stage of crop development, the amount of ground cover, and the soil moisture in the top 10 cm. Emergence counts were made on a more frequent basis, every 2 to 3 days where possible. Temperature data (daily maximum, and daily minimum) were obtained from the nearest Environment Canada weather station.

4.2 Field Site Locations

Five test sites within Agro-Manitoba (in collaboration with Aventis Crop Science) were used during the 1999 growing season, while three test sites were used in 2000 (Table 4.1 and Figure 4.1). The north to south distribution in site locations was selected to provide variation in growing degree-days and photoperiod.

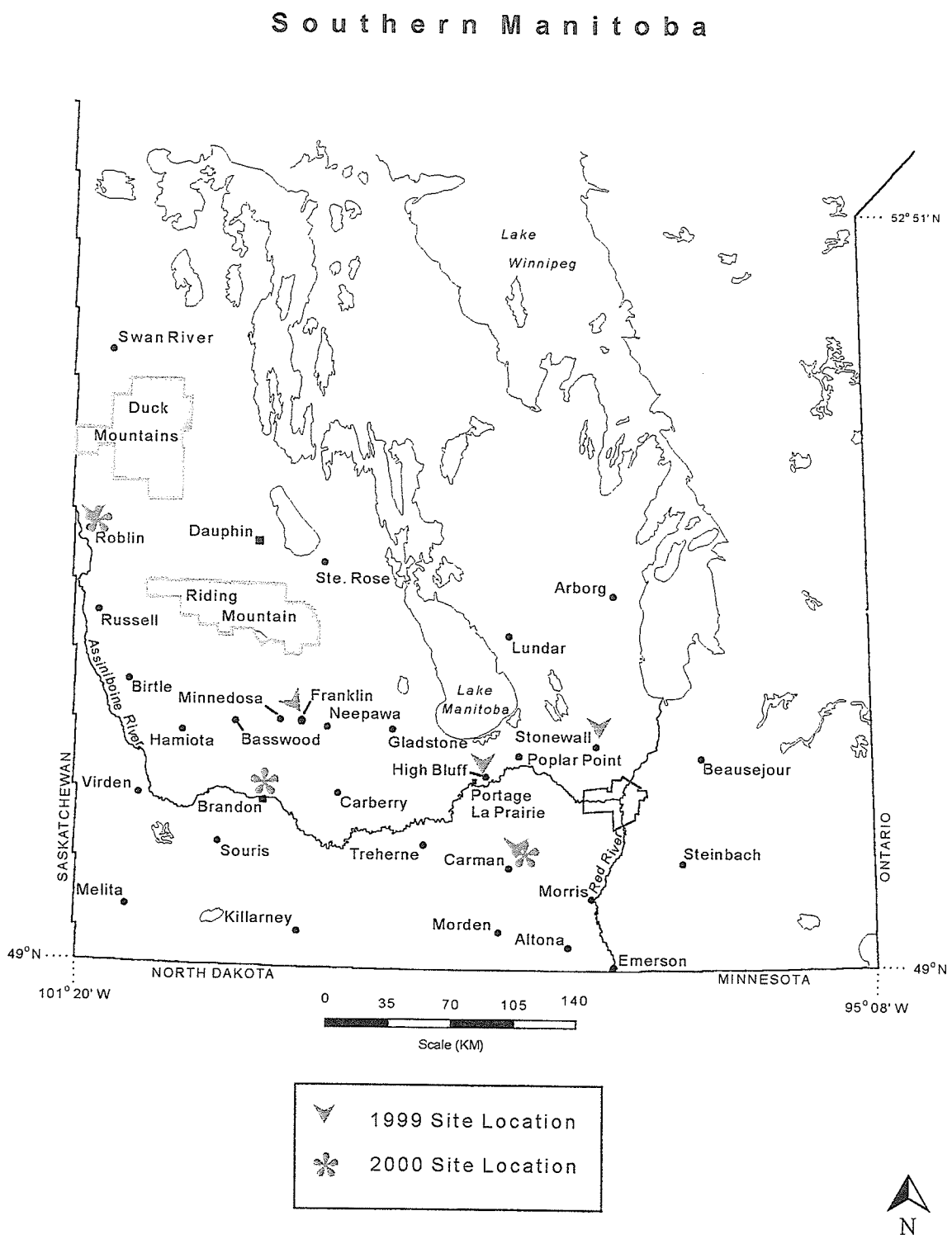
Table 4.1 Site locations for the 1999 and 2000 growing season in Southern Manitoba.

Site	Location					
	1/4 Sec	Sec	Twp	Range	Latitude	Longitude
Brandon (2000)	NE	2	12	19 W	49 ° 59'N	99° 58' W
Carman 1999	SE	9	6	4 W	49° 28'N	97° 50' W
Carman 2000	NE	32	6	4 W	49° 31' N	97° 57'W
Franklin (1999)	NW	18	15	16 W	50° 18' N	99° 41' W
High Bluff (1999)	NE	14	12	6 W	50° 01' N	98° 10' W
Roblin 1999	NE	20	25	28 W	51° 10' N	101° 21' W
Roblin 2000	NW	20	25	28 W	51 ° 10 N	101° 22' W
Stonewall (1999)	NW	22	13	1 E	50 ° 07 N	97° 22' W

4.2.1 Climate and soils of Agro-Manitoba

Soils in Manitoba are predominantly Black Chernozems and have a high agricultural potential. The agricultural region of Manitoba is situated in the southern portion of the province (Figure 4.1). This area is frequently referred to as the Prairies and is characterized by a semi-arid to sub-humid climate. In Manitoba, the prairies consist predominantly of grasslands and parklands (Scott 1995). The sites used in this study fall within the Grassland ecoregion and more specifically the transitional grassland area (Scott 1995). The natural vegetation consists of grasslands which include tall-grass prairie and aspen parkland (Scott 1995).

The grasslands area is characterized by temperature extremes due to its continental location. Winters tend to be very cold while summers are typically very hot. Annual temperature ranges are typically large. Precipitation is often the limiting factor in agricultural production and aridity typically increases in a westward progression across the Canadian prairies.



Source: Soil Survey and Mapping, Manitoba Agriculture

Figure 4.1 Site locations in southern Manitoba.

4.2.2 Brandon Climate and Soils

The Brandon site was situated above the Manitoba Escarpment on gently undulating topography. The predominant soil type is a clay loam belonging to the Newdale association. The average growing season (May 1 to August 30) growing degree-days (GDD) above 5°C is 1343.1 GDD (Table 4.2). In 2000, GDD for the growing season totaled 1228.6 GDD, 91.5% of normal. Normal growing season precipitation is 256.7 mm (Table 4.2). In 2000 there was 296.40 mm of precipitation, 141.36 % of normal. Month by month temperature, GDD, and precipitation are given in Table 4.2.

4.2.3 Carman Climate and Soils

Carman 1999 and Carman 2000 were both situated below the Manitoba Escarpment on extremely level topography. The predominant soil type is a fine loam belonging to the Altona Association for Carman 1999 and a very fine sandy loam belonging to the Almassippi Association for Carman 2000. In the growing season (May 1 to August 30) average GDD above 5°C is 1424.4 (Table 4.3). In 1999, GDD for the growing season totaled 1376.15 GDD, 96.6% of normal. Average growing season precipitation is 260.1 mm (Table 4.3). In 1999, 331.20 mm of precipitation accumulated, 127.3% of normal. Also in 2000, GDD for the growing season totaled 1342.15 GDD, which is 94.2% of normal. In 2000, 281.20 mm of precipitation was accumulated during the growing season, 108.1% of normal. Month by month temperature, GDD, and precipitation are given in Table 4.2.

Table 4.2 Growing season climate normals and mean monthly climate for Brandon, MB (Environment Canada).

WEATHER STATION		MAY		JUN		JUL		AUG		GROWING SEASON TOTALS	
		Normal	2000	Normal	2000	Normal	2000	Normal	2000	Normal	2000
Brandon A (1941 to 1990)	Daily Max (°C)	18.2	18.01	23.2	19.21	25.8	25.11	24.9	24.53		
	Daily Min (°C)	3.7	3.54	9.1	7.04	11.6	9.51	10.1	10.47		
	Daily Mean (°C)	11	10.78	16.2	13.13	18.7	18.50	17.5	17.50		
	Precipitation (mm)	48.4	54.80	66.9	63.00	72.1	133.00	69.3	45.60	256.7	296.40
	% of Normal		113.22		94.17		184.47		151.97		141.36
	GDD above 5 °C	194.7	178.75	335.4	243.75	425.5	418.60	387.5	387.50	1343.1	1228.6
	% of Normal		91.81		72.67		98.38		100.00		91.5

Table 4.3 Growing season climate normals and mean monthly climate for Carman, MB (Environment Canada).

Station		MAY			JUN			JUL			AUG			GROWING SEASON TOTALS		
		Normal	1999	2000	Normal	1999	2000	Normal	1999	2000	Normal	1999	2000	Normal	1999	2000
Graysville (1925-1988)	Daily Max (°C)	19.3	16.98	18.74	24.4	22.09	19.97	26.8	24.66	25.26	25.7	24.91	25.54			
	Daily Min (°C)	3.9	6.61	4.25	9.7	9.99	9.19	12.4	12.91	10.95	10.5	11.34	11.82			
	Daily Mean (°C)	11.5	11.79	11.50	17.1	16.04	14.58	19.6	18.79	18.96	18.1	18.13	18.68			
	GGD	216	210.60	198.10	354.6	331.20	287.45	454.6	427.45	432.65	399.2	406.90	423.95	1424.4	1376.2	1342.2
	% of Normal		97.50	91.71		93.40	81.06		94.03	95.17		101.93	106.20		96.6	94.2
Carman (1964 to 1990)	Precipitation (mm)	52.7	141.10	55.00	72.8	73.40	93.40	69.1	83.20	46.80	65.5	33.50	86.00	260.1	331.20	281.20
	% of Normal		267.74	104.36		100.82	128.30		120.41	67.73		51.15	76.16		127.3	108.1

4.3.4 Franklin Climate and Soils

The Franklin site was situated above the Manitoba Escarpment on irregular gently to steeply sloping topography. The predominant soil type is a clay loam belonging to the Newdale association. The soils above the escarpment tend to be well-drained (Ehrlich et al. 1958). The growing season (May 1 to August 30) average GDD above 5°C is 1402.5 GDD. In 1999, GDD for the growing season totaled 1353.15 GDD, 96.5% of normal. Growing season precipitation normal is 270.9 mm and in 2000, 432.10 mm of precipitation accumulated, 159.5% of normal. The mean monthly normal and 1999 values for the growing season are found in Table 4.4. The precipitation in May 1999 is of particular note because 231.60 mm of precipitation fell, 469.8% of normal.

4.3.5 High Bluff Climate and Soils

The topography of the High Bluff site is relatively flat, gently sloping to the east at about 0.07 % slope (Michalyna and Smith 1972). The predominant soil type at the site was a clay loam belonging to the Hobson Association. The average growing season (May 1 to August 30) GDD above 5°C for Portage la Prairie is 1451.3 GDD (Table 4.5). In 1999, GDD for the growing season totaled 1371.5 GDD, 94.5% of normal. Growing season precipitation normal is 287.5 mm (Table 4.5) and in 1999, 343 mm of precipitation accumulated, 119.3% of normal. Month by month temperature, GDD, and precipitation are given in Table 4.5.

Table 4.4 Growing season climate normals and mean monthly climate for Franklin, MB (Environment Canada).

WEATHER STATION		MAY		JUN		JUL		AUG		GROWING SEASON TOTALS	
		Normal	1999	Normal	1999	Normal	1999	Normal	1999	Normal	1999
Neepawa Water (1969 to 1990)	Daily Max (°C)	17.9	15.97	22.6	20.82	25.3	24.23	24 1	24.41		
	Daily Min (°C)	5.2	6.61	10.7	10.17	13.1	11.89	11 6	12.10		
	Daily Mean (°C)	11.6	11.29	16.7	15.49	19.2	18.90	17 9	18.25		
	Precipitation (mm)	49.3	231.60	75.7	59.00	76.6	84.10	69 3	57.40	270.92	432.10
	% of Normal		469.78		77.94		109.79		82.83		159.5
	GDD above 5 °C	212.2	196.75	350.3	314.75	440.3	430.75	399 7	410.90	1402.5	1353.15
	% of Normal		92.72		89.85		97.83		102.80		96.5

Table 4.5 Growing season climate normals and mean monthly climate for High Bluff, MB (Environment Canada).

STATION		MAY		JUN		JUL		AUG		GROWING SEASON TOTALS	
		Normal	1999	Normal	1999	Normal	1999	Normal	1999	Normal	2000
Portage La Prairie A (1941 to 1990)	Daily Max (°C)	18.3	16.52	23.4	21.11	26.1	24.56	25	24.01		
	Daily Min (°C)	4.8	6.63	10.7	10.21	13.5	13.61	11.8	12.52		
	Daily Mean (°C)	11.6	11.57	17.1	15.66	19.8	19.09	18.4	18.26		
	Precipitation (mm)	56.8	124.80	75	73.00	76.9	80.20	78.8	65.00	287.5	343
	% of Normal		219.72		97.33		104.29		82.49		119.3
	GDD above 5 °C	213.3	203.80	362.2	319.90	459.9	436.65	415.9	411.15	1451.3	1371.5
	% of Normal		95.55		88.32		94.94		98.86		94.5

4.3.6 Roblin Climate and Soils

Roblin 1999 and Roblin 2000 were both situated on the crest of a gently undulating slope typical in this area. The predominant soil type is a clay loam belonging to the Erickson Association for both years. The average growing season (May 1 to August 30) growing degree-days (GDD) above 5°C for Russell is 1266.4 GDD (Table 4.6). Data for Russell 50 kilometers south of Roblin were used for normals because there was insufficient length of record at Roblin to calculate normals. In 1999, GDD for the growing season totaled 1147.30 GDD, 90.6% of normal. Growing season precipitation normal is 253.7 mm (Table 4.6) and in 1999, 279.30 mm of precipitation accumulated, 110.09% of normal. In 2000, GDD for the growing season totaled 1118.65 GDD, 88.33% of normal. In 2000, 220.8 mm of precipitation was accumulated during the growing season, 87.03% of normal. Month by month temperature, GDD, and precipitation are given in Table 4.6.

4.3.7 Stonewall Climate and Soils

The predominant soil type of the Stonewall site was a fine sandy loam belonging to the Lakeland Association. The terrain has a smooth to very gently sloping topography. The average growing season (May 1 to August 30) growing degree-days (GDD) above 5°C is 1412.4 GDD. In 1999, GDD for the growing season totaled 1473.10 GDD, 104.3% of normal. Growing season precipitation normal is 297.9 mm (Table 4.7) and in 1999, 284.90 mm of precipitation accumulated, 95.64% of normal. Month by month temperature, GDD, and precipitation are given in Table 4.7.

Table 4.6 Growing season climate normals and mean monthly climate for Roblin, MB (Environment Canada).

STATION		MAY			JUN			JUL			AUG			GROWING SEASON TOTALS		
		Normal[z]	1999	2000	Normal[z]	1999	2000	Normal[z]	1999	2000	Normal[z]	1999	2000	Normal[z]	1999	2000
Roblin	Daily Max (°C)	16.7	15.28	16.54	21.7	19.47	18.41	24.4	22.49	23.78	23.4	22.94	22.06			
	Daily Min (°C)	4	4.76	3.55	9.2	8.54	6.57	11.7	9.69	11.55	10.2	9.99	9.78			
	Mean Monthly (°C)	10.4	10.02	10.04	15.5	14.00	12.49	18.1	16.65	17.66	16.7	16.46	15.92			
	Precipitation (mm)	45.9	96.30	23.40	73.1	117.80	76.60	69.9	28.00	59.40	64.8	37.20	61.40	253.7	279.30	220.8
	% of Normal[z]		209.80	50.98		161.15	104.79		40.06	84.98		174.19	94.75		110.09	87.03
	GDD above 5°C	179.8	160.85	162.70	314.2	270.10	224.75	407.3	361.00	392.60	365.1	355.35	338.60	1266.4	1147.30	1118.65
	% of Normal[z]		89.46	90.49		85.96	71.53		88.63	96.39		97.33	92.74		90.6	88.33

[z] Normal Period is from Environment Canada Weather station in Russell, Manitoba

Table 4.7 Growing season climate normals and mean monthly climate for Stonewall, MB (Environment Canada).

STATION		MAY		JUN		JUL		AUG		GROWING SEASON TOTALS	
		Normal	2000	Normal	2000	Normal	2000	Normal	2000	Normal	2000
Stonewall (1959 to 1990)	Daily Max (°C)	18.6	17.60	23.4	22.08	25.7	25.90	24.6	25.02		
	Daily Min (°C)	4.4	7.06	10.1	11.32	12.7	12.39	11	13.02		
	Daily Mean (°C)	11.5	12.33	16.8	16.70	19.2	19.67	17.8	19.02		
	Precipitation (mm)	60	96.30	81.1	54.90	80.4	75.80	76.4	57.90	297.9	284.90
	% of Normal		160.50		67.69		94.28		131.95		95.64
	GDD above 5°C[y]	204.8	232.75	351.7	351.00	457.6	454.75	398.3	434.60	1412.4	1473.10
	% of Normal		113.65		99.80		99.38		109.11		104.3

[y] GDD comes from the Winnipeg International Airport Environmental Canada Weather Station

4.3 Plot Description

4.3.1 Plot dimensions

Two cultivars of Argentine canola, InVigor 2273 (*Brassica napus* L. cv. 2273) and Quantum (*Brassica napus* L. cv. Quantum), were seeded adjacently at each site (see Appendix A for variety descriptions). Plot dimensions and orientation were determined by the amount of space available (Table 4.8).

Table 4.8 Plot dimensions and seeding dates.

Site	Year	Width (m)	Rows	Length (m)	Seeded (date)
Brandon	2000	4.00	16	28.00	19-Jun-00
Carman 1999	1999	3.00	12	14.50	26-May-99
Carman 2000	2000	4.00	16	35.00	19-May-00
Franklin	1999	3.00	12	18.00	01-Jun-99
High Bluff	1999	12.00	32	20.00	01-Jun-99
Roblin 1999	1999	1.60	7	26.50	11-Jun-99
Roblin 2000	2000	3.20	14	10.00	29-May-00
Stonewall	1999	3.00	12	15.00	03-Jun-99

4.3.2 Seeding Procedures

The sites were seeded with small plot seeders, except for the High Bluff site which was seeded with a regular drill seeder. All sites were seeded and managed by Aventis Crop Science, except for Roblin, which was seeded and maintained by the Prairie Crop Diversification Center. Typical seeding rates, fertilizer application, and management practices were employed (Table 4.9).

Table 4.9 Site agronomic information.

Site	Seeding Date	Row Spacing (cm)	Seeding Rate (lbs/acre)	Seeder	Seeding Depth (cm)
Brandon	19-Jun-00	25.00	Na[z]	Precision seeder	Na[z]
Carman 1999	26-May-99	25.00	Na[z]	Precision seeder	Na[z]
Carman 2000	19-May-00	25.00	Na[z]	Precision seeder	Na[z]
Franklin	01-Jun-99	25.00	Na[z]	Precision seeder	Na[z]
High Bluff	01-Jun-99	25.00	Na[z]	Drill	Na[z]
Roblin 1999	11-Jun-99	20.00	7	Small Plot seeder/hoe drill	3.75
Roblin 2000	29-May-00	20.00	7	Small Plot seeder/hoe drill	2.5
Stonewall	03-Jun-99	25.00	NA[z]	Precision Seeder	Na[z]

[z] not available.

4.4 Parameters Measured

4.4.1 Emergence Determination

At all locations, except High Bluff; one-meter sections were chosen randomly and marked with stakes (Figure 4.2). The number of emerged plants in a one-meter section was counted as often as possible until the population stabilized. A plant was considered emerged when both cotyledons were visible (Figure 4.3). At High Bluff, the distance between the stakes was measured and the number of plants per one-meter was calculated. The percentage emergence was then calculated for each variety based on the number of plants emerged when the population had stabilized (Appendix B). This information was plotted on probability graph paper (assuming a normal distribution) and the date of 50% emergence was calculated (Table 4.10).

Figure 4.2 Plot in Carman 1999, showing stakes for emergence counts.

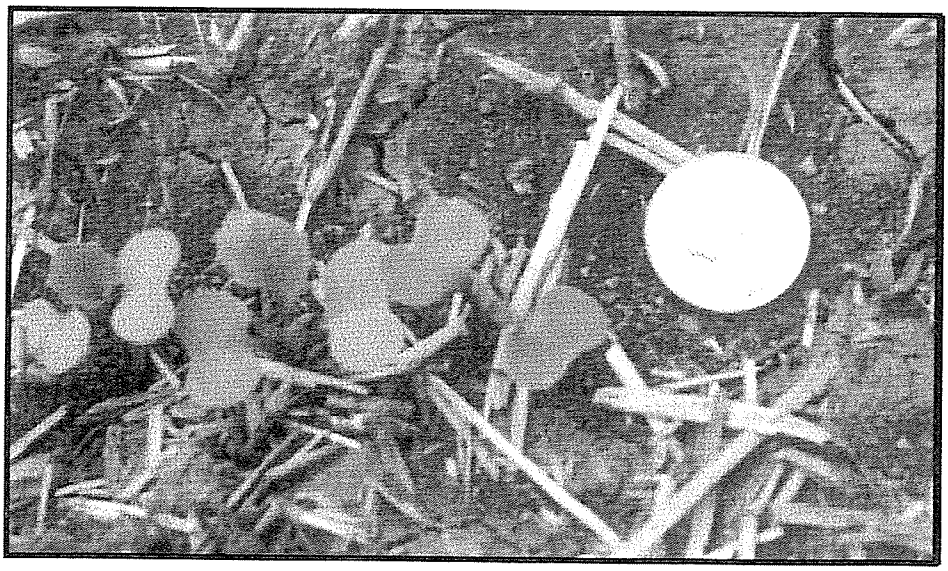


Figure 4.3 Cotyledons completely emerged.

Table 4.10 Date of 50% emergence.

Site	Cultivar	Date of 50% Emergence
Brandon	Quantum	NA[z]
	2273	NA[z]
Carman 1999	Quantum	June 3, 1999
	2273	June 3, 1999
Carman 2000	Quantum	May 27, 2000
	2273	May 27, 2000
Franklin	Quantum	June 7, 1999
	2273	June 7, 1999
High Bluff	Quantum	June 6, 1999
	2273	June 7, 1999
Roblin 1999	Quantum	June 21, 1999
	2273	June 21, 1999
Roblin 20000	Quantum	June 4, 2000
	2273	June 4, 2000
Stonewall	Quantum	June 10, 1999
	2273	June 10, 1999

[z]Flea beetle damage to cotyledons prevented accurate emergence counts.

4.4.2 Phenology

The transects initially established for the emergence counts were used in order to determine the phenology. Phenology was assessed on a weekly basis. Five plants in close proximity to each transect were chosen randomly and evaluated as to the crop stage using the growth stage key used by the Canola Council of Canada (Table 2.2 and Figure 2.4). The same plants were not used every time the phenology was assessed and the transects were used as an approximate location.

4.4.3 Fractional Leaf Area Measurements

Ground cover measurements were taken on a weekly basis as soon as plant population had stabilized based on the emergence counts. Observations made during the 1999 growing season did not begin until well after plant population stabilization due to initial setup difficulties.

The percentage ground cover was evaluated from photographs using a Single Lens Reflex (SLR) 35-mm camera (Pentax MX^Z) mounted on an adjustable extensor pole (Figure 4.4). The camera was mounted on the pole at an angle so that when the pole was fully extended, the camera would be perpendicular with the ground (Figure 4.4). A brace was built so that the approximate angle of the pole would remain constant and the camera would remain at a level position (Figure 4.4). Difficulties in maintaining a level camera position were encountered as a result of wind causing the pole to bend. This was compensated for by having a second person indicate when the camera was approximately level. A 20-foot air cable release was used to take the picture. Stakes were semi randomly placed at the edge of the plot so that the brace could be butted up against them and the pictures could be snapped at the same location each week. The phenology assessment locations were purposely avoided because these areas experienced heavy trampling. Three ground cover pictures for each variety were taken as part of the weekly field observations.

A manual SLR camera was chosen because of the flexibility with respect to focusing, depth of field, exposure, and shutter speed. The focusing was adjusted using the height of the camera above the crop. The focusing ring on all SLR lenses is engraved with a distance scale (point of focus indicator or distance indicator) which can be used to focus

the camera when the approximate distance from the camera to the subject is known (Grimm and Grimm, 1974).

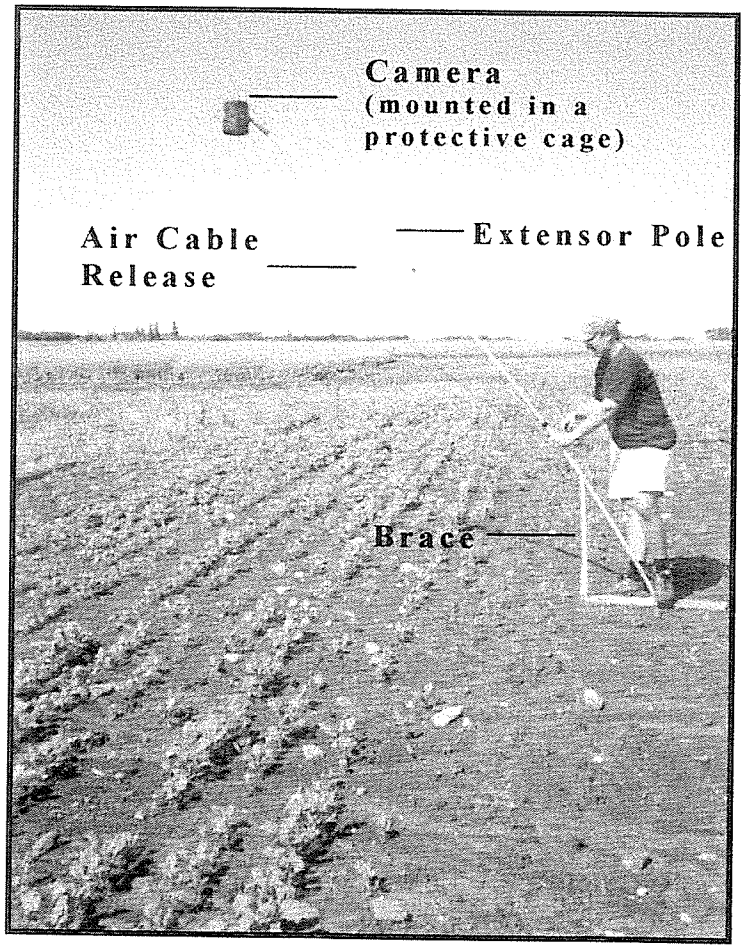


Figure 4.4 Fractional leaf area evaluation using a SLR camera, Brandon, MB, 2000.

As the crop grew, the distance between the camera and the crop decreased and thus the focus was easily adjusted in order to compensate for crop growth. A high shutter speed of 1/60 to 1/500 second was required in order to capture the ground cover of crop in a still position. This was essential in order to obtain a clear picture, otherwise the wind and the person holding the pole would cause the camera to shake in addition to the natural movement of the crop from wind. A faster film speed was used (400 ISO) even in

bright sunshine in order to maintain a high shutter speed. This allowed an F-stop between 22-8 to be used so that the depth of field would be adequate in order to clearly capture the ground cover. By maintaining a good depth of field, the focusing of the camera was substantially easier because the camera would be in focus for a specified range, and therefore, the exact distance from the camera to the crop was not needed, and an estimation was sufficient.

The pictures (10 cm * 15 cm) were digitally scanned using a resolution of 100 dpi and the fractional leaf area was analyzed using an image analysis program, Assess (Formerly ImageX32 for Windows (Lamari 2002) (Figure 4.5). This program separated the green cover from the ground using hue. The appropriate pixels were selected using a user-defined threshold. Leaf area was determined using this method until the crop reached stage 5.2. Beyond this stage, the L_A was more a function of pods and stems which would be photosynthetically inactive. Although the determination of fractional leaf area in this manner is still a visual assessment, this method had three main advantages compared to traditional sampling techniques:

(1) Ground cover was assessed in a non-destructive manner. Traditional techniques require the researcher to make evaluations directly within the plot itself. Since canola is highly susceptible to damage, sampling fractional leaf area from in the plot itself would bias the results.

(2) A complete record was obtained over the growing season, and the pictures are easily archived.

(3) Fractional leaf area did not have to be assessed immediately. Pictures could be taken and analyzed later.

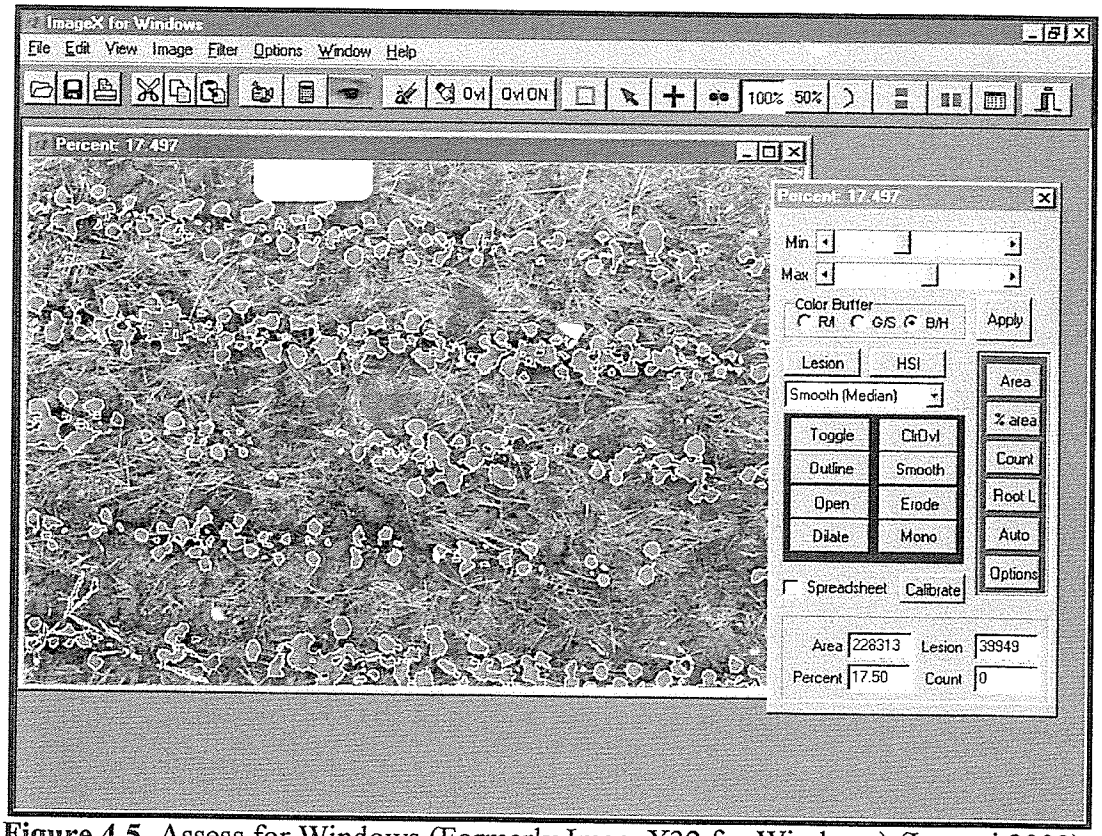


Figure 4.5 Assess for Windows (Formerly ImageX32 for Windows) (Lamari 2002) and fractional leaf area picture analysis.

4.4.4 Meteorological Data

4.4.4.1 Temperature and Rainfall

Temperature data was obtained from the nearest Environment Canada station (Table 4.11). Daily maximum and minimum temperatures were obtained. Rainfall was obtained on-site at the Roblin 1999 and 2000 sites from the Environment Canada station, while rainfall data was obtained on site using a Belfort Universal Precipitation Gage (Series 5-780/5195) at Carman 1999, Carman 2000, Stonewall (1999), Franklin (1999), and Brandon (2000).

Table 4.11 Environment Canada station locations.

Site	Station Name	ID	Data Type	Latitude	Longitude
Brandon	Brandon A (YBR)	5010480	Max/Min	49 ° 55' N	99° 57' W
Carman 1999	Carman U of M CS (WNK)	502I001	Max/Min	49° 30' N	98° 02' W
Carman 2000	Carman U of M CS (WNK)	502I001	Max/Min	49° 30' N	98° 02' W
Franklin	Neepawa Water (XNE)	5042005	Max/Min	50° 3' N	99° 28' W
High Bluff	Portage la Prairie CDA (YPG)	5012321	Max/MIn	49° 57' N	98° 16' W
Roblin 1999	Roblin (WXB)	5012469	Max/Min	51° 11' N	101° 22' W
Roblin 2000	Roblin (WXB)	5012469	Max/Min	51° 11' N	101° 22' W
Stonewall	Stoney Mountain (ST0)	5022790	Max/Min	50 ° 04' N	97 ° 14' W

4.4.5 Available Water Holding Properties of Soils

4.4.5.1 Field Capacity

Field Capacity may be defined as "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased, which usually takes place 2-3 days after a rain or irrigation in pervious soils of uniform structure and texture" (Veihmeyer and Hendrickson 1949).

A one-meter square location close to the plot location was selected at each site. A perimeter of soil was mounded up approximately 15 cm high to form a ring dyke around the one-meter square area. The area inside the ring dike was flooded with approximately 10 cm of water (eight 20 liter water jugs). Water was poured on to a piece of plastic so the falling water would not impact the soil surface and alter its a priori state. The water was allowed to infiltrate and the plot was covered with a piece of plastic to

prevent evaporation. Soil was placed around the edge of the plastic to secure it. The water was then allowed to redistribute for three days.

Following three days, the area was sampled for soil moisture and bulk density utilizing the method described by Zwarich and Shaykewich (1969). Soil was sampled at 15 cm increments using an Iwan type auger. The volume of the increment was calculated from measurements of the depth of the increment (using a meter stick placed in the same location for each subsequent measurement) and diameter (using a caliper) of the hole to the nearest millimeter. The wet soil from each 15 cm increment was weighed using a portable digital balance (precision ± 1 g). A sample of approximately 300 g was retained for moisture content analysis, weighed wet using a digital balance (precision ± 0.01 g) and was dried in an oven at 110°C to constant weight in order to determine the gravimetric moisture content. The moisture content in the sample divided by its dry weight gave the gravimetric moisture content (ω).

$$\omega = \text{weight of water/dry weight of soil} \qquad \textbf{(4.1)}$$

The gravimetric moisture content of the sample and the total wet weight of the soil removed from the hole was used to calculate the total dry weight of soil removed from the hole.

$$\text{total dry weight of soil} = \text{total wet weight of soil}/(1 + \omega) \qquad \textbf{(4.2)}$$

The bulk density (B.D.) was then calculated using the dry weight of all the soil removed from the 15 cm increment divided by the volume.

$$\text{B.D.} = \text{dry weight/volume} \qquad \textbf{(4.3)}$$

Field capacity on a volume basis was obtained by multiplying the gravimetric moisture content by the bulk density.

$$\theta = \omega * B.D. * 1\ g * cm^{-3} \quad \textbf{(4.4)}$$

The soil was sampled at 15 cm increments down to 60 cm and then at 30 cm increments down to 120 cm. The procedure is replicated 4 times for each one-meter site. The results are presented as the average of four replicates for each sampling increment.

4.4.5.2 Wilting Percentage

The samples collected at the various 15 cm and 30 cm increments for the field capacity determination were used to determine the permanent wilting percentage (PWP). The replicates for each increment were combined into a composite sample. The samples were crushed using a mortar and pestle and passed through a 2 mm sieve. Plastic containers (1 cm high and 5 cm in diameter) with cloth bottoms were filled to ¾ full with soil from each increment. The samples were placed in a plastic tray and allowed to saturate with distilled water overnight. The samples were subsequently placed on a pressure membrane apparatus and a pressure of 15 bars was imposed using a tank of compressed nitrogen. A burette was attached to the pressure membrane so that the outflow of water could be monitored. When the water ceased to flow out of the samples, the samples were assumed to have reached an equilibrium at 15 bars. The pressure membrane apparatus was dismantled and the gravimetric moisture content of each sample was determined. The average of four replicates for each increment was used as the wilting percentage.

4.4.5.3 Available Water

The available water (AW) of the soil is the difference between the field capacity (FC) and the wilting percentage (PWP) expressed on a weight basis:

$$AW = FC - PWP \quad \textbf{(4.5)}$$

Available water on a volume basis (AW_θ) is calculated using the available water on a weight basis multiplied by the Bulk density.

$$AW_\theta = AW * B.D. \quad \textbf{(4.6)}$$

The amount of water available in each layer expressed as an equivalent amount of rain is given by:

$$AW_{mm} = AW_\theta * \text{depth of layer} \quad \textbf{(4.7)}$$

The mm of water in each layer is summed to give the water holding capacity expressed as mm of water in the profile.

4.4.5.4 Soil Water Parameters

The field capacity and wilting percentage values were used to classify each site into one of 12 soil textural classes as described by Wetzel and Chang (1987) in Cosby et al. (1984). The capillary potentials and volumetric water contents at saturation have been established for eleven soil texture classes given in Table 4.12 and are used in the Canola Phenology and Water-Use Model developed by Raddatz (1993). Soil at the site in question is placed into one of the eleven textural classes in which the water potential, volumetric water contents at saturation, and the subscript b have been predetermined.

Table 4.12 Soil physical parameters.

Site	Depth (cm)	B.D. ($g*cm^{-3}$)	FC ($m^3 m^{-3}$)	PWP ($m^3 m^{-3}$)	Textural Class[z]
Brandon	0 -15	1.13	0.44	0.22	11 Light Clay
	15-30	1.52	0.53	0.20	
Carman 1999	0 -15	1.16	0.35	0.18	8 Silt Clay Loam
	15-30	1.54	0.37	0.22	
Carman 2000	0 -15	1.31	0.27	0.08	6 Sandy Clay Loam
	15-30	1.44	0.27	0.08	
Franklin	0 -15	1.07	0.39	0.27	11 Light Clay
	15-30	1.26	0.36	0.27	
High Bluff	0 -15	1.08	0.36	0.22	11 Light Clay
	15-30	1.28	0.39	0.22	
Roblin 1999	0 -15	1.26	0.34	0.22	11 Light Clay
	15-30	1.42	0.32	0.18	
Roblin 2000	0 -15	1.22	0.30	0.14	7 Clay Loam
	15-30	1.46	0.31	0.12	
Stonewall	0 -15	1.29	0.34	0.26	11 Light Clay
	15-30	1.71	0.42	0.29	

[z] According to Wetzel and Chang (1987).

4.5 Evaluation of Stage of Development

The overall stage of development for each test site was determined using the percentage of each stage observed on a sampling date for 2273 and Quantum separately (Appendix C). The stage of development for each variety on an observation date was assigned using the following criteria;

(1) 40% percent or more of the plants sampled at each plot had to be at the same stage.

(2) Observations dates for which the stage of development were not obvious were not assigned a stage of development. This situation occurred when several stages of development were observed on the same date and the percentages of the crop did not meet the 40% criteria, or the percentage distribution was not distinctly different enough to establish one stage of development for the observation date. For example, this occurred when three developmental stages were observed and the percentages of the stages were 40%, 40%, and 20%.

The date of the first appearance of each observed developmental stage was determined for 2273 and Quantum at each test site (Table 4.13). Stages 1.1 and 1.2 were not included in Table in Table 4.13 as these were recorded in the emergence counts found in appendix B.

4.6 Heat Units

Heat units for the observed developmental stage were calculated using the maximum and minimum daily temperatures from the nearest Environment Canada weather station. Calendar days, growing degree-days above 5°C, and a modified P-Days equation (Table 4.14) were calculated for each site and observed stage. (See section 2.3.2.2 for equation for the general P-Days model). The coefficient of variation was calculated for each observed stage of development that was represented by five or more test sites.

The modified P-days equation will be abbreviated using the following notation:

$$\text{P-Days}_{(\text{base temperature, optimum temperature, maximum temperature})}$$

The coefficient of variation (*cv*) was determined for each heat unit system and for calendar days using the following method:

$$cv\ (\%) = \text{stdev/mean} * 100 \quad \textbf{(4.8)}$$

Where

cv is the coefficient of variation,
stdev is the standard deviation.

The coefficient of variation indicates the degree of precision and is an index of reliability of the experiment (Gomez and Gomez 1984).

Coefficients of variation were calculated for calendar days, growing degree-days above 5°C, and the modified P-Day equations listed in Table 4.14. The heat unit which had the lowest coefficient of variation was then utilized to determine if there was a difference in the phenological development between the two cultivars using a P-$Days_{(5,17,30)}$. This P-Day was used because it had the lowest average coefficient of variation. Using $Jump_{In}$ software (SAS 1996), a paired t-test comparing the number of P-$Days_{(5,17,30)}$ required to reach each observed stage of development was performed for each test site (Appendix E).

Table 4.13 Date of observed development stages.

Stage	Brandon (2000)			Carman 1999			Carman 2000		
	2273	Quantum	Site Average	2273	Quantum	Site Average	2273	Quantum	Site Average
Seeding	19-Jun	19-Jun	19-Jun	26-May	26-May	26-May	19-May	19-May	19-May
50% Emergence	NA	NA	NA	3-Jun	3-Jun	3-Jun	27-May	27-May	27-May
2.1							5-Jun	5-Jun	5-Jun
2.2	5-Jul	5-Jul	5-Jul	11-Jun	11-Jun	11-Jun	7-Jun	7-Jun	7-Jun
2.3				16-Jun	14-Jun	16-Jun		13-Jun	13-Jun
2.4	13-Jul	13-Jul	13-Jul		16-Jun				
2.5		19-Jul						22-Jun	
3.1	19-Jul	26-Jul	26-Jul	1-Jul		1-Jul	27-Jun	27-Jun	27-Jun
3.2		3-Aug	3-Aug	8-Jul	8-Jul	8-Jul	4-Jul	4-Jul	4-Jul
4.1	3-Aug	16-Aug							
4.2	9-Aug	23-Aug	9-Aug	16-Jul	16-Jul	16-Jul	12-Jul	12-Jul	12-Jul
4.3	16-Aug			22-Jul	22-Jul	22-Jul	17-Jul	17-Jul	17-Jul
4.4	23-Aug								
5.1		30-Aug					1-Aug		
5.2	30-Aug	7-Sep	30-Aug	6-Aug	6-Aug	6-Aug	8-Aug	1-Aug	1-Aug
5.3	14-Sep			19-Aug	19-Aug	19-Aug		22-Aug	22-Aug
5.4	20-Sep	20-Sep	20-Sep	25-Aug	25-Aug	25-Aug			
5.5				1-Sep	8-Sep	8-Sep	29-Aug	29-Aug	29-Aug

Table 4.13[con't]

Stage	Franklin (1999)			High Bluff (1999)			Roblin 1999		
	2273	Quantum	Site Average	2273	Quantum	Site Average	2273	Quantum	Site Average
Seeding	1-Jun	1-Jun	1-Jun	1-Jun	1-Jun	1-Jun	11-Jun	11-Jun	11-Jun
50% Emergence	7-Jun	7-Jun	7-Jun	6-Jun	7-Jun	7-Jun	21-Jun	21-Jun	21-Jun
2.1	16-Jun	16-Jun	16-Jun						
2.2	19-Jun	19-Jun	19-Jun	16-Jun	14-Jun	16-Jun	29-Jun	29-Jun	29-Jun
2.3	23-Jun	23-Jun	23-Jun		18-Jun		7-Jul		
2.4	29-Jun		29-Jun	23-Jun	23-Jun	23-Jun		7-Jul	7-Jul
2.5		29-Jun		30-Jun		30-Jun			
2.6								13-Jul	
3.1		6-Jul	6-Jul	7-Jul	7-Jul	7-Jul	20-Jul		20-Jul
3.2	13-Jul	13-Jul	13-Jul		13-Jul		26-Jul	20-Jul	26-Jul
4.1	20-Jul			13-Jul					
4.2				20-Jul	20-Jul	20-Jul	3-Aug	3-Aug	3-Aug
4.3	26-Jul	20-Jul	26-Jul		27-Jul	27-Jul	10-Aug		10-Aug
5.1	3-Aug	3-Aug	3-Aug				18-Aug	18-Aug	18-Aug
5.2	10-Aug	10-Aug	10-Aug	4-Aug	4-Aug	4-Aug	24-Aug	24-Aug	24-Aug
5.3	18-Aug								
5.4	31-Aug-	31-Aug	31-Aug	25-Aug	25-Aug	25-Aug			
5.5		22-Sep	22-Sep	31-Aug	31-Aug	31-Aug	22-Sep	22-Sep	22-Sep

Table 4.13[cont]

Stage	Roblin 2000			Stonewall (1999)		
	2273	Quantum	Site Average	2273	Quantum	Site Average
Seeding	29-May	29-May	29-May	3-Jun	3-Jun	3-Jun
50% emergence	4-Jun	4-Jun	4-Jun	10-Jun	10-Jun	10-Jun
2.1				18-Jun	14-Jun	
2.2	21-Jun	21-Jun	21-Jun		18-Jun	18-Jun
2.3	28-Jun	28-Jun	28-Jun	24-Jun		
2.4				1-Jul		
2.7				8-Jul		
3.1	5-Jul	5-Jul	5-Jul		16-Jul	
3.2	13-Jul	13-Jul	13-Jul	16-Jul		16-Jul
4.1					27-Jul	
4.2	20-Jul	20-Jul	20-Jul	22-Jul		22-Jul
4.3					6-Aug	
5.1	2-Aug	2-Aug	2-Aug	6-Aug		
5.2	9-Aug	9-Aug	9-Aug	12-Aug-	20-Aug	12-Aug
5.3	30-Aug	30-Aug	30-Aug			
5.4	7-Sep	7-Sep	7-Sep		2-Sep	2-Sep
5.5				2-Sep	9-Sep	

Table 4.14 Base, optimum, and maximum threshold temperature combinations utilized in the P-Days calculation.

Base Temperature	Optimum Temperature	Maximum Threshold Temperature
7°C	21°C	30°C
5°C	21°C	30°C
5°C	20°C	30°C
5°C	19°C	30°C
5°C	18°C	30°C
5°C	17°C	30°C
5°C	16°C	30°C
5°C	16°C	27°C
5°C	16°C	34°C
5°C	16°C	35°C
5°C	20°C	34°C
5°C	18°C	34°C
5°C	17°C	32°C
5°C	17°C	34°C

5.0 RESULTS AND DISCUSSION

5.1 Phenological Development

Weekly phenological observations were made throughout the growing season and detailed assessments for each site are found in Appendix C. Seeding dates varied from May 19 at the Carman 2000 site to June 19 at the Brandon 2000 site. The earliest appearance of the rosette (stage 2.1) occurred June 2 at the Carman 2000 site, while the latest appearance occurred June 19 at the Franklin (1999) site. The earliest occurrence of budding (stage 3.1) occurred June 22 at the Carman 2000 site an the latest was July 26 at the Brandon 2000 site. Flowering (stage 4.1) occurred earliest at Carman 2000, July 4 while the latest occurrence was at the Brandon 2000 site on August 23. The first occurrence of ripening (stage 5.1) occurred at the Carman 2000 site on July 25, while the latest appearance occurred at the Brandon 2000 site on September 7.

The coefficients of variation for heat unit accumulations at each stage of development for eleven heat units systems for cultivars 2273 and Quantum are found in Tables 5.1 and 5.2, respectively. Mean heat unit values are found in Appendix D. Heat units were calculated from planting and from 50% emergence.

A general trend for both cultivars occurred in that for the early stages of development (stages 2.2 and 2.3) and the final stage of development (5.5), the coefficient of variation was higher when thermal time was accumulated from 50% emergence then from planting. Previous studies (Shaykewich 1995, and Morrison 1988) suggest accumulating thermal time from 50% emergence would provide more accurate estimates of crop phenological development because emergence is governed by soil temperature and not by air temperature.

Table 5.1 Coefficients of variation for eleven heat unit systems for *Brassica napus* L. cv. 2273.

Heat Unit	Thermal Time Accumulation Beginning at:	STAGE										Average
		2.2	2.3	3.1	3.2	4.2	4.3	5.1	5.2	5.4	5.5	(3.1–5.4)
Calendar Days	Planting	15.62	19.69	8.91	3.44	3.61	3.27	6.55	6.50	6.18	5.91	**5.49**
	50% emergence	29.53	28.67	5.27	4.94	4.30	2.77	6.96	6.93	7.49	5.09	**5.52**
GDD above (5°C)	Planting	9.41	16.44	11.15	14.85	10.48	11.00	10.64	10.36	6.32	7.38	**10.69**
	50% emergence	16.64	12.42	10.01	6.69	7.32	5.18	10.33	8.31	4.60	9.35	**7.49**
P-Days (7,21,30)	Planting	6.54	6.76	10.72	7.44	7.48	2.78	8.34	6.44	4.52	4.66	**6.82**
	50% emergence	20.76	12.46	9.02	5.59	6.04	3.73	6.60	5.69	3.34	6.00	**5.72**
P-Days (5,21,30)	Planting	5.94	6.03	9.54	5.32	5.61	1.67	7.43	6.06	3.31	3.43	**5.56**
	50% emergence	21.31	14.84	6.77	3.64	4.21	2.24	5.96	5.42	2.62	4.52	**4.41**
P-Days (5,18,30)	Planting	6.71	8.09	9.66	4.17	4.72	1.52	7.33	6.02	3.12	3.17	**5.22**
	50% emergence	22.36	17.12	5.88	2.47	3.53	0.90	5.90	5.34	3.10	3.70	**3.87**
P-Days (5,17,30)	Planting	6.92	9.75	9.13	1.36	2.00	1.87	5.22	5.74	3.47	3.39	**4.11**
	50% emergence	22.85	18.12	5.58	2.19	3.36	0.45	5.99	5.40	3.45	3.60	**3.77**
P-Days (5,16,30)	Planting	7.69	10.20	9.87	3.70	4.43	2.32	7.50	6.18	3.30	3.76	**5.33**
	50% emergence	23.42	19.21	5.30	2.09	3.28	0.37	6.13	5.50	3.91	3.65	**3.80**
P-Days (5,19,30)	Planting	6.36	7.22	9.60	4.52	4.97	1.36	7.31	6.00	3.14	3.13	**5.27**
	50% emergence	21.94	16.24	6.18	2.84	3.74	1.37	5.87	5.33	2.84	3.92	**4.02**
P-Days (5,20,30)	Planting	6.10	6.52	9.56	4.91	5.27	1.43	7.34	6.01	3.21	3.23	**5.39**
	50% emergence	21.59	15.48	6.48	3.25	3.97	1.82	5.89	5.36	2.69	4.20	**4.21**
P-Days (5,16,27)	Planting	8.52	12.53	10.49	3.94	4.92	3.52	8.25	6.64	3.72	4.81	**5.93**
	50% emergence	24.32	20.97	5.43	2.45	3.67	1.22	6.82	5.84	4.69	4.14	**4.30**
P-Days (5,16,34)	Planting	6.87	9.19	8.89	1.41	1.71	1.70	5.06	5.68	3.32	3.37	**3.97**
	50% emergence	22.85	18.02	5.35	2.10	3.14	0.59	6.00	5.50	3.40	3.68	**3.73**

Table 5.2 Coefficients of variation for eleven different heat unit systems for *Brassica napus* L. cv. Quantum.

Heat Unit	Thermal Time Accumulation Beginning at:	STAGE									Average
		2.2	2.3	3.1	3.2	4.2	4.3	5.2	5.4	5.5	(3.1-5.4)
Calendar Days	Planting	17.29	24.30	7.36	5.46	10.29	9.36	6.62	5.57	7.11	**7.44**
	50% emergence	32.53	35.30	8.29	10.01	4.29	9.90	5.97	6.88	7.64	**7.56**
GDD above 5°C	Planting	9.98	11.50	21.71	16.97	20.68	17.96	12.91	7.41	8.81	**16.27**
	50% emergence	20.16	17.95	20.40	45.29	6.71	15.75	10.50	5.65	10.51	**17.38**
P-Days (7,21,30)	Planting	7.86	12.00	17.28	8.75	15.45	11.21	8.73	4.87	7.63	**11.05**
	50% emergence	24.27	21.35	17.42	10.75	6.03	10.86	8.07	3.37	8.95	**9.42**
P-Days (5,21,30)	Planting	8.79	12.76	15.93	6.34	6.45	9.98	7.67	3.13	6.92	**8.25**
	50% emergence	25.24	23.22	14.42	9.63	4.14	9.91	7.01	2.75	8.19	**7.98**
P-Days (5,18,30)	Planting	9.46	13.96	11.87	5.55	11.99	8.36	6.96	2.88	6.69	**7.93**
	50% emergence	26.49	24.76	12.16	8.86	3.28	8.57	6.19	3.16	7.83	**7.03**
P-Days (5,17,30)	Planting	9.97	14.77	8.65	4.84	10.14	7.82	6.20	3.05	6.71	**6.78**
	50% emergence	27.06	25.46	11.28	8.61	2.95	8.13	5.91	3.51	7.76	**6.73**
P-Days (5,16,30)	Planting	10.82	15.13	10.12	4.75	10.82	7.32	6.52	2.95	6.78	**7.08**
	50% emergence	27.70	26.24	10.38	8.39	2.63	7.72	5.66	3.95	7.74	**6.46**
P-Days (5,19,30)	Planting	8.91	13.48	12.71	6.01	12.56	8.90	7.21	3.02	6.73	**8.40**
	50% emergence	26.00	24.17	12.98	9.12	3.59	9.02	6.47	2.92	7.93	**7.35**
P-Days (5,20,30)	Planting	8.47	13.08	13.50	6.48	13.13	9.45	7.47	3.21	6.81	**8.87**
	50% emergence	25.58	23.66	13.74	9.38	3.87	9.47	6.74	2.79	8.05	**7.67**
P-Days (5,16,27)	Planting	12.09	16.19	8.89	4.41	9.53	6.03	6.27	3.46	7.03	**6.43**
	50% emergence	28.59	27.41	9.07	8.09	2.56	6.52	5.44	4.81	7.78	**6.08**
P-Days (5,16,34)	Planting	9.88	14.75	8.87	5.13	10.85	8.44	6.38	2.99	6.69	**7.11**
	50% emergence	27.17	25.55	11.32	8.64	2.78	8.76	6.02	3.41	7.74	**6.82**

With the exceptions noted above, this was also generally true in this study. However, the improvements were more distinct for InVigor 2273 than for Quantum. While 2273 showed reduced coefficients of variation from stages 3.1 to 5.2 except for the calendar days, Quantum had lower coefficients of variation only in stages 4.2 and 5.2. In general, calculation from 50% emergence did lower the coefficient of variation. The average of the coefficient of variation from stages 3.1 to 5.4 was utilized because these contained the most important phenological stages that were observed during this study. Stages 3.1 to 3.2 would coincide with a fractional leaf area of 1.0 which is an important consideration when determining sclerotinia risk. Stages 4.2 to 4.3 would coincide with 20–30% bloom stage which is the ideal time for applying foliar fungicides to control sclerotinia stem rot. Stages 5.2 to 5.4 were utilized because physiological maturity (when the crop would be swathed) occurs at stage 5.3. The average coefficients of variation were lower with 50% emergence as the starting point for heat unit accumulation, except for the cultivar Quantum, which did not show an improvement for the calendar days and growing degree-days above 5°C systems (Table 5.2).

The growing degree-day above 5°C is the current method used to predict phenological development in canola. According to the coefficients of variation in Tables 5.1 and 5.2, GDD above 5°C has the highest average coefficient of variation (stages 3.1–5.4) of all the heat unit systems tested, including calendar days. The use of calendar days proved better overall than the growing degree-day to predict phenology. Growing degree-days have been utilized for modeling because it is believed that it is a better predictor of phenology than calendar days. The data collected in thus study suggest that growing degree-days is an inadequate predictor of canola phenology.

The coefficients of variation were lower for P-Days$_{(7,21,30)}$ than for the growing degree-day above 5°C system (see section 2.3.2.2 for the equation of the P-Days model). This non-linear system which used the base, optimum, and maximum threshold temperature for potatoes shows a lower coefficient of variation for all stages of development compared to the GDD above 5°C . The same trend of improving coefficients of variation from growing degree-days to P-Days$_{(7,21,30)}$ was also evident in the average coefficient of variation. Although this method was an improvement over the growing degree-day above 5°C system, it was not an improvement over the calendar days method, which suggested that fine tuning of the base, optimum, and maximum temperature thresholds was required. The average coefficient of variation from stages 3.1 to 5.4 was lower for calendar days than it was for P-days (7,21,30).

Previous research by Morrison (1989) suggested that an overall base temperature of 5°C should be used for canola. An improvement in the coefficient of variation using a P-Day$_{(5,21,30)}$ immediately lowered the average coefficient of variation for both varieties from the thermal time used for potatoes; P-day$_{(7,21,30)}$. There was an improvement in each developmental stage from the P-day$_{(7,21,30)}$ to the P-day$_{(5,21,30)}$ in both varieties except for stages 2.2, 2.3 for Quantum.

The optimum and upper threshold temperatures were modified according to Table 4.14. P-Days$_{(5,17,30)}$ had the lowest coefficient of variation and was an improvement over calendar days. P-Days$_{(5,17,30)}$ was subsequently utilized to test if there was a difference between the phenological development of the two cultivars used in this study.

5.1.1 Phenological difference between Cultivars

The paired t-test showed no significant difference between the two cultivars using P-Days$_{(5,17,30)}$, except for the Brandon site (Appendix E). The Brandon site was eliminated because the data from the site was unreliable. This was apparent early in the growing season as it was seeded late (June 19, 2000) and had severe flea beetle damage, which completely obscured emergence counts and caused abnormal phenological development.

5.1.1.2 Heat Units From Combined Cultivar Data

The stage of development of each site was recalculated, combining the percentages of observed stages for both the Quantum and the 2273 cultivars. The first date of observation for the combined cultivar data was determined using the criteria described in section 4.4. This combined data is listed in Table 4.13 as the site average. Heat units were recalculated as in some instances the combining of data changed the date of appearance of some stages, and also allowed some stages to be included that did not previously meet the criteria set out in section 4.4 when the stage of development for 2273 and Quantum were determined separately at each site.

This averaged data showed trends very similar to those of the individual varieties (Table 5.3). Calendar days were a better estimator of phenological development than GDD above 5°C, i.e. the coefficient of variation for GDD above 5°C was greater for each stage of development and for the averaged coefficient of variation. This is not in agreement with phenological studies conducted by Morrison (1988) which concluded that GDD above 5°C was a better in field predictor of canola phenological development.

Table 5.3 Coefficients of variation for seven heat unit systems for *Brassica napus* L. cv. 2273 and Quantum.

Heat Unit	Thermal Time Accumulation Beginning at:	Stage								Average
		2.2	3.1	3.2	4.2	4.3	5.2	5.4	5.5	(3.1-5.4)
Calendar Days	Planting	15.02	4.40	3.44	3.95	3.55	4.78	6.21	7.60	**4.39**
	50% emergence	28.96	3.95	4.38	3.84	1.65	4.18	6.88	8.26	**4.15**
GDD (5°C)	Planting	8.62	11.05	10.32	10.24	4.31	7.97	7.58	10.04	**8.58**
	50% emergence	21.11	8.66	7.11	7.10	5.94	6.66	5.65	11.53	**6.85**
P-days (5,17,30)	Planting	8.83	6.95	3.88	4.96	1.84	4.77	2.70	7.39	**4.18**
	50% emergence	23.29	4.91	2.47	3.52	0.75	3.80	3.29	8.56	**3.12**
P-days (5,16,30)	Planting	9.65	6.70	3.70	4.84	2.22	4.86	2.94	7.39	**4.21**
	50% emergence	25.63	3.94	2.17	3.01	0.57	3.76	3.95	8.48	**2.90**
P-days (5,18,30)	Planting	8.08	7.21	4.17	5.15	1.53	4.73	2.63	7.43	**4.24**
	50% emergence	24.44	4.40	2.43	3.22	1.14	3.66	3.16	8.68	**3.00**
P-days (5,17,34)	Planting	8.03	7.02	4.20	5.12	1.47	4.72	2.69	7.46	**4.20**
	50% emergence	24.53	4.20	2.34	3.05	1.31	3.62	3.10	8.69	**2.94**
P-days (5,17,32)	Planting	8.36	7.08	4.12	5.06	1.72	4.74	2.65	7.45	**4.23**
	50% emergence	24.72	4.17	2.27	3.04	1.09	3.63	3.25	8.63	**2.91**

Calculation from 50% emergence also lowered the average coefficient of variation for all of the thermal time systems tested. Similar trends to those found for the individual cultivars occurred, i.e. using 50% emergence did not improve the heat unit accumulation at stage 2.2 and stage 5.5. The heat units which showed the lowest coefficients of variation for the individual cultivars were recalculated for the combined cultivar phenological development data. The coefficients of variation for these methods were very similar. The P-Day$_{(5,17\ 30)}$ was chosen because it had the lowest average coefficient of variation from planting for the critical stages 3.1 to 5.4. Although there were other combinations that had lower average coefficients of variation when calculated from 50% emergence, the lowest method from planting was chosen because it would be more applicable to the Raddatz (1993) canola model. In-field observations would be required for 50% emergence determination and currently a relationship predicting 50% emergence from air temperature does not exist. The use of a heat unit accumulated from planting would be more practical.

5.1.2 Recommendations

The above data suggests that the growing degree-day above 5°C is not an appropriate predictor of canola phenology. Calendar days proved to be a better predictor than growing degree-days suggesting that the linear heat unit system is inadequate. The non-linear P-Days$_{(5,17,30)}$ is recommended because it was, overall the best predictor of canola phenology from planting. The following procedure patterned after the P-Days$_{(7,21,30)}$ for potatoes (Sands et al. 1979) for calculating the P-Days$_{(5,17,30)}$ is recommended:

P-days$_{(5,17,30)}$ are calculated from the following equation:

$$P-Days_{(5,17,30)} = \frac{1}{24} * \left(5 * P(T_1) + 8 * P(T_2) + 8 * P(T_3) + 3 * P(T_4)\right) \qquad \textbf{(5. 1)}$$

Where

$$T_1 = T_{MIN}$$

$$T_2 = \frac{(2 * T_{MIN}) + T_{MAX}}{3}$$

$$T_3 = \frac{T_{MIN} + (2 * T_{MAX})}{3}$$

$$T_4 = T_{MAX}$$

The accumulation of heat is calculated from a function of temperature, P(T), where the temperatures T_1 through T_4 are used to define the value of P by the following formula:

$P = 0$ When: $T < 5$

$P = k * \left(1 - \left((T-17)^2 / (17-5)^2\right)\right)$ When: $5 \le T < 17$

$P = k * \left(1 - \left((T-17)^2 / (30-17)^2\right)\right)$ When: $17 \le T < 30$

$P = 0$ When: $T \ge 30$

Where: k is a scale factor set to a value of 10

The P-Days$_{(5,17,30)}$ equation is better suited to describing the plant development temperature response because it is a non-linear heat unit system that utilizes maximum and minimum daily temperatures, breaking the day up into four parts to recognize that a greater portion of the day is spent closer to the minimum than to the maximum daily temperature. In addition, the equation allows for the use of the base, optimum and

maximum threshold temperatures. Although a base temperature of 5°C has been determined for canola by Morrison et al (1989), the optimum and maximum temperature thresholds have not been defined as precisely. Limited information regarding heat stress and optimum temperatures exists for canola, but specific threshold temperatures are currently not available. The heat unit recommended from this study utilized the base temperature of 5°C and an optimum of 17°C and a maximum threshold temperature of 30°C (Figure 5.1). The proposed canola P-Days(5,17,30) versus temperature curve and the comparable curve for potatoes ($P\text{-}Days_{(7,21,30)}$) is shown in Figure 5.1.

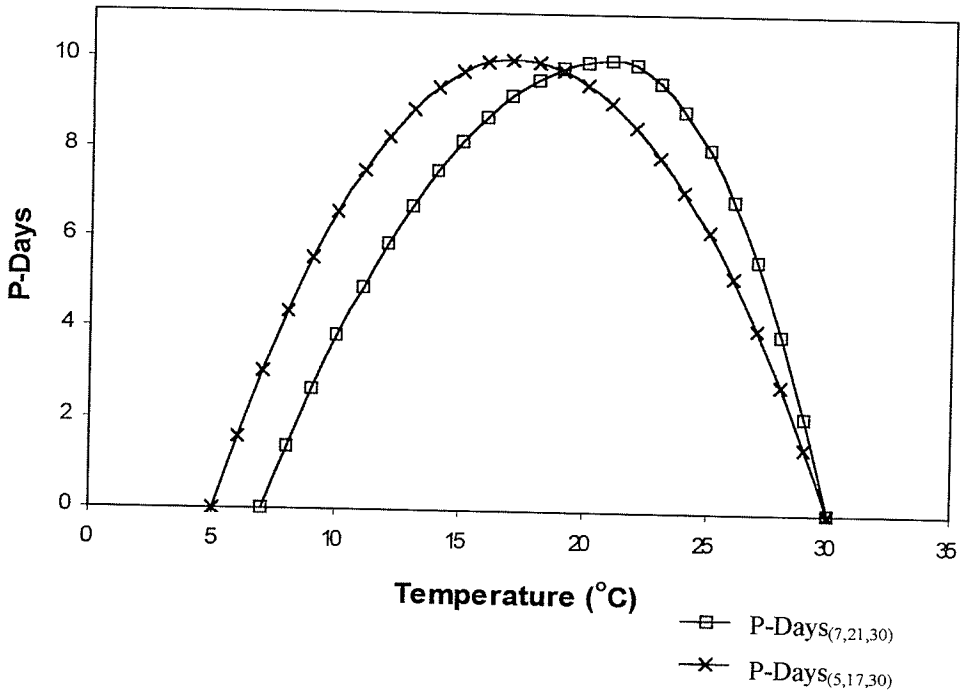


Figure 5.1 $P\text{-}Days_{(7,21,30)}$ and $P\text{-}Days_{(5,17,30)}$ as a function of temperature.

The recommended guidelines using the P-Days$_{(5,17,30)}$ heat unit system are found in Table 5.4.

Table 5.4 Mean P-Days$_{(5,17,30)}$ for several stages of development.

Stage	Thermal Time Accumulation Beginning at:	
	Planting	50% emergence
2.2	139.7	85.2
3.1	299.0	244.9
3.2	359.8	304.3
4.2	419.2	363.7
4.3	478.6	420.8
5.1	528.7	475.5
5.2	583.3	528.8
5.4	757.5	707.7
5.5	835.9	778.1

5.2 Fractional Leaf Area

The current method for predicting fractional leaf area (L_A) in the Raddatz (1993) model uses the following linear relationships:

Planting to Emergence:

0 – 98 GDD: $L_A = 0$ **(5.2)**

Seedling to Full Canopy:

98 – 354 GDD: $L_A = (GDD - 98)/(354 - 98)$ **(5.3)**

5 Leaves to Flowering Complete:

354 – 863 GDD: $L_A = 1.0$ **(5.4)**

Seeds Translucent to all Seeds Brown:

863 – 1157 GDD: $L_A = 1.0 - [(GDD - 863)/(1157 - 863)]$ **(5.5)**

In Figure 5.2, observed fractional leaf area (Appendix F) was plotted against fractional ground cover estimated from the phenological relationship used in the Canola Phenology and Water-Use Model (described in sections 2.3.4 and 3.2.11).

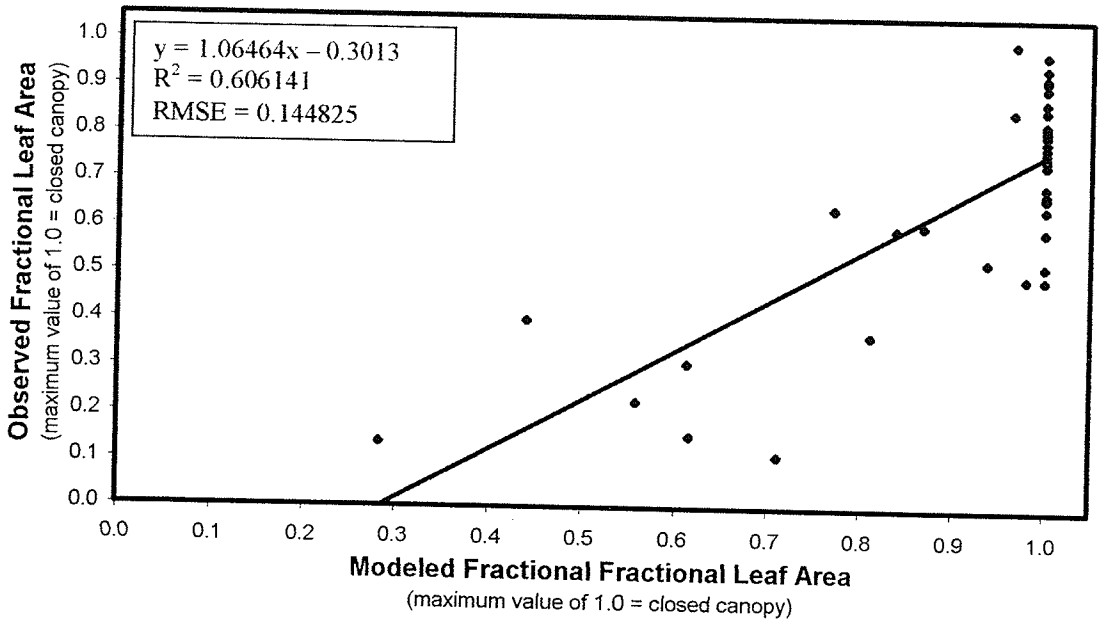


Figure 5.2 Observed fractional leaf area versus modeled fractional leaf area.

The current method for predicting fractional leaf area overestimated the amount of ground cover. The R^2 value of 0.61 and root mean square error (RMSE) of 0.15 suggest that there is room for improvement in this model. The use of growing degree-days above 5°C for this relationship may contribute to the inaccuracy in predicting ground cover and the use of a heat unit that more closely predicts phenological development would most likely improve the relationship.

Since there is a lack of empirical data estimating the fractional leaf area from temperature, observed fractional leaf area (up to stage 5.2) was plotted against growing degree-days above 5°C to determine the nature of the actual relationship from stages 1.0-

5.2 (Figure 5.3). The L_A for the senescence phase of the crop, that is stage 5.3 to 5.5 were not investigated in this study.

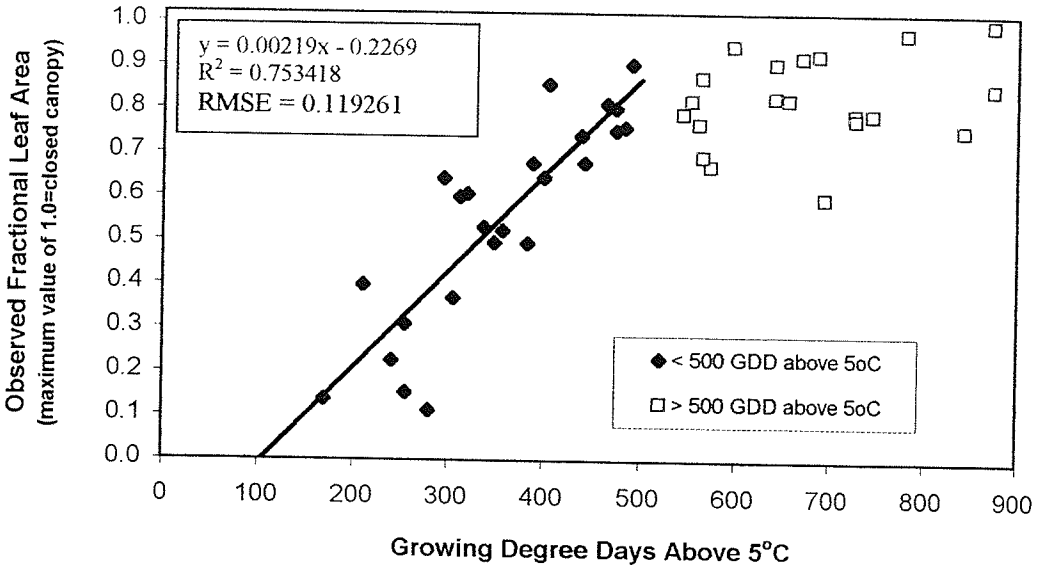


Figure 5.3 Fractional leaf area as a function of growing degree-days above 5°C.

The data were divided into two populations. The first population included L_A up to and including 500 GDD above 5°C and is described by the following linear relationship:

$$y = 0.00219x - 0.2269 \qquad \textbf{(5.6)}$$

where

y is equal to fractional leaf area, and
x is equal to GDD above 5°C.

The inflection point of 500 GDD above 5°C was derived visually and subsequently corresponded to stage 5.2.

The above relationship has an R^2 of 0.75 and a RMSE of 0.12. This differs from the relationship derived by Raddatz for several reasons.

(1) Fractional leaf area begins to accumulate at 104 rather than at 93 GDD above 5°C.

(2) A fractional leaf area of 1.0 was never reached and maximum values were around 0.8.

(3) The inflection point for maximum L_A occurred at 500 GDD above 5°C, rather than 354 GDD above 5°C used in the Raddatz model.

The different inflection points may be a result of interpretation of transpiring leaf area. Since previous research suggests that the crop continues to transpire into the ripening stage 5.2, pods and stems were considered in the determination of fractional leaf area up to stage 5.2.

Figure 5.4 shows observed ground cover plotted against the P-Days$_{(5,17,30)}$. The data was analyzed as two separate populations. The inflection point of 300 P-Days$_{(5,17,30)}$ was chosen based on a visual assessment of the data.

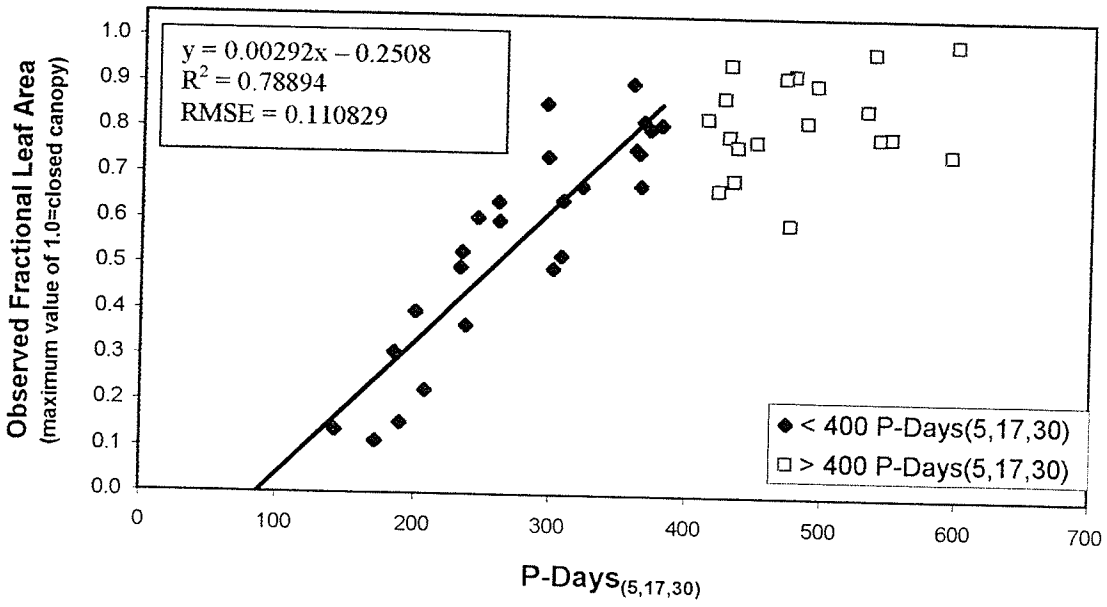


Figure 5.4 Observed fractional leaf area versus P-Days$_{(5,17,30)}$.

A linear portion from 0 to 400 P-Days$_{(5,17,30)}$ had an improved linear relationship over the GDD above 5°C.

The following equation described the linear portion of the curve;

$$y = 0.00292x - 0.2508 \quad \textbf{(5.7)}$$

Where

y is equal to fractional leaf area, and
x is equal to P-Days$_{(5,17,30)}$.

This equation was an overall better fit than the linear relationship with GDD above 5°C, and had an R^2 of 0.79 with a RMSE of 0.11. An average maximum L_A of 0.82 occurred at approximately 400 P-Days$_{(5,17,30)}$ which coincides with stage 4.1 (flowering). Fractional leaf area of approximately 0.82 would be maintained after this point until the crop began to ripen, beyond the 5.2 stage. Fractional leaf area would begin to accumulate at approximately 86 P-Days$_{(5,17,30)}$.

Only a portion of the ground cover relationship was investigated in this study, from 0.0 to less than 1.0 ground cover. The computer software developed by Lamari (2002) was used to determine the fractional leaf area from overhead photographs. Using this procedure, a fractional leaf area of 1.0 was never actually observed. This may have resulted from the sampling technique and the image analysis program. A fractional leaf area of 1.0 may in fact be only theoretical and while values close to 1.0 would occur, it could be that 100% of the ground would not be covered.

5.3 Soil Moisture

Soil moisture estimated from the Canola Phenology and Water-Use Model was compared with observed soil moisture in the top-zone (Appendix G) using regression

analysis (Figure 5.5). On average, predicted soil moisture values were lower than those observed. The R^2 value of 0.60 suggests that there is room for improvement in estimating soil moisture using the Canola Phenology and Water-Use Model (Raddatz 1993).

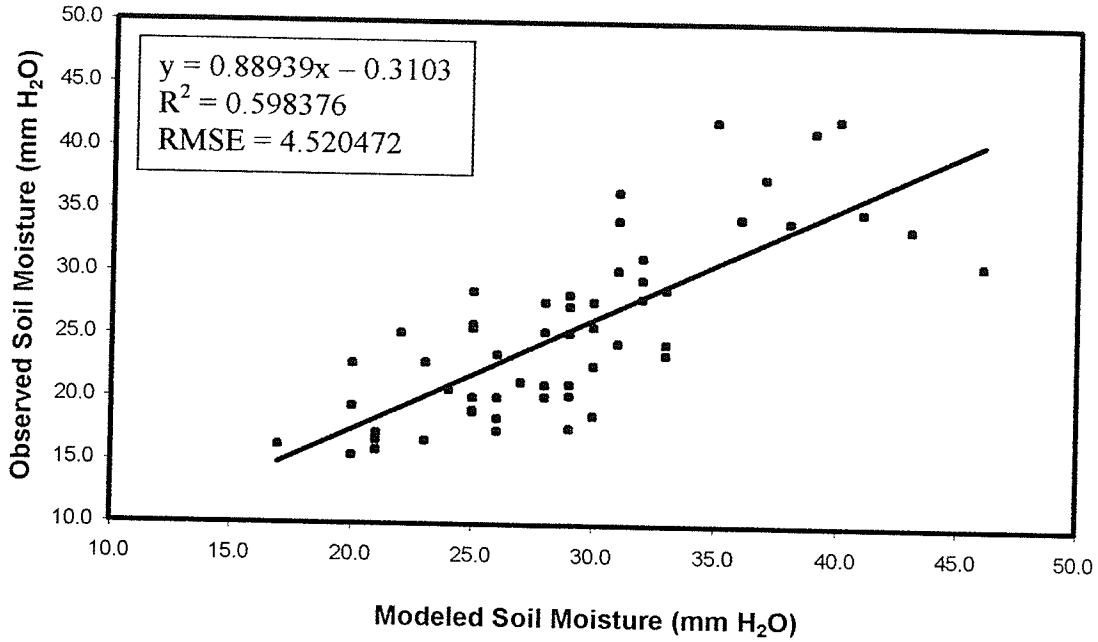


Figure 5.5 Observed top-zone soil moisture versus predicted top-zone soil moisture.

The poor estimation of soil moisture may have been linked to the use off-site precipitation data at all sites except for the Roblin 1999 and 2000 sites. To test this hypothesis, regression analyses were done for on-site and off-site precipitation locations separately. The use of imprecise phenological relationship used to estimate fractional ground cover may also be a contributing factor.

Modeled soil moisture was better estimated when on-site precipitation data was available (Figure 5.6). Roblin 1999 and 2000 (on-site precipitation data) had an R^2 of 0.83 and a RMSE of 2.32 mm while sites with off-site precipitation had a substantially lower R^2 of 0.61 and a RMSE of 4.45 mm. Thus, precipitation is a key component for

modeling top-zone soil moisture in the canola phenology and water-use model. The spatial variability of rainfall and the poor estimation of soil moisture at sites with off-site precipitation data indicates that rainfall is the most important parameter (R. L. Raddatz, personal communication, Environment Canada, Winnipeg, MB). In order to more adequately assess the accuracy of the Canola Phenology and Water-Use Model, on site precipitation data should be included. Thus, the third objective to assess modeled top-zone soil moisture was only partially achieved.

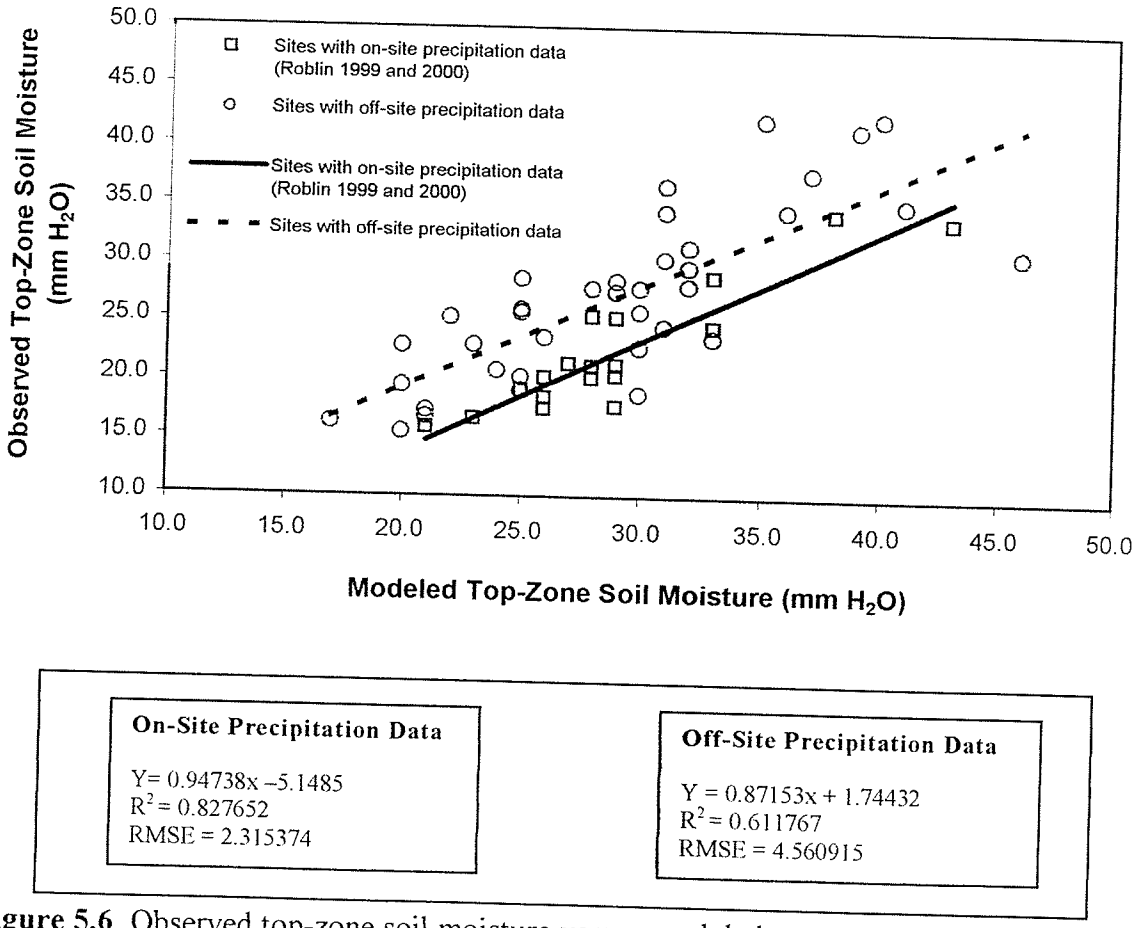


Figure 5.6 Observed top-zone soil moisture versus modeled top-zone soil moisture for sites with on-site and off-site precipitation data.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Canola, *Brassica napus* L. is an important cash crop on the Canadian Prairies. Even though canola is an important economic contributor to the Canadian agricultural sector, basic agronomic information is inadequate. The aim of this project was to improve this basic agronomic information required for effective crop management decisions. The objectives of this project were to:

(1) Develop a heat unit specific for canola to improve the prediction of crop phenology and to verify the appropriateness of the simple growing degree-day above 5°C.

(2) Empirically derive a relationship between fractional leaf area and a heat unit developed specifically for canola.

(3) To evaluate the accuracy of soil moisture (on a limited basis) modeled from the Canola Phenology and Water-Use Model (Raddatz 1993).

6.1 Main Findings

The current method for predicting canola phenology using a simple growing degree-day above 5°C is inadequate. A modified P-Days$_{(5,17,30)}$ was an overall better predictor of canola phenology. The following guidelines (Table 6.1) for estimating canola phenology were determined:

Table 6.1 Mean P-Days$_{(5,17,30)}$ for several stages of development.

Stage	Thermal Time Accumulation Beginning at:	
	Planting	50% emergence
2.2	139.7	85.2
3.1	299.0	244.9
3.2	359.8	304.3
4.2	419.2	363.7
4.3	478.6	420.8
5.1	528.7	475.5
5.2	583.3	528.8
5.4	757.5	707.7
5.5	835.9	778.1

The current method for estimating fractional leaf area was deterministically derived and empirical verification showed that the relationship relating fractional leaf area to growing degree-days above 5°C was better predicted by using a linear relationship between 100 to 500 GDD above 5°C. Further, the P-Days$_{(5,17,30)}$ was an overall better predictor of fractional leaf area using a linear relationship between 86 to 400 P-Days$_{(5,17,30)}$ using the following equation:

$$y = 0.00292x - 0.2508 \qquad \textbf{(6.1)}$$

Where

y is equal to fractional leaf area, and
x is equal to P-Days$_{(5,17,30)}$.

The Canola Phenology and Water-Use Model (Raddatz 1993) which estimates top-zone soil moisture in the plant canopy often underestimated soil moisture and the R^2 of 0.60 could possibly be improved if on-site precipitation data were used. Where on-site

perception data were available (Roblin 1999 and 2000 sites), an R^2 of 0.83 suggests the importance of on-site precipitation data as a critical invariable in the Canola Phenology and Water-Use model. In addition, if the relationships for estimating fractional leaf area from P-Days$_{(5,17,30)}$ determined in this study were used, improvements in modeling soil moisture may also occur.

6.2 Recommendations for Further Research

6.2.1 Phenological Modeling

Despite the importance of canola to the agricultural sector in Canada, there is inadequate agronomic information available for phenological modeling. In order for phenological modeling to be utilized in local scale agrometeorological models, information regarding the base temperature, optimum temperatures, and maximum threshold temperatures need to be investigated. Current knowledge of base temperatures, and particularly optimum and maximum threshold temperatures is inadequate. This will prove challenging to the canola industry as high variety turnover rate makes investigation into these cardinal temperatures a challenging task. Currently, a plant-development-temperature response curve has not yet been produced for canola. To facilitate further scientific advancement, a basic plant-development-temperature response curve for canola which identifies base, optimum, and maximum threshold temperatures should be determined. Once the cardinal temperatures have been identified through growth chamber and field studies, then other environmental variables such as photoperiod interactions could be investigated. Although a modest amount of work has been conducted on the response of canola to photoperiod (Major 1980, Hodgson 1978a, King and Kondra 1986), results seem to have been complicated by inadequate knowledge of

the plant-development-temperature response. Since temperature is the major factor influencing development of canola (Morrison et al. 1989), and considering the importance of canola to the Canadian economy, the starting point for phenological development models needs to begin with the basics of plant-development-temperature response. Ideally, thermal time equations that include genetic coefficients for base, optimum, maximum temperature thresholds, and photoperiod interaction should be developed. This type of detail can only come about with co-operation and commitment from plant breeders and industry to provide such vital information when developing new varieties.

6.2.2 Fractional Leaf Area

More investigation into this relationship is required. The relationship used by Raddatz (1993) is deterministic, and therefore, empirical verification is required. This study suggests that the earlier component of the ground cover relationship (from 0.0 to near 1.0) would be better described by a linear relationship from 86 to 400 P-days$_{(5,17,30)}$. The senescence of the crop was not investigated, although the linear relationship utilized by Raddatz (1993) and described in section (3.2.1.1) does require fine-tuning and empirical verification. In all likelihood, fractional ground cover would not linearly decline from 1.0 to 0 for as actively transpiring vegetation decreases rapidly after ripening begins.

Ground cover is also an important consideration in sclerotinia modeling and a model that did not focus solely on transpiring vegetation would be very useful for modeling sclerotinia development. The model for fractional leaf area would require modification once maturity was reached at stage 5.3 for several reasons. Firstly, once

maturity is reached at stage 5.3, the crop is swathed, and allowed to continue ripening on the field. Therefore, until the crop is removed from the field, it is expected that the ground cover would remain relatively constant, at some value below complete ground cover (taking into consideration the rows left bare between the windrows). Studies investigating the fractional ground cover of a swathed canola crop, and the ground cover once the crop is removed would permit the completion of the above relationship and make it applicable for sclerotinia modeling.

6.2.4 Canola Phenology and Water-Use Model

In terms of phenological relationships, the Canola Phenology and Water-Use Model could potentially be improved with a more accurate estimate of ground cover using a thermal time equation specific for canola. In addition, the current method for estimating root growth utilizes a growing degree-day above 5°C. This relationship was not evaluated with respect to $P\text{-}Days_{(5,17,30)}$ in this study, but future studies would allow this to be included in the Raddatz (1993) model. The fractional leaf area relationship developed in this study should be included in the Canola Phenology and Water-Use Model, along with on site precipitation data, to see if this improves the top-zone soil moisture estimates vital to the Sclerotinia Risk Forecast Model.

6.2.5 Sclerotinia Risk Forecasting - Regional

The current method for estimating sclerotinia risk uses a very broad regional approach. Information for growth stage and top-zone soil moisture Canola Phenology and Water-Use Model use average seeding dates for each station location. This does not take into account the variation in seeding dates that occur throughout agro-Manitoba. Thus, the broad crop stage window is utilized to account for variations in seeding date.

The growing-degree day accumulations and top-zone soil moisture (as a percent of capacity) are combined in a GIS to provide broad regional estimates of disease pressure. Several improvements to the current regional model are recommended. These include using a P-Day$_{(5,17,30)}$ to estimate phenological development.

6.2.6 Regional to Local Level Sclerotinia Disease Risk Forecasting

Ideally, the sclerotinia risk forecast program would be more beneficial to producers if predictions could be made at the field level and included recommendations for foliar fungicide applications. Although the current risk forecast program provides a broad overview of conditions conducive to sclerotinia formation, it incorporates only two of the factors promoting sclerotinia development; (1) soil moisture, and (2) crop stage. Sclerotinia risk should be divided into two stages of infection; sclerotia germination and ascospore germination. The first stage would model the development of apothecia. Environmental factors favoring apothecia development include surface soil moisture at or near field capacity for a prolonged period (approximately ten days) and moderate temperatures. These conditions occur in fields when the canopy closes over and shades the soil surface. Top-zone soil moisture and fractional leaf area estimated by the Canola Phenology and Water-Use Model and daily maximum and minimum temperatures could be used to model this first phase. If the first phase was conducive to apothecia production, then a second phase determining ascospore infection would be required. Ascospore infection would occur if the ascospores were released when the canola was flowering. This could be determined using a thermal time relationship specific for canola. If flowering occurred during ascospore release, the senesced petals would fall onto the leaves and stems and provided the conditions remained moist, the spores would

germinate and infect the crop. This could be determined by modeling crop stage, and using rainfall measurements, and humidity in the plant canopy modeled by the Canola Phenology and Water-Use Model.

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8.0 APPENDICES

Tables in Appendices

Table **Page**

Table **Page**

Appendix A

Table A.1 Cultivar description for *Brassica napus* L. cv. 2273 and Quantum for 1999 and 2000 growing season in Manitoba.

	Variety		Manitoba
	2273	**Quantum**	
Area 1999[z]	96,355.88 hectares 238,098 acres	19,573.24 hectares 48,366 acres	1,185,292.48 hectares 2,931,361 acres
1999 Rank (Acres grown)[z]	2	12	
Area 2000[z]	104,488.93 hectares 258,195 acres	13,756.22 hectares 33,992 acres	800,724.09 hectares 1,978,611 acres
2000 Rank (acres grown)[z]	1	14	
Yield 1999[z]	37 bu/ac	31 bu/ac	33.3 bu/ac
Yield 2000[z]	31 bu/ac	26 bu/ac	20.1 bu/ac
Days to Maturity[z]	2.2 (Relative to 46A65 at 96 days average Co-operative trials)	0 (Relative to 46A65 at 96 days average Co-operative trials)	
Blackleg[z]	Medium Resistance (29.5 % to 49.5 % Infection relative to Westar)	Resistant (0 - 29.5 % Infection relative to Westar)	
Type[z]	Liberty Tolerant Hybrid		
Heights[z]	Tall	Tall	
Lodging Resistance[z]	Good	Good	

[z]Source: Yield Manitoba 2000.

Appendix B Plant emergence counts.

Table B.1 Number of plants emerged per sampling transect, Carman 1999.

Date	2273				Quantum			
	Trans 1	Trans 2	Trans 3	%[z]	Trans 4	Trans 5	Trans 6	%[z]
25-May-99	0	0	0	**0.0%**	0	0	0	**0.0%**
2-Jun-99	4	2	9	**31.9%**	6	9	12	**37.5%**
4-Jun-99	14	9	14	**78.7%**	15	18	20	**73.6%**
7-Jun-99	15	11	15	**87.2%**	20	20	24	**88.9%**
9-Jun-99	20	11	16	**100.0%**	22	22	22	**91.7%**
11-Jun-99	19	12	15	**97.9%**	24	24	24	**100.0%**
14-Jun-99	16	10	14	**85.1%**	22	20	23	**90.3%**
16-Jun-99	17	11	16	**93.6%**	20	23	20	**87.5%**

Table B.2 Number of plants emerged per sampling transect, Carman 2000.

Date	2273						Quantum					
	Trans 6	Trans 7	Trans 8	Trans 9	Transt 10	%[z]	Trans 1*	Trans 2	Trans 3	Trans 4	Trans 5	%[z]
19-May-00	0	0	0	0	0	**0.0%**	0	0	0	0	0	**0.0%**
26-May-00	4	14	10	17	9	**42.2%**	0	0	0	5	0	**17.9%**
29-May-00	21	18	25	28	31	**96.1%**	0	10	6	8	2	**92.9%**
31-May-00	22	17	27	31	29	**98.4%**	19	12	6	8	2	**100.0%**
02-Jun-00	23	16	27	32	30	**100.0%**	19	12	6	8	2	**100.0%**
05-Jun-00	23	17	27	30	30	**99.2%**	18	12	6	7	2	**96.4%**
07-Jun-00	22	17	24	29	30	**95.3%**	7	11	5	5	2	**82.1%**

[z]Percentages based on total emergence count when plant population had stabilized.

Appendix B Plant emergence counts.

Table B.3 Number of plants emerged per sampling transect, Franklin (1999).

Date	Quantum				2273			
	Trans 19	Trans 20	Trans 21	%[z]	Transect 22	Trans 23	Trans 24	%[z]
1-Jun	0	0	0	**0.0%**	0	0	0	**0.0%**
9-Jun	19	25	23	**81.7%**	17	18	27	**82.7%**
11-Jun	24	34	21	**96.3%**	18	20	33	**94.7%**
14-Jun	26	39	22	**106.1%**	20	20	38	**104.0%**
16-Jun	25	35	22	**100.0%**	19	20	36	**100.0%**
18-Jun	27	36	22	**103.7%**	21	19	37	**102.7%**
23-Jun	28	36	22	**104.9%**	18	18	34	**93.3%**

Table B.4 Number of plants emerged per sampling transect, High Bluff (1999).

Date	2273				Quantum			
	Trans 7	Trans 8	Trans 9	%[z]	Trans 10	Trans 11	Trans 12	%[z]
1-Jun-99	0	0	0	**0.0%**	0	0	0	**0.0%**
7-Jun-99	17	5	13	**71.4%**	43	11	24	**58.6%**
9-Jun-99	18	6	16	**81.6%**	61	11	32	**78.2%**
11-Jun-99	19	9	16	**89.8%**	74	14	45	**100.0%**
14-Jun-99	21	10	18	**100.0%**	74	15	47	**102.3%**
16-Jun-99	20	10	18	**98.0%**	73	15	47	**101.5%**
18-Jun-99	19	10	18	**95.9%**	77	13	47	**103.0%**

Table B.5 Number of plants emerged per sampling transect, Roblin 1999.

Date	2273				Quantum			
	Trans 25	Trans 26	Trans 27	%[z]	Trans 28	Trans 29	Trans 30	%[z]
11-Jun	0	0	0	**0.0%**	0	0	0	**0.0%**
18-Jun	0	0	0	**0.0%**	0	0	0	**0.0%**
21-Jun	37	53	29	**98.3%**	47	32	9	**97.8%**
23-Jun	39	53	29	**100.0%**	47	32	10	**98.9%**
25-Jun	39	53	29	**100.0%**	47	33	10	**100.0%**
28-Jun	40	53	29	**100.8%**	47	33	10	**100.0%**

[z]Percentages based on total emergence count when plant population had stabilized.

Appendix B Plant emergence counts.

Table B.6 Number of plants emerged per sampling transect, Roblin 2000.

Date	Quantum					2273				
	Trans 15	Trans 16	Trans 17	Trans 18	%[z]	Trans 11	Trans 12	Trans 13	Trans 14	%[z]
29-May-00	0	0	0	0	**0.0%**	0	0	0	0	**0.0%**
07-Jun-00	66	39	48	22	**92.6%**	44	24	26	60	**98.1%**
13-Jun-00	66	43	55	25	**100.0%**	43	24	29	61	**100.0%**
14-Jun-00	60	43	57	28	**99.5%**	44	24	28	61	**100.0%**
19-Jun-00	66	43	55	25	**100.0%**	43	24	29	61	**100.0%**

Table B.7 Number of plants emerged per sampling transect, Stonewall (1999).

Date	2273				Quantum			
	Trans 13	Trans 14	Trans 15	%[z]	Trans 16[y]	Trans 17	Trans 18	%[z]
3-Jun-99	0	0	0	**0.0%**	0	0	0	**0.0%**
7-Jun-99	1	2	4	**10.4%**	13	0	0	**0.0%**
9-Jun-99	12	16	14	**62.7%**	35	4	7	**30.6%**
11-Jun-99	19	23	16	**86.6%**	37	7	21	**77.8%**
14-Jun-99	21	23	17	**91.0%**	36	12	24	**100.0%**
16-Jun-99	25	23	19	**100.0%**	37	12	24	**100.0%**
18-Jun-99	27	22	19	**101.5%**	36	13	24	**102.8%**
24-Jun-99	32	22	21	**111.9%**	25	16	23	**108.3%**

[z]Percentages based on total emergence count when plant population had stabilized.
[y]transect omiited - outlier

Appendix C Phenological observations (percentage of plot at a particuclar Stage of development).

Table C.1 Phenological observations for Brandon (2000), *Brassica napus* L. cv. Quantum.

Stage	5-Jul	13-Jul	19-Jul	26-Jul	3-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep	14-Sep	20-Sep
1.0												
2.1	16.0%											
2.2	80.0%	4.0%										
2.3	4.0%	8.0%										
2.4		52.0%	20.0%									
2.5		32.0%	40.0%									
2.6		4.0%	12.0%	4.0%								
2.7												
3.1			28.0%	52.0%								
3.2				44.0%	76.0%	40.0%						
3.3					8.0%	8.0%						
4.1					16.0%	20.0%	64.0%	4.0%				
4.2						32.0%	4.0%	68.0%				
4.3							28.0%	8.0%				
4.4							4.0%	8.0%	20.0%	8.0%		
5.1								12.0%	44.0%	4.0%		
5.2									36.0%	84.0%	100.0%	13.3%
5.3										4.0%		26.7%
5.4												40.0%
5.5												20.0%

Appendix C Phenological observations (percentage of plot at a particuclar Stage of development).

Table C.2 Phenological observations for Brandon (2000), *Brassica napus* L. cv. 2273.

Stage	5-Jul	13-Jul	19-Jul	26-Jul	3-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep	14-Sep	20-Sep
1.0												
2.1	40.0%											
2.2	60.0%											
2.3												
2.4		72.0%	12.0%									
2.5		28.0%	24.0%									
2.6			16.0%									
2.7			4.0%									
3.1			44.0%	96.0%								
3.2				4.0%	4.0%							
3.3					4.0%	4.0%						
4.1					52.0%	20.0%	4.0%					
4.2					40.0%	76.0%	20.0%					
4.3							48.0%					
4.4							24.0%	48.0%				
5.1							4.0%	36.0%	24.0%			4.0%
5.2								16.0%	68.0%	75.0%	44.0%	
5.3									8.0%	25.0%	56.0%	28.0%
5.4												52.0%
5.5												16.0%

Appendix C Phenological observations (percentage of plot at a particuclar Stage of development).

Table C.3 Phenological observations for entire Brandon (2000) site, Brassica napus L. cv. 2273 and Quantum.

State	5-Jul	13-Jul	19-Jul	26-Jul	3-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep		20-Sep
1.0												
2.1	28.0%											
2.2	70.0%	2.0%										
2.3	2.0%	4.0%										
2.4		62.0%	16.0%									
2.5		30.0%	32.0%									
2.6		2.0%	14.0%	2.0%								
2.7			2.0%	0.0%								
3.1			36.0%	74.0%								
3.2				24.0%	40.0%	20.0%						
3.3					6.0%	6.0%						
4.1					34.0%	20.0%	34.0%	2.0%				
4.2					20.0%	54.0%	12.0%	34.0%				
4.3							38.0%	4.0%				
4.4							14.0%	28.0%	10.0%	4.0%		
5.1							2.0%	24.0%	34.0%	2.0%		2.0%
5.2								8.0%	52.0%	79.5%	72.0%	6.7%
5.3									4.0%	14.5%	28.0%	27.3%
5.4												46.0%
5.5												18.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.4 Phenological observations for Carman 1999, *Brassica napus* L. cv. 2273.

Stage	11-Jun	14-Jun	16-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	29-Jul	6-Aug	12-Aug	19-Aug	25-Aug	1-Sep	8-Sep
1.0	6.7%	6.7%													
2.1	26.7%	6.7%													
2.2	66.7%	46.7%	26.7%												
2.3		40.0%	60.0%												
2.4			13.3%	6.7%											
2.5				26.7%											
2.6				20.0%	13.3%										
2.7				26.7%	13.3%										
2.8															
2.9				6.7%											
2.1				13.3%											
2.11															
2.12					6.7%										
2.?															
3.1					66.7%	26.7%									
3.2						66.7%									
3.3															
4.1						6.7%	33.3%								
4.2							66.7%	46.7%							
4.3								46.7%	40.0%						
4.4								6.7%	33.3%						
5.1									26.7%						
5.2										100.0%	100.0%	33.3%			
5.3												46.7%	13.3%		
5.4												20.0%	86.7%	40.0%	
5.5														60.0%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.5 Phenological observations for entire Carman 1999 site, *Brassica napus* L. cv. Quantum.

Stage	11-Jun	14-Jun	16-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	29-Jul	6-Aug	12-Aug	19-Aug	25-Aug	1-Sep	8-Sep
1.0															
2.1	26.7%														
2.2	53.3%	33.3%	13.3%												
2.3	20.0%	40.0%	26.7%	13.3%											
2.4		26.7%	40.0%	6.7%											
2.5			13.3%	6.7%											
2.6			6.7%	6.7%											
2.7				33.3%											
2.8				20.0%											
2.9				6.7%											
2.1															
2.11															
2.12				6.7%											
2.?					66.7%										
3.1					26.7%	6.7%									
3.2					6.7%	80.0%									
3.3						6.7%	13.3%								
4.1						6.7%	13.3%								
4.2							73.3%	26.7%							
4.3								73.3%	53.3%						
4.4									33.3%						
5.1										6.7%					
5.2									13.3%	93.3%	100.0%	33.3%			
5.3												46.7%			
5.4												20.0%	100.0%	66.7%	13.3%
5.5														33.3%	86.7%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.6 Phenological observations for entire Carman 1999 site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	11-Jun	14-Jun	16-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	29-Jul	6-Aug	12-Aug	19-Aug	25-Aug	1-Sep	8-Sep
1.0	3.3%	3.3%													
2.1	26.7%	3.3%													
2.2	60.0%	40.0%	20.0%												
2.3	10.0%	40.0%	43.3%	6.7%											
2.4		13.3%	26.7%	6.7%											
2.5			6.7%	16.7%											
2.6			3.3%	13.3%	6.7%										
2.7				30.0%	6.7%										
2.8				10.0%											
2.9				6.7%											
2.1				6.7%											
2.11															
2.12				3.3%	3.3%										
2.?					33.3%										
3.1					46.7%	16.7%									
3.2					3.3%	73.3%									
3.3						3.3%	6.7%								
4.1						6.7%	23.3%								
4.2							70.0%	36.7%							
4.3								60.0%	46.7%						
4.4								3.3%	33.3%						
5.1									13.3%	3.3%					
5.2									6.7%	96.7%	100.0%	33.3%			
5.3												46.7%	6.7%		
5.4												20.0%	93.3%	53.3%	6.7%
5.5														46.7%	93.3%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.7 Phenological observations for Carman 2000, *Brassica napus* L. cv. Quantum.

Stage	2-Jun	5-Jun	7-Jun	13-Jun	22-Jun	27-Jun	4-Jul	12-Jul	17-Jul	25-Jul	1-Aug	8-Aug	15-Aug	22-Aug	29-Aug	8-Sep
1.0	54.0%	4.0%														
2.1	46.0%	70.0%	8.0%													
2.2		26.0%	92.0%	30.7%	4.0%											
2.3				44.7%												
2.4				24.7%	20.0%											
2.5					44.0%											
2.6					28.0%											
2.7																
3.1					4.0%	88.0%				8.0%						
3.2						12.0%	72.0%			4.0%						
3.3							12.0%									
4.1							16.0%	20.0%	12.0%							
4.2								72.0%	12.0%	28.0%	12.0%					
4.3								8.0%	76.0%	16.0%	24.0%					
4.4										0.0%	8.0%	8.0%				
5.1										32.0%	4.0%	24.0%				
5.2										12.0%	52.0%	64.0%	64.0%	24.0%	4.0%	
5.3												4.0%	24.0%	44.0%	32.0%	4.0%
5.4													12.0%	24.0%	16.0%	37.0%
5.5														8.0%	48.0%	59.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.8 Phenological observations for Carman 2000, *Brassica napus* L. cv. 2273.

Stage	2-Jun	5-Jun	7-Jun	13-Jun	22-Jun	27-Jun	4-Jul	12-Jul	17-Jul	25-Jul	1-Aug	8-Aug	15-Aug	22-Aug	29-Aug	8-Sep
1.0	60.0%	20.0%	4.0%													
2.1	35.0%	52.0%	36.0%													
2.2	5.0%	28.0%	60.0%	44.0%												
2.3				44.0%												
2.4				12.0%	24.0%											
2.5					32.0%											
2.6					24.0%	4.0%										
2.7																
3.1					20.0%	72.0%										
3.2						24.0%	80.0%	4.0%								
3.3							4.0%	4.0%								
4.1							12.0%	16.0%								
4.2							4.0%	64.0%	40.0%	20.0%						
4.3								12.0%	60.0%	36.0%						
4.4										4.0%						
5.1										32.0%	52.0%	12.0%				
5.2										8.0%	48.0%	88.0%	48.0%	16.0%		
5.3													24.0%	36.0%	12.0%	
5.4													28.0%	36.0%	32.0%	4.0%
5.5														12.0%	56.0%	96.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.9 Phenological observations for entire Carman 2000 site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	2-Jun	5-Jun	7-Jun	13-Jun	22-Jun	27-Jun	4-Jul	12-Jul	17-Jul	25-Jul	1-Aug	8-Aug	15-Aug	22-Aug	29-Aug	8-Sep
1.0	57.0%	12.0%	2.0%	0.0%												
2.1	40.5%	61.0%	22.0%	0.0%												
2.2	2.5%	27.0%	76.0%	37.3%	2.0%											
2.3				44.3%												
2.4				18.3%	22.0%											
2.5					38.0%											
2.6					26.0%	2.0%										
2.7																
3.1					12.0%	80.0%				4.0%						
3.2						18.0%	76.0%	2.0%		2.0%						
3.3							8.0%	2.0%								
4.1							14.0%	18.0%	6.0%							
4.2							2.0%	68.0%	26.0%	24.0%	6.0%					
4.3								10.0%	68.0%	26.0%	12.0%					
4.4										2.0%	4.0%	4.0%				
5.1										32.0%	28.0%	18.0%				
5.2										10.0%	50.0%	76.0%	56.0%	20.0%	2.0%	
5.3												2.0%	24.0%	40.0%	22.0%	2.0%
5.4													20.0%	30.0%	24.0%	20.5%
5.5														10.0%	52.0%	77.5%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.10 Phenological observations for Franklin (1999), *Brassica napus* L. cv. Quantum.

Stage	11-Jun	14-Jun	16-Jun	19-Jun	23-Jun	29-Jun	6-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep
1.0	100.0%	66.7%	33.3%															
2.1		33.3%	40.0%	13.3%														
2.2			26.7%	73.3%	13.3%													
2.3				13.3%	46.7%	6.7%												
2.4					40.0%	33.3%												
2.5						53.3%	6.7%											
2.6						6.7%	13.3%											
2.7							6.7%											
3.1							73.3%	13.3%										
3.2								73.3%	6.7%									
3.3								13.3%										
4.1																		
4.2									26.7%	26.7%								
4.3									66.7%	73.3%	6.7%	6.7%						
4.4											13.3%							
5.1											80.0%	20.0%						
5.2												73.3%	80.0%	100.0%	20.0%			
5.3													20.0%		13.3%	6.7%		
5.4															66.7%	86.7%	86.7%	
5.5																6.7%	13.3%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.11 Phenological observations for Franklin (1999), *Brassica napus* L. cv. 2273.

Stage	11-Jun	14-Jun	16-Jun	19-Jun	23-Jun	29-Jun	6-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep
1.0	93.3%	80.0%	26.7%	6.7%														
2.1	6.7%	13.3%	66.7%	26.7%														
2.2		6.7%	6.7%	66.7%	40.0%													
2.3					53.3%	26.7%												
2.4					6.7%	40.0%	6.7%											
2.5						26.7%	26.7%											
2.6						6.7%	26.7%											
2.7							13.3%											
3.1							26.7%	6.7%										
3.2								80.0%										
3.3								13.3%	13.3%									
4.1									66.7%									
4.2									20.0%	40.0%								
4.3										60.0%	6.7%							
4.4											13.3%							
5.1											80.0%	6.7%						
5.2												93.3%	33.3%	100.0%	20.0%			
5.3													66.7%		13.3%		20.0%	
5.4															66.7%	100.0%	80.0%	
5.5																		100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.12 Phenological observations for entire Franklin (1999) site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	11-Jun	14-Jun	16-Jun	19-Jun	23-Jun	29-Jun	6-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep
1.0	96.7%	73.3%	30.0%	3.3%														
2.1	3.3%	23.3%	53.3%	20.0%														
2.2		3.3%	16.7%	70.0%	26.7%													
2.3				6.7%	50.0%	16.7%												
2.4					23.3%	36.7%	3.3%											
2.5						40.0%	16.7%											
2.6						6.7%	20.0%											
2.7							10.0%											
3.1							50.0%	10.0%										
3.2								76.7%	3.3%									
3.3								13.3%	6.7%									
4.1									33.3%									
4.2									23.3%	33.3%								
4.3									33.3%	66.7%	6.7%	3.3%						
4.4											13.3%							
5.1											80.0%	13.3%						
5.2												83.3%	56.7%	100.0%	20.0%			
5.3													43.3%		13.3%	3.3%	10.0%	
5.4															66.7%	93.3%	83.3%	
5.5																3.3%	6.7%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.13 Phenological observations for High Bluff (1999), *Brassica napus* L. cv. 2273.

Stage	11-Jun	14-Jun	16-Jun	18-Jun	23-Jun	30-Jun	7-Jul	13-Jul	20-Jul	27-Jul	4-Aug	11-Aug	18-Aug	25-Aug	31-Aug	8-Sep
1.0	93.3%	40.0%	26.7%													
2.1	6.7%	33.3%	20.0%	26.7%												
2.2		26.7%	53.3%	73.3%	40.0%											
2.3					13.3%	6.7%										
2.4					46.7%	26.7%	6.7%									
2.5						60.0%	0.0%									
2.6						6.7%	13.3%									
2.7																
2.8							6.7%									
3.1							73.3%	6.7%								
3.2								6.7%								
3.3								20.0%	6.7%							
4.1								60.0%								
4.2									66.7%	13.3%						
4.3								6.7%	26.7%	40.0%						
4.4										40.0%						
5.1										6.7%	6.7%					
5.2											93.3%	100.0%	73.3%	6.7%		
5.3													26.7%	33.3%	6.7%	
5.4														60.0%	13.3%	
5.5															80.0%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.14 Phenological observations for High Bluff (1999), *Brassica napus* L. cv. Quantum.

Stage	11-Jun	14-Jun	16-Jun	18-Jun	23-Jun	30-Jun	7-Jul	13-Jul	20-Jul	27-Jul	4-Aug	11-Aug	18-Aug	25-Aug	31-Aug	8-Sep
1.0	60.0%	40.0%	20.0%													
2.1	40.0%	6.7%	26.7%	20.0%												
2.2		53.3%	53.3%	26.7%	13.3%											
2.3				53.3%	26.7%	13.3%										
2.4					46.7%	6.7%										
2.5					13.3%	33.3%										
2.6						6.7%										
2.7						26.7%										
2.8						6.7%										
3.1						6.7%	86.7%									
3.2							13.3%	46.7%								
3.3								26.7%								
4.1								13.3%	6.7%							
4.2								13.3%	53.3%							
4.3									40.0%	60.0%	6.7%					
4.4										40.0%	0.0%					
5.1											13.3%					
5.2											80.0%	100.0%	86.7%	13.3%		
5.3													13.3%	26.7%		
5.4														60.0%	20.0%	
5.5															80.0%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.15 Phenological observations for entire High Bluff (1999) site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	11-Jun	14-Jun	16-Jun	18-Jun	23-Jun	30-Jun	7-Jul	13-Jul	20-Jul	27-Jul	4-Aug	11-Aug	18-Aug	25-Aug	31-Aug	8-Sep
1.0	76.7%	40.0%	23.3%													
2.1	23.3%	20.0%	23.3%	23.3%												
2.2		40.0%	53.3%	50.0%	26.7%											
2.3				26.7%	20.0%	10.0%										
2.4					46.7%	16.7%	3.3%									
2.5					6.7%	46.7%										
2.6						6.7%	6.7%									
2.7						13.3%										
2.8						3.3%	3.3%									
3.1						3.3%	80.0%	3.3%								
3.2							6.7%	26.7%								
3.3								23.3%	3.3%							
4.1								36.7%	3.3%							
4.2								6.7%	60.0%	6.7%						
4.3								3.3%	33.3%	50.0%	3.3%					
4.4										40.0%						
5.1										3.3%	10.0%					
5.2											86.7%	100.0%	80.0%	10.0%		
5.3													20.0%	30.0%	3.3%	
5.4														60.0%	16.7%	
5.5															80.0%	100.0%

Appendix C Phenological obserations (percentage of plot at a particular stage of development).

Table C.16 Phenological observations for Roblin 1999, *Brassica napus* L. cv. 2273.

Stage	22-Jun	29-Jun	7-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep	1-Oct
1.0	80.0%														
2.1	20.0%	26.7%													
2.2		73.3%													
2.3			60.0%												
2.4			40.0%												
2.5				33.3%											
2.6				33.3%											
2.7				13.3%											
3.1				20.0%	93.3%										
3.2					6.7%	46.7%									
3.3						13.3%									
4.1						33.3%									
4.2						6.7%	80.0%								
4.3							20.0%	73.3%							
4.4								13.3%	13.3%						
5.1								13.3%	53.3%						
5.2									33.3%	100.0%	100.0%	93.3%	80.0%		
5.3												0.0%	6.7%	26.7%	
5.4												6.7%	13.3%	26.7%	
5.5														46.7%	100.0%

Appendix C Phenological obserations (percentage of plot at a particular stage of development).

Table C.17 Phenological observations for Roblin 1999, *Brassica napus* L. cv. Quantum.

Stage	22-Jun	29-Jun	7-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep	1-Oct
1.0	46.7%	6.7%													
2.1	40.0%	20.0%													
2.2	13.3%	60.0%	13.3%												
2.3		13.3%	26.7%												
2.4			60.0%	6.7%											
2.5				20.0%											
2.6				40.0%											
2.7				33.3%											
3.1					40.0%										
3.2					60.0%	46.7%									
3.3						26.7%									
4.1						26.7%	13.3%								
4.2							46.7%	6.7%							
4.3							33.3%	33.3%							
4.4							6.7%	26.7%							
5.1								33.3%	60.0%	13.3%					
5.2									40.0%	86.7%	100.0%	93.3%	66.7%		
5.3												6.7%	33.3%		
5.4														40.0%	
5.5														60.0%	100.0%

Appendix C Phenological obserations (percentage of plot at a particular stage of development).

Table C.18 Phenological observations for entire Roblin 1999 site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	22-Jun	29-Jun	7-Jul	13-Jul	20-Jul	26-Jul	3-Aug	10-Aug	18-Aug	24-Aug	31-Aug	7-Sep	13-Sep	22-Sep	1-Oct
1.0	63.3%	3.3%													
2.1	30.0%	23.3%													
2.2	6.7%	66.7%	6.7%												
2.3		6.7%	43.3%												
2.4			50.0%	3.3%											
2.5				26.7%											
2.6				36.7%											
2.7				23.3%											
3.1				10.0%	66.7%										
3.2					33.3%	46.7%									
3.3						20.0%									
4.1						30.0%	6.7%								
4.2						3.3%	63.3%	3.3%							
4.3							26.7%	53.3%							
4.4							3.3%	20.0%	6.7%						
5.1								23.3%	56.7%	6.7%					
5.2									36.7%	93.3%	100.0%	93.3%	73.3%		
5.3												3.3%	20.0%	13.3%	
5.4												3.3%	6.7%	33.3%	
5.5														53.3%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.19 Phenological observations for Roblin 2000, *Brassica napus* L. cv. Quantum.

Stage	8-Jun	14-Jun	21-Jun	28-Jun	5-Jul	13-Jul	20-Jul	26-Jul	2-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep
1.0	100.0%	100.0%												
2.1			8.0%											
2.2			72.0%											
2.3			20.0%	60.0%										
2.4				40.0%										
2.5														
2.6														
2.7														
3.1					100.0%									
3.2						96.0%								
3.3						4.0%								
4.1							32.0%	4.0%						
4.2							68.0%	88.0%						
4.3								8.0%						
4.4									28.0%					
5.1									72.0%	12.0%				
5.2										88.0%	100.0%	100.0%	20.0%	
5.3													80.0%	24.0%
5.4														60.0%
5.5														16.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.20 Phenological observations for Roblin 2000, *Brassica napus* L. cv. 2273.

Stage	8-Jun	14-Jun	21-Jun	28-Jun	5-Jul	13-Jul	20-Jul	26-Jul	2-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep
1.0	100.0%	100.0%												
2.1			10.0%											
2.2			65.0%											
2.3			25.0%	65.0%										
2.4				35.0%										
2.5														
2.6														
2.7														
3.1					100.0%									
3.2						100.0%								
3.3														
4.1							35.0%	5.0%						
4.2							65.0%	90.0%						
4.3								5.0%						
4.4									25.0%					
5.1									75.0%	15.0%				
5.2										85.0%	100.0%	100.0%	25.0%	
5.3													75.0%	30.0%
5.4														70.0%
5.5														

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.21 Phenological observations for entire Roblin 2000 site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	8-Jun	14-Jun	21-Jun	28-Jun	5-Jul	13-Jul	20-Jul	26-Jul	2-Aug	9-Aug	16-Aug	23-Aug	30-Aug	7-Sep
1.0	100.0%	100.0%												
2.1			9.0%											
2.2			68.5%											
2.3			22.5%	62.5%										
2.4				37.5%										
2.5														
2.6														
2.7														
3.1					100.0%									
3.2						98.0%								
3.3						2.0%								
4.1							33.5%	4.5%						
4.2							66.5%	89.0%						
4.3								6.5%						
4.4									26.5%					
5.1									73.5%	13.5%				
5.2										86.5%	100.0%	100.0%	22.5%	
5.3													77.5%	27.0%
5.4														65.0%
5.5														8.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.22 Phenological Observations for Stonewall (1999), *Brassica napus* L. cv. 2273.

Stage	14-Jun	16-Jun	18-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	27-Jul	6-Aug	12-Aug	20-Aug	26-Aug	2-Sep	9-Sep
1.0	100.0%	73.3%	6.7%												
2.1		26.7%	60.0%												
2.2			33.3%	33.3%	6.7%										
2.3				60.0%	20.0%										
2.4				6.7%	46.7%	6.7%									
2.5					26.7%	20.0%									
2.6						20.0%									
2.7						46.7%									
2.8						6.7%									
2.9															
3.1							13.3%								
3.2							80.0%	6.7%							
3.3							6.7%								
4.1								26.7%							
4.2								66.7%	73.3%						
4.3									26.7%	6.7%					
4.4										26.7%					
5.1										53.3%	6.7%				
5.2										13.3%	93.3%	86.7%	41.7%		
5.3												13.3%	35.0%		
5.4													23.3%	46.7%	
5.5														53.3%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.23 Phenological Observations for Stonewall (1999), *Brassica napus* L. cv. Quantum.

Stage	14-Jun	16-Jun	18-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	27-Jul	6-Aug	12-Aug	20-Aug	26-Aug	2-Sep	9-Sep
1.0	40.0%	40.0%	20.0%	13.3%											
2.1	53.3%	26.7%	13.3%												
2.2	6.7%	33.3%	60.0%	40.0%	6.7%										
2.3			6.7%	6.7%	20.0%										
2.4				33.3%	26.7%	20.0%									
2.5				6.7%	33.3%	13.3%									
2.6					6.7%	13.3%	13.3%								
2.7					6.7%	13.3%	6.7%								
2.8						20.0%									
2.9						6.7%									
3.1						13.3%	53.3%	6.7%							
3.2							26.7%	33.3%	6.7%						
3.3								6.7%	6.7%						
4.1								40.0%	20.0%						
4.2								13.3%	60.0%	20.0%	6.7%				
4.3									6.7%	46.7%	6.7%				
4.4										26.7%	13.3%				
5.1										6.7%	53.3%	6.7%			
5.2											20.0%	86.7%	40.0%		
5.3												6.7%	33.3%		
5.4													26.7%	80.0%	
5.5														20.0%	100.0%

Appendix C Phenological observations (percentage of plot at a particular stage of development).

Table C.24 Phenological Observations for entire Stonewall (1999) site, *Brassica napus* L. cv. 2273 and Quantum.

Stage	14-Jun	16-Jun	18-Jun	24-Jun	1-Jul	8-Jul	16-Jul	22-Jul	27-Jul	6-Aug	12-Aug	20-Aug	26-Aug	2-Sep	9-Sep
1.0	70.0%	56.7%	13.3%	6.7%											
2.1	26.7%	26.7%	36.7%												
2.2	3.3%	16.7%	46.7%	36.7%	6.7%										
2.3			3.3%	33.3%	20.0%										
2.4				20.0%	36.7%	13.3%									
2.5				3.3%	30.0%	16.7%									
2.6					3.3%	16.7%	6.7%								
2.7					3.3%	30.0%	3.3%								
2.8						13.3%									
2.9						3.3%									
3.1						6.7%	33.3%	3.3%							
3.2							53.3%	20.0%	3.3%						
3.3							3.3%	3.3%	3.3%						
4.1								33.3%	10.0%						
4.2								40.0%	66.7%	10.0%	3.3%				
4.3									16.7%	26.7%	3.3%				
4.4										26.7%	6.7%				
5.1										30.0%	30.0%	3.3%			
5.2										6.7%	56.7%	86.7%	40.8%		
5.3												10.0%	34.2%		
5.4													25.0%	63.3%	
5.5														36.7%	100.0%

Appendix D Mean heat unit values.

Table D.1 Mean values for eleven heat unit systems for *Brassica napus* L. cv. 2273.

Heat Unit	Thermal Time Accumulation Beginning at:	Stage									
		2.2	2.3	3.1	3.2	4.2	4.3	5.1	5.2	5.4	5.5
Calendar Days	Planting	18.9	25.0	37.2	45.0	52.3	58.8	67.8	72.9	93.2	98.0
	50% emergence	12.0	17.6	31.0	37.5	45.0	50.8	60.4	65.7	86.8	90.4
GDD above 5°C	Planting	175.9	243.3	367.0	473.5	580.9	675.8	775.5	869.2	1098.5	1179.8
	50% emergence	113.0	171.5	305.8	402.5	497.0	582.8	706.0	793.6	1049.0	1101.1
P-Days (7,21,30)	Planting	115.9	157.1	243.2	309.4	368.9	423.9	481.1	533.1	676.6	718.2
	50% emergence	73.9	111.8	205.0	263.3	319.8	371.5	435.1	487.9	648.5	668.6
P-Days (5,21,30)	Planting	129.8	174.1	267.9	336.5	397.5	455.1	516.9	568.4	722.5	764.4
	50% emergence	82.8	123.8	225.7	285.3	344.7	397.8	466.1	518.7	688.3	709.8
P-Days (5,18,30)	Planting	139.0	184.6	285.6	354.9	415.1	474.0	537.5	587.1	746.8	787.8
	50% emergence	88.9	131.6	241.3	300.9	361.4	415.1	484.2	535.6	709.3	730.6
P-Days (5,17,30)	Planting	139.9	184.6	296.6	365.2	425.9	478.4	556.2	596.8	748.3	792.1
	50% emergence	90.7	133.8	245.8	304.9	365.5	419.1	488.2	538.8	713.0	734.2
P-Days (5,16,30)	Planting	144.4	190.6	295.1	363.8	422.5	481.6	545.8	593.1	755.0	794.3
	50% emergence	92.4	135.9	249.8	308.1	368.6	422.0	491.1	540.6	714.9	735.8
P-Days (5,19,30)	Planting	136.0	181.3	280.0	349.3	410.0	468.5	531.5	582.1	740.1	781.7
	50% emergence	86.9	129.1	236.4	296.2	356.5	410.1	479.1	531.1	703.8	725.3
P-Days (5,20,30)	Planting	132.9	177.8	274.1	343.2	404.1	462.2	524.6	575.8	732.0	773.8
	50% emergence	84.9	126.5	231.2	291.0	350.9	404.3	473.0	525.4	696.8	718.2
P-Days (5,16,27)	Planting	140.2	183.6	286.2	350.5	403.7	458.9	518.4	560.7	713.8	749.6
	50% emergence	89.8	131.2	242.8	297.1	353.8	403.1	466.2	511.1	674.7	693.6
P-Days (5,16,34)	Planting	147.2	195.5	301.3	373.1	436.1	498.5	566.2	617.3	785.2	828.2
	50% emergence	94.2	139.1	254.6	315.9	379.3	435.8	509.8	562.5	743.8	767.8

Appendix D Mean heat unit values

Table D.2 Mean values for eleven heat unit systems for *Brassica napus* L. cv. Quantum.

Heat Unit	Thermal Time Accumulation Beginning at:	Stage									
		2.2	2.3	3.1	3.2	4.2	4.3	5.1	5.2	5.4	5.5
Calendar Days	Planting	18.3	23.6	38.8	44.1	55.0	58.0	68.0	74.0	93.0	103.0
	50% emergence	11.1	16.8	32.4	36.5	45.2	51.0	59.0	65.7	86.2	95.5
GDD above 5°C	Planting	176.0	218.1	406.3	467.1	599.7	689.2	770.8	877.1	1122.9	1221.4
	50% emergence	105.4	159.4	333.7	383.7	486.8	615.0	662.2	792.6	1064.8	1144.3
P-Days (7,21,30)	Planting	114.5	143.9	264.5	303.7	382.5	429.6	479.4	539.3	684.4	749.9
	50% emergence	68.9	104.1	221.1	254.3	316.4	382.8	420.0	487.7	650.2	700.9
P-Days (5,21,30)	Planting	127.4	161.2	288.2	330.2	413.9	457.8	515.9	575.7	727.7	800.1
	50% emergence	77.1	116.2	241.3	276.3	342.7	406.4	451.9	518.6	687.8	745.9
P-Days (5,18,30)	Planting	135.6	172.7	304.0	348.2	433.9	473.9	537.3	595.4	749.1	827.1
	50% emergence	82.6	124.3	255.9	292.7	361.0	420.0	472.4	535.7	706.2	770.1
P-Days (5,17,30)	Planting	135.8	170.2	317.7	356.3	450.7	477.1	561.2	606.7	750.3	832.6
	50% emergence	84.2	126.7	259.9	297.1	365.7	422.5	477.5	539.0	708.9	774.7
P-Days (5,16,30)	Planting	140.1	179.5	311.7	356.9	442.9	479.0	546.4	602.0	754.8	835.9
	50% emergence	85.7	129.0	263.2	300.7	369.5	423.8	481.4	540.8	709.6	777.4
P-Days (5,19,30)	Planting	133.0	169.0	299.2	342.7	428.0	469.5	531.1	590.0	743.6	819.7
	50% emergence	80.8	121.7	251.4	287.7	355.5	416.4	466.4	531.1	701.7	763.6
P-Days (5,20,30)	Planting	130.3	165.1	293.9	336.7	421.3	464.1	523.9	583.4	736.4	810.6
	50% emergence	79.0	119.0	246.5	282.2	349.3	411.8	459.5	525.4	695.5	755.5
P-Days (5,16,27)	Planting	135.5	174.3	300.3	343.6	424.4	454.3	519.7	569.7	711.2	790.5
	50% emergence	83.2	125.0	254.8	290.9	355.8	401.7	459.4	511.6	667.7	734.4
P-Days (5,16,34)	Planting	143.4	183.1	319.8	366.3	456.4	497.1	566.4	626.2	787.2	870.0
	50% emergence	87.4	131.7	269.1	307.4	379.1	440.2	497.2	562.5	740.5	809.8

Appendix D Mean heat unit values.

Table D.3 Mean values for seven heat unit systems for *Brassica napus* L. cv. 2273 and Quantum.

Heat Unit	Thermal Time Accumulation Beginning at:	STAGE								
		2.2	**3.1**	**3.2**	**4.2**	**4.3**	**5.1**	**5.2**	**5.4**	**5.5**
Calendar Days	Planting	18.71	38.00	45.00	52.33	58.40	66.33	71.86	92.80	103.80
	50% emergence	11.43	30.67	37.50	44.83	50.80	59.00	64.57	86.20	96.20
GDD (5°C)	Planting	177.05	371.25	473.53	567.11	663.97	720.63	846.40	1130.92	1204.25
	50% emergence	107.15	307.16	402.52	495.06	592.43	662.18	776.50	1064.83	1132.71
P-days (5,17,30)	Planting	139.74	298.96	359.76	419.19	478.61	528.66	583.30	757.49	835.90
	50% emergence	85.19	244.93	304.32	363.67	420.82	475.49	528.75	707.68	778.11
P-days (5,16,30)	Planting	142.08	303.85	363.78	422.97	482.12	533.80	585.95	758.88	840.54
	50% emergence	87.57	249.69	308.48	367.67	423.24	481.35	531.44	709.64	781.66
P-days (5,18,30)	Planting	137.22	293.46	354.92	414.41	473.87	522.32	579.18	754.16	829.25
	50% emergence	84.39	241.58	301.37	360.70	417.24	472.41	526.35	706.18	772.62
P-days (5,17,34)	Planting	142.55	303.97	367.88	429.98	492.69	543.46	603.89	786.84	864.91
	50% emergence	87.60	250.13	312.12	374.09	433.95	491.71	548.94	736.76	806.17
P-days (5,17,32)	Planting	141.52	302.14	364.83	425.71	487.25	537.78	595.48	774.67	852.61
	50% emergence	86.97	248.43	309.36	370.24	428.63	485.86	540.92	725.20	794.59

Appendix E Paired t-test comparison

Table E.1 P-Days$_{(5,17,30)}$ values for various stages of phenological development for *Brassica napus* L. cv. 2273 and Quantum used in paired t-test comparisons.

Brandon

Stage	P-days$_{(5,17,30)}$	
	2273	Quantum
2.2	137.37	137.37
2.4	207.26	207.26
3.1	251.22	305.69
4.1	367.61	473.89
4.2	419.99	531.94
5.2	584.04	645.26
5.4	729.92	729.92
[z]P-value: 0.0215		

Carman 2000

Stage	P-days$_{(5,17,30)}$	
	2273	Quantum
2.1	126.12	126.12
2.2	141.59	141.59
3.1	307.27	307.27
3.2	365.04	365.04
4.2	435.70	435.70
4.3	476.54	476.54
5.2	653.83	594.25
5.5	819.14	819.14
[z]P-value: 0.3506		

Carman 1999

Stage	P-days$_{(5,17,30)}$	
	2273	Quantum
2.2	135.71	135.71
2.3	168.53	155.89
3.2	358.21	358.21
4.2	429.90	429.90
4.3	477.35	477.35
5.2	600.02	600.02
5.3	713.34	713.34
5.4	762.09	762.09
5.5	817.45	869.57
[z]P-value: 0.3506		

Franklin

Stage	P-days$_{(5,17,30)}$	
	2273	Quantum
2.1	130.06	130.06
2.2	155.50	155.50
2.3	189.68	189.68
3.2	363.91	363.91
4.3	470.46	425.54
5.1	536.23	536.23
5.2	598.31	598.31
5.4	777.81	777.81
[z]P-value: 0.3506		

[z]The P-value is the probability that the difference in P-day requirements is due to chance alone. The common criterion is that if $p<0.05$, then differences between cultivars are regarded as real, i.e. not due to chance.

High Bluff

Stage	P-days(5,17,30)	
	2273	Quantum
2.2	126.16	114.25
2.4	185.19	185.19
3.1	307.83	307.83
4.2	422.37	422.37
5.2	540.21	540.21
5.4	723.38	723.38
5.5	772.85	772.85
[z]P-value: 0.3559		

Roblin 1999

Stage	P-days(5,17,30)	
	2273	Quantum
2.2	143.02	143.02
3.2	372.01	321.76
4.2	433.38	433.38
5.1	563.27	563.27
5.2	614.58	614.58
5.5	792.68	792.68
[z]P-value: 0.3632		

Roblin 2000

Stage	P-days(5,17,30)	
	2273	Quantum
2.2	153.01	153.01
2.3	200.23	200.23
3.1	260.58	260.58
3.2	332.73	332.73
4.2	380.02	380.02
5.1	486.47	486.47
5.2	549.14	549.14
5.3	710.87	710.87
5.4	765.82	765.82
[z]P-value: -2		

Stonewall

Stage	P-days(5,17,30)	
	2273	Quantum
2.1	123.17	95.40
5.2	586.56	653.98
5.5	758.36	815.80
[z]P-value: 0.3961		

[z]The P-value is the probability that the difference in P-day requirements is due to chance alone. The common criterion is that if $p<0.05$, then differences between cultivars are regarded as real, i.e. not due to chance.

Appendix F Observed and modeled fractional leaf area.

Table F.1 Observed and modeled fractional leaf area for Brandon (2000).

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
13-Jul-00	298.2	207.3	0.0519	0.1300	0.0910	0.78
19-Jul-00	357.3	251.2	0.0813	0.1876	0.1344	1.00
26-Jul-00	450.0	305.7	0.1280	0.4323	0.2802	1.00
03-Aug-00	582.6	367.6	0.4197	0.7294	0.5745	1.00
09-Aug-00	663.9	420.0	0.5363	0.7609	0.6486	1.00
16-Aug-00	753.3	473.9	0.7297	0.8267	0.7782	1.00

[z] maximum value of 1.0 = closed canopy

Table F.2 Observed and modeled fractional leaf area for Carman 1999.

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
24-Jun-99	337.6	234.3	0.5562	0.5032	0.5297	0.94
1-Jul-99	404.3	295.1	0.8655	0.8486	0.8571	1.00
8-Jul-99	490.3	358.2	0.8879	0.9190	0.9035	1.00
16-Jul-99	596.7	429.9	0.9442	0.9482	0.9462	1.00
22-Jul-99	686.7	477.4	0.9350	0.9149	0.9250	1.00

[z] maximum value of 1.0 = closed canopy

Table F.3 Observed and modeled fractional leaf area for Carman 2000.

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
27-Jun-00	356.7	307.3	0.6615	0.3853	0.5234	1.00
04-Jul-00	441.55	365.0	0.7805	0.5760	0.6782	1.00
12-Jul-00	560.9	435.7	0.7834	0.7501	0.7667	1.00
25-Jul-00	725.75	540.5	0.7492	0.8295	0.7894	1.00
01-Aug-00	841.9	594.3	0.7264	0.7833	0.7549	1.00

[z] maximum value of 1.0 = closed canopy

Appendix F Observed and modeled fractional leaf area.

Table F.4 Observed and modeled fractional leaf area for Franklin (1999).

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
23-Jun-99	255.25	189.7	0.1327	0.1746	0.1536	0.62
29-Jun-99	305.25	237.7	0.3387	0.3995	0.3691	0.81
6-Jul-99	383.00	301.3	0.5005	0.4881	0.4943	1.00
13-Jul-99	475.00	363.9	0.7513	0.7527	0.7520	1.00
20-Jul-99	564.00	425.5	0.8442	0.9020	0.8731	1.00
26-Jul-99	669.75	470.5	0.9062	0.9340	0.9201	1.00
3-Aug-99	780.50	536.2	0.9737	0.9764	0.9751	1.00
10-Aug-99	873.50	598.3	0.9963	0.9956	0.9960	0.97

[z] maximum value of 1.0 = closed canopy

Table F.5 Observed and modeled fractional leaf area for High Bluff (1999).

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
23-Jun-99	254.60	185.2	0.3234	0.2935	0.3084	0.61
30-Jun-99	319.90	245.1	0.6076	0.6046	0.6061	0.87
7-Jul-99	400.10	307.8	0.6387	0.6497	0.6442	1.00
13-Jul-99	483.70	361.5	0.8104	0.7067	0.7586	1.00
20-Jul-99	573.55	422.4	0.7106	0.6296	0.6701	1.00
27-Jul-99	694.05	475.1	0.5893	0.6055	0.5974	1.00

[z] maximum value of 1.0 = closed canopy

Table F.6 Observed and modeled fractional leaf area for Roblin 1999.

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
29-Jun-99	170.10	143.0	0.1383	0.1367	0.1375	0.28
7-Jul-99	240.45	207.8	0.2145	0.2371	0.2258	0.56
13-Jul-99	312.15	261.1	0.6074	0.5891	0.5983	0.84
20-Jul-99	388.60	321.8	0.6944	0.6580	0.6762	1.00
26-Jul-99	473.65	372.0	0.8263	0.7809	0.8036	1.00
3-Aug-99	565.20	433.4	0.7003	0.6855	0.6929	1.00
10-Aug-99	641.75	493.6	0.8899	0.9191	0.9045	1.00

[z] maximum value of 1.0 = closed canopy

Appendix F Observed and modeled fractional leaf area.

Table F.7 Observed and modeled fractional leaf area for Roblin 2000.

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
28-Jun-00	210.50	200.2	0.4259	0.3701	0.3980	0.44
05-Jul-00	294.80	260.6	0.6367	0.6451	0.6409	0.77
20-Jul-00	465.05	380.0	0.8164	0.8101	0.8133	1.00
26-Jul-00	543.95	429.6	0.8012	0.7778	0.7895	1.00
02-Aug-00	655.90	486.5	0.8358	0.8110	0.8234	1.00
09-Aug-00	744.25	549.1	0.7622	0.8180	0.7901	1.00

[z] maximum value of 1.0 = closed canopy

Table F.8 Observed and modeled fractional leaf area for Stonewall (1999).

Date	Thermal Time		Fractional Leaf Area[z]			
	GDD above 5°C	P-Days (5,17,30)	Observed			Modeled
			Quantum	2273	Average	
24-Jun-99	279.75	172.41	0.1154	0.1103	0.1129	0.71
1-Jul-99	348.50	233.12	0.5020	0.4898	0.4959	0.98
8-Jul-99	438.00	296.27	0.7638	0.7174	0.7406	1.00
16-Jul-99	553.00	366.67	0.8466	0.7934	0.8200	1.00
22-Jul-99	641.25	413.77	0.8354	0.8188	0.8271	1.00
27-Jul-99	726.75	449.50	0.7830	0.7722	0.7776	1.00
6-Aug-99	873.75	531.01	0.8143	0.8888	0.8515	0.96

[z] maximum value of 1.0 = closed canopy

Appendix G Observed and modeled top-zone soil moisture content.

Table G.1 Observed and modeled top-zone soil moisture content for Brandon (2000).

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
3-Aug-00	0.3173	0.2650	0.2911	35.86	29.94	32.90	23
9-Aug-00	0.2738	0.3338	0.3038	30.94	37.73	34.34	45
16-Aug-00	0.2800	0.3148	0.2974	31.65	35.57	33.61	33
23-Aug-00	0.2916	0.2357	0.2637	32.96	26.64	29.80	26
30-Aug-00	0.2294	0.2472	0.2383	25.92	27.94	26.93	26
7-Sep-00	0.3492	0.3720	0.3606	39.46	42.04	40.75	41
14-Sep-00	0.2919	0.3416	0.3168	32.99	38.60	35.80	29
22-Sep-00	0.2966	0.3169	0.3067	33.52	35.81	34.67	32

Bulk Density: 1.1301 g *cm^{-3}

Table G.2 Observed and modeled top-zone soil moisture content for Carman 1999.

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
15-Jul-99	0.2652	0.2668	0.2660	30.73	30.91	30.82	46
22-Jul-99	0.2640	0.2584	0.2612	30.59	29.94	30.27	31
29-Jul-99	0.1981	0.1965	0.1973	22.96	22.76	22.86	23
6-Aug-99	0.1842	0.1388	0.1615	21.35	16.09	18.72	30
12-Aug-99	0.2464	0.2367	0.2415	28.55	27.42	27.99	32
19-Aug-99	0.2479	0.2297	0.2388	28.72	26.61	27.67	28
25-Agug-99	0.2322	0.2100	0.2211	26.91	24.34	25.62	25
1-Sep-99	0.1879	0.1593	0.1736	21.77	18.46	20.12	25

Bulk Density: 1.1587 g*cm^{-3}

Table G.3 Observed and modeled top-zone soil moisture content for Carman 2000.

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
12-Jul-00	0.1947	0.1995	0.1971	25.57	26.20	25.89	25
17-Jul-00	0.1414	0.1125	0.1269	18.57	14.78	16.67	21
25-Jul-00	0.1391	0.1233	0.1312	18.27	16.19	17.23	21
1-Aug-00	0.1440	0.1029	0.1235	18.92	13.52	16.22	17
8-Aug-00	0.1454	0.1435	0.1444	19.09	18.84	18.97	25
15-Aug-00	0.1793	0.1669	0.1731	23.55	21.92	22.74	20
22-Aug-00	0.1584	0.1364	0.1474	20.80	17.92	19.36	20
29-Aug-00	0.1284	0.1060	0.1172	16.86	13.92	15.39	20
8-Sep-00	0.1988	0.1847	0.1918	26.12	24.26	25.19	22

Bulk Density: 1.3134 g*cm^{-3}

Appendix G Observed and modeled top-zone soil moisture content.

Table G.4 Observed and modeled top-zone soil moisture content for Franklin (1999).

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
25-Jul-99	0.3572	0.3436	0.3504	38.39	38.39	37.66	37
03-Aug-99	0.2775	0.2530	0.2653	29.82	29.82	28.51	25
10-Aug-99	0.3270	0.3138	0.3204	35.14	35.14	34.43	36
18-Aug-99	0.3932	0.3913	0.3923	42.26	42.26	42.16	35
24-Aug-99	0.3464	0.3328	0.3396	37.23	37.23	36.50	31
31-Aug-99	0.3243	0.3131	0.3187	34.85	34.85	34.25	31
07-Sep-99	0.3914	0.3790	0.3852	42.06	42.06	41.39	39
13-Sep-99	0.4092	0.3790	0.3941	43.98	43.98	42.35	40

Bulk Density: 1.0747 $g*cm^{-3}$

Table G.5 Observed and modeled top-zone soil moisture content for High Bluff (1999).

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
27-Jul-99	0.2194	0.2162	0.2178	23.67	23.32	23.50	26
04-Aug-99	0.1961	0.1870	0.1915	21.15	20.17	20.66	24
11-Aug-99	0.2191	0.2176	0.2183	23.63	23.48	23.56	33
18-Aug-99	0.3186	0.3304	0.3245	34.37	35.65	35.01	41
24-Aug-99	0.2715	0.2759	0.2737	29.29	29.77	29.53	32
31-Aug-99	0.2430	0.2343	0.2386	26.21	25.28	25.74	30

Bulk Density: 1.0789 $g*cm^{-3}$

Table G.6 Observed and modeled top-zone soil moisture content for Roblin 1999.

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
25-Jul-99	0.1546	0.1648	0.1597	19.49	20.78	20.14	26
3-Aug-99	0.1322	0.1308	0.1315	16.67	16.50	16.59	23
10-Aug-99	0.1657	0.1704	0.1680	20.89	21.48	21.19	29
18-Aug-99	0.2718	0.2706	0.2712	34.28	34.12	34.20	38
24-Aug-99	0.2012	0.1992	0.2002	25.38	25.12	25.25	29
31-Aug-99	0.1553	0.1470	0.1511	19.58	18.53	19.06	25
7-Sep-99	0.1627	0.1721	0.1674	20.52	21.70	21.11	28
13-Sep-99	0.2664	0.2678	0.2671	33.60	33.77	33.68	43
22-Sep-99	0.2006	0.2015	0.2010	25.29	25.41	25.35	28

Bulk Density 1.2610 $g*cm^{-3}$

Appendix G Observed and modeled top-zone soil moisture content.

Table G.7 Observed and modeled top-zone soil moisture content for Roblin 2000.

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
13-Jul-00	0.1640	0.1659	0.1649	20.04	20.26	20.15	28
20-Jul-00	0.1449	0.1405	0.1427	17.70	17.16	17.43	26
26-Jul-00	0.2113	0.1891	0.2002	25.81	23.11	24.46	33
2-Aug-00	0.1375	0.1217	0.1296	16.79	14.87	15.83	21
9-Aug-00	0.1554	0.1338	0.1446	18.98	16.35	17.67	29
16-Aug-00	0.1635	0.1384	0.1510	19.98	16.91	18.44	26
23-Aug-00	0.1762	0.1731	0.1746	21.52	21.15	21.33	27
30-Aug-00	0.1759	0.1559	0.1659	21.49	19.04	20.26	29
7-Sep-00	0.2385	0.2326	0.2355	29.13	28.42	28.77	33

Bulk Density: 1.2216 $g*cm^{-3}$

Table G.8 Observed and modeled top-zone soil moisture content for Stonewall 1999.

Date	Observed Top-Zone Soil Moisture Content						Modeled Soil Moisture (mm H_2O)
	Gravimetric			mm H_2O			
	Variety		Average	Variety		Average	
	2273	Quantum		2273	Quantum		
27-Jul-99	0.2236	0.2159	0.2198	28.81	27.82	28.31	29
06-Aug-99	0.1892	0.1907	0.1900	24.38	24.58	24.48	31
11-Aug-99	0.2136	0.2117	0.2126	27.52	27.27	27.39	29
20-Aug-99	0.2489	0.2365	0.2427	32.07	30.47	31.27	32
26-Aug-99	0.2098	0.2205	0.2151	27.03	28.41	27.72	30
02-Sep-99	0.1695	0.1824	0.1759	21.83	23.50	22.67	30

Bulk Density: 1.2885 $g*cm^{-3}$