Determination of Climatically Suitable Areas for Soybean Production in Manitoba

by

Ronald Bruce Burnett

A thesis
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ABSTRACT

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The effects of maximum and minimum temperature and photoperiod on soybean development were studied for 1981 and 1982. Sites were located at Dauphin, Brandon, Morden, Waskada, Vita, Bagot, Teulon, Mariapolis and Winnipeg. This data was combined with that of a previous study (Falk, 1981) to produce a growth model for three cultivars of soybean, Maple Presto, McCall and Portage. The growth model used was the Biometeorological Time Scale. The time scale model was applied to historical weather information to calculate the date of maturity at each climatological station. This date was then compared to that of the first killing frost. The proportion of years in which maturity occurred before the first killing frost established the probability of maturing a given cultivar at that station. The probabilities for each station were then used to produce a map for each cultivar showing the probability of maturing soybeans in Manitoba. The calculations show that the probability of maturing Maple Presto in most areas of Manitoba is greater

than 80%. For the Portage and McCall cultivars the 80% probability region lies south of Winnipeg between the escarpments.

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Chapter I

INTRODUCTION

There has been increased interest in the potential for soybean production in Manitoba recently. Corn acreage increases in Manitoba have increased the demand for crops which can be grown in rotation with corn cropping. Soybeans are such a crop.

The first consideration when growing a new crop is the crops suitability to the climate. There is currently very little information on the climatic requirements of the soybean cultivars grown in Manitoba. Current recommendations are based on a corn heat unit growth model.

The purpose of this study was to formulate a crop development model which could be used to predict soybean development. A research program was initiated in 1979 to monitor the phenological development of soybeans throughout the growing season. This program was continued for four years.

A growth model, the biometeorological time scale (Robertson, 1968) was selected to estimate the growth of soybeans (Falk, 1981). The phenological data were used to determine the growth coefficients for all growth stages. When these coefficients were established, they were tested on an independant year to give some indication of their reliability. After this, the coefficients then were applied to historical weather station data to determine which regions were most suited to produce soybeans. These results were then mapped to give an indication of the areas in Manitoba which were suitable for soybean production.

Chapter II

LITERATURE REVIEW

The estimation of stage of phenological development of crops has been the subject of many studies in the area of modeling. Modeling can be described as:

> "...the attempt to quantify relations between processes (including phenological events) and environmental parameters or between different biological processes in order to more accurately describe, understand, predict, simulate correlations between or causes of biological processes and their driving or controlling nature"[1]

In order to quantify the relationship between phenological events and environmental parameters, it is necessary to have a basic understanding of the plant response to the environment. This review therefore will concentrate on describing the basic plant-environment relationships before describing specific plant growth models. Specific attention will be paid to the response of soybeans to the environment.

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[1] H. Leith (Editor) Phenology and Seasonality Modeling. Springer-Verlag, New York. 1974. p. 5.

2.1 GROWTH RESPONSES TO ENVIRONMENT

2.1.1 Germination

Germination according to Mayer and Poljakoff-Mayber (1981) is the "consecutive number of steps which causes a quiescent seed, with a low water content to show a rise in its general metabolic activity and to initiate the formation of a seedling from an embryo". Water, temperature, gases and light (for certain seeds only) have been identified as requirements for germination (Mayer and Poljakoff-Mayber, 1981).

The initial process which occurs during germination is the imbibition of water by the seed. Moisture availability is thus an important factor in germination. Hunter and Erickson (1952) determined that the minimum seed moisture content for the germination of soybeans was 52 percent on a dry weight basis. Under field conditions soil water potential is an important factor in determining the water availability for seed germination. Absolute values for minimum soil water potentials are difficult to ascertain and may not be representative of the true field situation (Mayer and Poljakoff-Mayber, 1981). One of the problems in determining minimum potentials for germination is that soil water potential is not the only factor involved in the water availability to seeds during imbibition (Hadas and Russo, 1974). Factors such as soil-seed contact can also determine water availability. Despite these limitations, Hicks (1978) states that the minimum soil water potential for soybean germination is -6.6 bars (for germination within 5-8 days at 25°C).

Germination is also dependent upon the temperature of the environment in which the seed germinates. The relationship between germination and temperature is considered to be quadratic in nature, with an optimal temperature as well as maximum and minimum temperature (Mayer and Poljakoff-Mayber, 1981). The optimum temperature for soybean germination is considered to be close to 30°C (Wilson, 1928; Whigham and Minor, 1979).

High temperatures interfere with the germination process possibly by damaging the membranes inside the seed (Mayer and Poljakoff-Mayber, 1981). Whigham and Minor (1979) consider 40°C to be the maximum temperature for germination of soybeans. Hatfield and Elgi (1974) reported no germination of seeds incubated at 40°C. It was noted by Emmerson and Minor (1979) that the tolerance of soybean seeds to high temperatures is dependent upon the cultivar.

Germination response at low temperatures is especially important in the fringe areas of soybean production where soil temperatures are cool in the spring (Littlejohns and Tanner, 1976). The minimum temperature for seed germination is more difficult to determine than the maximum temperature, therefore values of minimum temperature requirements tend to be more variable when reported in the literature.

Wilson (1928) reported a minimum germination temperature of 10°C. A temperature of 5°C was considered by Whigham and

Minor (1979) as being the minimum for germination. Temperatures below 15°C, however, have been shown to cause seedling damage (Knypl and Janas, 1979; Obendorf and Hobbs, 1970; Hobbs and Obendorf, 1972; Bramlage et al., 1978). There is considerable interaction between moisture content of the seed and the degree of chilling injury. Imbibition of seeds at 6 percent soil moisture in a clay loam soil at 5°C resulted in a lower survival rate, dry matter accumulation and lower height of seedlings, when compared to seeds imbibed at a moisture content of 16 percent (Hobbs and Obendorf, 1970). This cold chilling injury is due probably to interference with cell membrane reorganization (Bramlage et al., 1978; Knypl and Janas, 1979). Pretreatment to increase the moisture content of seeds has been suggested as a possibility for reducing cold chilling injury in soybeans planted in low temperature environments (Knypl and Janas, 1979; Hobbs and Obendorf, 1970).

The transition from the germination process to the next stage of development, hypocotyl elongation and emergence is not very well defined (Mayer and Poljakoff-Mayber, 1981). For this reason many modelers consider germination and emergence as a single stage of development. The moisture and temperature requirements for germination in most seeds differ from the emergence requirements (Mayer and Poljakoff-Mayber, 1981).

2.1.2 Hypocotyl Elongation and Emergence

The factors affecting soybean hypocotyl elongation are similar to those for germination. Moisture plays a role in determining the rate of emergence in soybeans (Heatherly and Russell, 1979) but does not seem to have as much effect as temperature (Knittle et al., 1979). Soil water potentials from -.4 to -.6 bars in a silt loam and from -.1 to -.7 bars in a clay soil were optimal for soybean emergence. These values were higher than requirements for cotton, sorghum and wheat (Heatherly and Russell, 1979).

As stated previously temperature is considered to be a major factor in soybean hypocotyl elongation and emergence. Grabbe and Metzer (1969) discovered an inhibition of hypocotyl elongation in some soybean cultivars at 25°C. The other temperature regimes used in the study, 15, 20 and 30°C, exhibited normal growth. The degree of inhibition was shown to be cultivar dependent. Gilman et al. (1973) tested six cultivars (four of which were susceptable to hypocotyl inhibition) at temperatures between 20 and 30°C. Inhibition of susceptible cultivars occurred between 21 and 28°C and maximal inhibition occurred at 25°C. Subsequent work by Burris and Knittle (1975) and Siammy and Lamotte (1976) suggests that the production of an inhibitory substance (possibly ethylene) in the susceptible cultivars is responsible for this phenomenon.

Hatfield and Elgi (1974) reported that the rate of hypocotyl elongation for two cultivars of soybeans, Lee and

Cutler, increased rapidly from 10 to 25°C, slowly increased from 25 to 30°C and decreased rapidly above 30°C. (See Figure 1 and Figure 2).

From the data for these two cultivars a model for germination and emergence was constructed using regression analysis. The equation for radicle elongation was:

$$Y = .4136463 - 0.6716088T + .003759T^2 - .0000594\ T^3 \qquad R^2 = .96$$

where Y = rate of elongation (mm hr^{-1})
T = temperature at seed depth (°C)

Numerical integration was used to determine the absolute growth by using hourly intervals of temperature. Knittle et al. (1979) developed a model for hypocotyl elongation in the field using moisture, temperature, hypocotyl length, and soil resistance. Two separate equations, one for the germination phase (hypocotyl less than 1.1 cm) and one for the elongation phase (hypocotyl greater than 1.1 cm) were developed. The equation for the germination phase was:

$$HER = -1.396 + .126M - .00275M^2 + .00375T^2 \qquad R^2 = .86$$

where HER = hypocotyl elongation rate (mm hr^{-1})
M = soil moisture content (percent by weight)
T = soil temperature (°C)

The equation for the elongation rate during the elongation phase was determined to be:

$$HER = .611 - .313L + .1240L^2 + .0110LT - 0..201RT \qquad R^2 = .96$$

where HER = hypocotyl elongation rate (mm hr^{-1})
L = hypocotyl length (mm)
R = soil resistance (kg cm^{-2}) as measured by a cone penetrometer.

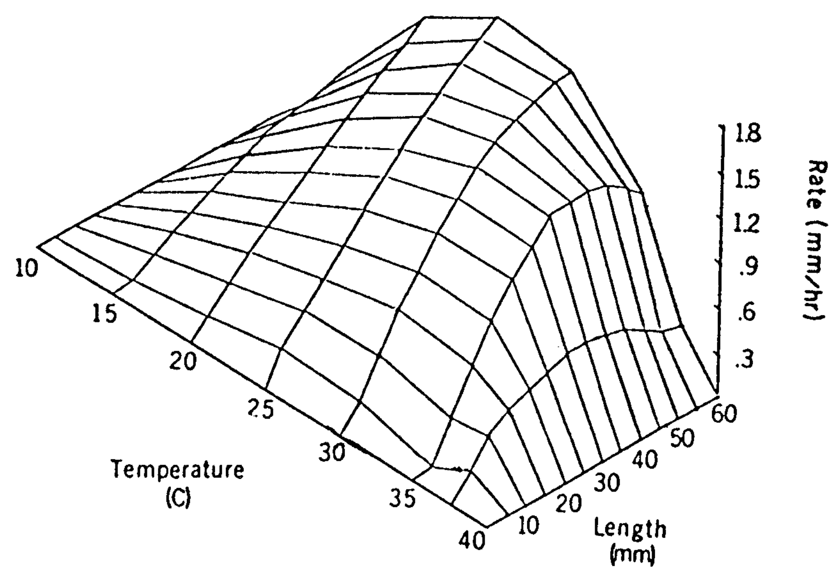

Figure 1: Rate of hypocotyl elongation in Glycine max. L. Merril cv. Lee as a function of temperature and initial hypocotyl length (after Hatfield and Elgi, 1974).

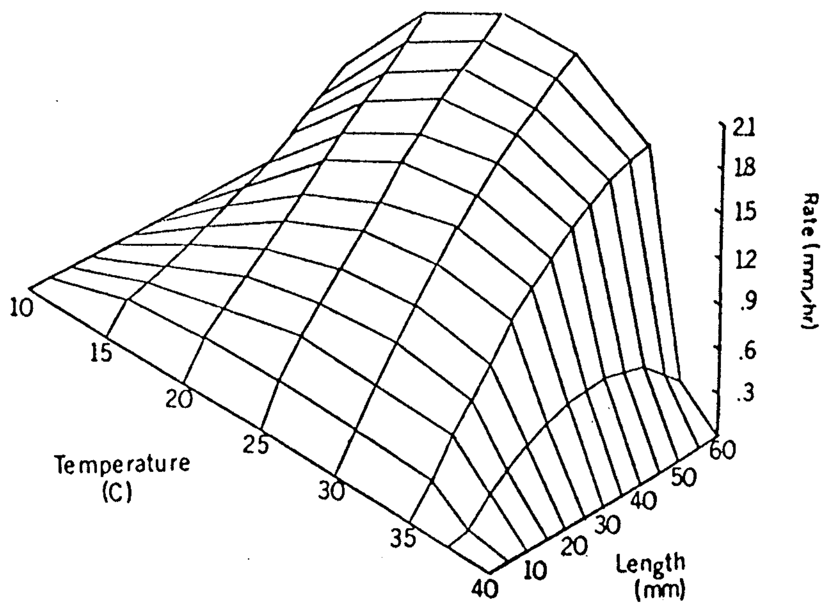

Figure 2: Rate of hypocotyl elongation in Glycine max. L. Merril cv. Cutler as a function of temperature and initial hypocotyl length (after Hatfield and Elgi, 1974).

These results seem to indicate that soil moisture is an important factor during germination and the early parts of seedling development.

Waterer (1982) studied the germination and emergence of three soybean cultivars, McCall, Maple Presto, and Portage at 8, 11, 14, 20, and 30°C. The cultivar McCall showed superior germination and emergence characteristics at low temperatures. From this data regression equations relating soil temperature to rate of emergence (defined as the reciprocal of days to 50% emergence) can be calculated for each cultivar. These equations are shown in Table 1.

TABLE 1

Regression equations describing germination and emergence for three soybean cultivars (from Falk, 1981 and Waterer, 1982)

CULTIVAR	SOURCE	EQUATION
Maple Presto	Falk	1/D = .03899 + .0030(T)a
Maple Presto	Waterer	1/D = -.151 + .014(T)b
McCall	Falk	1/D = .03838 + .00353(T)a
McCall	Waterer	1/D = -.142 + .017(T)b
Portage	Falk	1/D = .02548 + .00394(T)a
Portage	Waterer	1/D = -.167 + .015(T)b

(T)a = temperature (°C) at 20 cm
(T)b = temperature (°C) at seed depth
D = days to emergence

Falk (1981) also used regression analysis on field data to characterize emergence for the same three cultivars. The model giving the best fit was a linear model involving soil temperatures at the 20 cm depth. These equations are also shown in Table 1.

2.1.3 Vegetative Growth

Temperature is considered to be the single most important factor in determining the rate of development of a plant in the vegetative stage (Brown, 1962). Brown (1962) studied temperature effects on the rate of development of soybeans between planting and flowering. The rate of development (defined as the reciprocal of the total number of night hours from planting to harvesting multiplied by 10,000) was found to vary in a curvilinear fashion with temperature (see Figure 3).

Stone and Taylor (1983) reported that main root elongation was related to temperature in the form of a quadratic function. Hesketh et al. (1973) reported a linear relationship between temperature and the rate of trifoliate leaf development in soybeans. The temperature range of the experiment, however, corresponds with the linear portion of Brown's quadratic formula (See Figures 3 and 4). In the same study Hesketh et al. (1973) reported that soybeans died when grown at an ambient temperature of 40°C. The degree of temperature response in soybeans during the planting to flowering stage was found to be cultivar dependent (Falk, 1981; Major et al. 1975a).

The length of the vegetative period is not the only parameter that is affected by temperature. Hofstra (1972) conducted an extensive study concerned with different growth responses to controlled daytime and nighttime temperatures. Leaf area increase was found to be maximal at 27°C. The

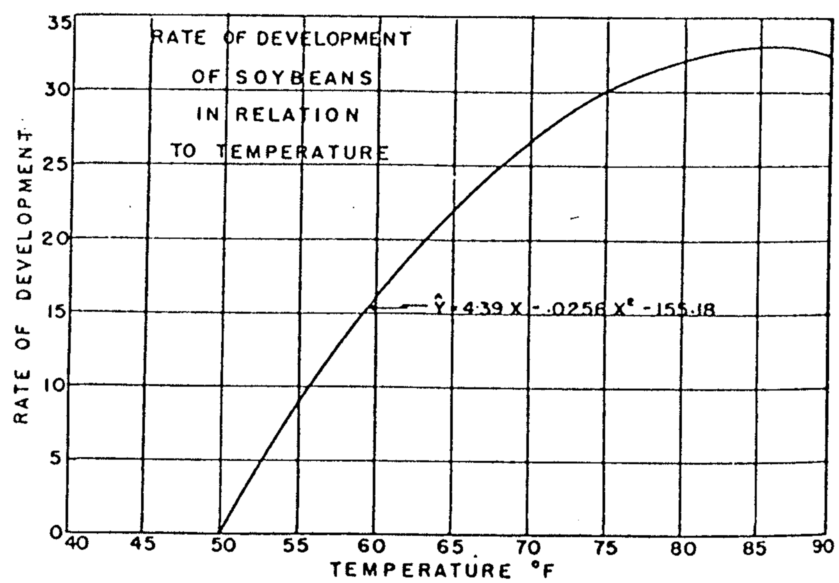

Figure 3: Rate of soybean development (as expressed by the reciprocal of total night hours) versus temperature (after Brown, 1962).

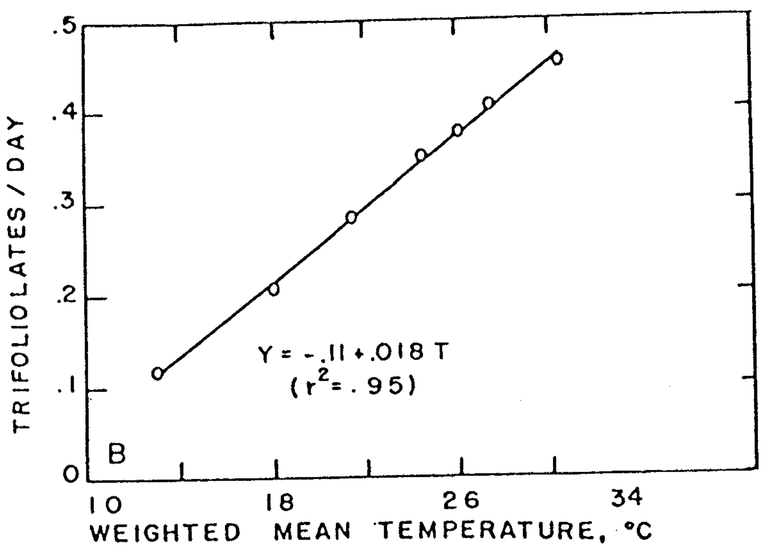

Figure 4: Effect of temperature on the rate of trifoliate leaf development in soybeans (after Hesketh et al., 1973).

temperature effect on leaf area was most prominent during the early growth stages. The leaf area increase can be explained by the fact that at 27°C not only were the leaves larger than at other temperatures but the rate of leaf appearance was at a maximum at 27°C.

Availability of moisture also influences vegetative growth of soybeans. Boyer (1970) found that the rate of leaf enlargement in soybeans was reduced at leaf water potentials between -4 and -12 bars and was minimal at potentials less than -12 bars. Read and Bartlett (1972) and Ciha and Brun (1975) observed that leaf area index decreased when stressed soybeans were compared with unstressed. Read and Bartlett (1972) also found that net assimilation rate increased in the stressed plants. Assimilates were also redistributed from the shoot to the root in the stressed plants.

Heatherly and Russell (1977) also showed that leaf enlargement was reduced by 75% at leaf water potentials less than -4 bars and was zero at -12 bars.

A third environmental factor which plays an important role in the vegetative development of soybeans is light. There are two types of plant response to light. Firstly, the plant responds to the duration of the light period. This response is called the photoperiodic response. Secondly, plants respond to the intensity of the light source.

Light provides the energy for the carbon assimilation process in plants. It therefore follows that a change in the energy level of light will affect plant growth. Under relatively low levels of incident radiation, net photosynthesis increases with increasing light intensity (Salisbury and Ross, 1977). Gourdon and Planchon (1982) studied the effect of three levels of light intensity (40, 64, and 112 Wm^{-2}) and three levels of temperature (20, 25, and 30°C) on the net photosynthesis for two soybean cultivars. The net photosynthesis for all temperature levels increased with increasing irradiance. The authors noted that the soybean plant appears to modify plant structures, especially leaf thickness in response to different levels of irradiation. The two cultivars, Amsoy71 (American) and GSZ_3 (Eastern European) exhibited differences in temperature - photoperiod interactions. During exposures to temperatures of 20°C, GSZ_3 increased photosynthesis over the three levels of light intensity. Amsoy71, however, showed a substantially smaller increase in photosynthesis over the light intensity levels at 20°C. At the higher temperatures Amsoy71 showed increases in photosynthesis over the different light intensity levels. This difference between the two cultivars was attributed to the fact that the cultivars were developed for growth in different climates. The Eastern European cultivar was developed for a cooler climate than the American cultivar and consequently shows an adaptation for cooler climates. Thus one would expect that under cooler temperatures the cooler temperature cultivar would show different responses to that of the warmer temperature cultivar.

Under field conditions the crop canopy has a pronounced influence on light reception. Beuerlein and Pendleton (1971) found that the upper canopy leaves became light saturated at intensities close to the intensity of sunlight. Leaves in the lower portion of the canopy became light saturated at much lower intensities. There is a change in the leaf morphology when one moves from the upper to the lower portions of the crop canopy (Salisbury and Ross, 1977). Leaf thickness, chlorophyll content and leaf area are all parameters which are altered by light intensity (Gourdon and Planchon, 1983). The upper portion of the canopy develops leaves which have the same characteristics of leaves developed under high intensities. These leaves are usually smaller, thicker and have lower chlorophyll content than the leaves found in the lower part of the canopy. In the lower part of the canopy the converse is true. Due to the lower light intensities of the lower canopy the leaves usually have a larger area, higher chlorophyll content and are thinner than leaves in the uppper parts of the canopy (Gourdon and Planchon, 1982; Salisbury and Ross, 1977).

Any factor which alters light intensity in the canopy will affect photosynthetic production by individual plants. (Beuerlein and Pendleton, 1971) found a relationship between row spacing and photosynthetic rates of individual soybean plants. With increased row spacings, soybean plants increased photosynthetic production by individual plants. This result was attributed to the increased light interception by the leaves in the lower portion of the canopy under increased row spacings.

The response of soybeans to photoperiod also plays an important role in determining the duration of the vegetative growth phase. The floral initiation process in most plants is influenced by the photoperiod (Zeevaart, 1976). Floral initiation marks the change of plant development from a vegetative to a reproductive state. Therefore the duration of vegetative development is dependent on the processes which influence floral initiation.

The soybean is generally classified as a qualitative short day plant (Salisbury and Ross, 1977; Garner and Allard, 1920). A short day flowering response occurs when a plant has a requirement for a critical amount of daylength above which no floral initiation will occur (Salisbury and Ross, 1977). Although daylength appears to be the controlling mechanism it is generally accepted that the change in daylength, not absolute daylength, is the important factor (Salisbury and Ross, 1977; Zeevaart, 1976).

Although soybeans are classified as a qualitative short day plant, the response of soybeans to different photoperiods is dependent on the cultivar. Several experiments have been conducted to identify cultivars which have a decreased sensitivity to photoperiod. Polson (1972) screened approximately 400 strains of soybeans of maturity groups 0 and 00 (00 group has earlier maturing cultivars than group 0) for daylength sensitivity under different photoperiods. Cultivars of the same flowering time at a photoperiod of 12 hours had an increased time to flowering at longer photoperiods. Soybeans of maturity class 00 were generally less sensitive to longer daylength than soybeans of group 0. This led the authors to conclude that early maturity and response to daylength may be related. Nissly et al. (1981) screened 515 strains of soybeans of maturity group III for photoperiod sensitivity. Thirty - two of these were determined to have low photoperiod sensitivity as indicated by small delays in floral initiation under extended photoperiods. It appears therefore that photoperiod insensitivity, although more prevalent in early maturing cultivars is found throughout the maturity groups.

In summary, vegetative growth is influenced by moisture, light and temperature. These environmental factors do not influence vegetative growth independently but interact to produce an effect on the vegetative growth phase. It should be noted that the plant responds to the total environment, not just the three factors mentioned above. Other factors (such as fertility status and fertility balance) will also influence the vegetative growth phase.

2.1.4 Reproductive Phase

The reproductive phase of a plant begins with the initiation of flowering and ends when the plant is mature. In soybeans, the reproductive phase, as in the vegetative phase, is influenced by the environmental factors of temperature, moisture and light.

The temperature influence on the reproductive phase is not as well defined as that for the vegetative period (Brown, 1962). Temperatures between 20 and 30°C seem to have no effect on the length of the reproductive phase (Brown, 1962). Cool temperatures (below 21°C) delay the development of the reproductive phase of soybeans under constant daylength (van Schaik and Probst, 1958). Low temperatures can retard the rate of pod fill (Thomas and Raper, 1976) and leaf senescence at pod fill (Kao, 1980). These two phenomena can be explained by the temperature influence on the metabolic rates. Low temperatures decrease the rate of the metabolism in the leaves as well as the transport away from the leaves to the pods. This effect results in slower leaf senesence and lower rates of pod filling. Low temperature delay during the reproductive period, however, increases seed quality and yield of soybeans (Elgi and Wardlaw, 1980; Elgi et al., 1978).

Photoperiod is also an important factor in determining the length of the reproductive phase. The length of the pod fill stage of soybeans is dependent upon photoperiod (Thomas and Raper, 1976). Thomas and Raper (1976) observed that the pod weights and pod fill rates increased with the number of critical short days to which the plants were exposed. This would indicate that the number of photoinductive short days would have a large affect on the length of the reproductive period. Patterson et al. (1977) found that increased daylengths decreased the length of the pod fill stage, contrary to the observations of Thomas and Raper (1976). Major et al. (1975a) using a growth model, concluded that short days decreased the time from flowering to maturity.

Moisture also plays an important role in influencing reproductive development especially with respect to yield. Doss et al. (1974) showed that moisture stress reduced yield with the greatest effect occuring if the plants were stressed during the pod fill stage. Moisture stress during vegetative development will also effect final soybean yield. Yield reductions are the greatest when plants are stressed throughout the growing season (Doss et al., 1974).

2.2 GROWTH MODELS

As was stated previously, modeling is an attempt to quantify a biological process. There have been many attempts to model plant growth and development. These models can arbitrarily be divided into two basic types, statistically based phenological models and differential equation based models.

2.2.1 Phenological Models

Phenological models are models which are used to simulate the phenological development of a plant using climatological data (usually maximum and minimum temperatures). The stage of development described by these models is usually emergence to maturity. The three most commonly used phenological models are growing degree days, corn heat units and biophotothermal units (Biometeorological Time Scale).

2.2.2 Growing Degree Days

The calculation of growing degree days for a crop is one of the oldest types of models used to relate temperature to phenological growth (Robertson, 1968). The growing degree day units assume that there is a base temperature, below which there is no growth, and a linear relationship between temperature and growth. The formula for the calculation of growing degree days is

$$GDD = \sum_{i} \left\{ \frac{MAXT(i) + MINT(i)}{2} - TBASE \right\}$$

where GDD = number of growing degree days
MAXT = maximum daily temperature
MINT = minimum daily temperature
TBASE = base temperature for crop
i = days over which growing degrees are calculated

There are many weaknesses with the growing degree day method of modeling crop growth. The major drawback is that growing degree days assume that the temperature-growth response is homogeneous throughout the life of the plant. The other disadvantages of growing degree days are:

1. The temperature growth relationship is assumed to be linear, even for high temperatures.
2. Day and night temperatures are assumed to contribute equally to plant growth.
3. The only climatic variable considered to affect plant growth is temperature.

Despite these limitations, Growing Degree Days are still considered to be accurate enough to be used in climatological analysis. This degree of accuracy is attributed to the fact that temperatures encountered by crops (in temperate regions) usually lie within the linear portion of the temperature-growth response curve.

2.2.3 Corn Heat Units - Soybean Development Units

As was stated previously, Brown (1962) developed a curvilinear growth equation for the vegetative phase of soybean growth. This type of analysis was done using corn and resulted in the corn heat unit equation. Corn heat units for a growing season are obtained by applying the equation from May 15 to the first full frost (Dunlop, 1981). Corn heat units are calculated by using the following equation.

$$CHU = \sum_{i} (3.3\{MAXT(i)-10\} - .084\{MAXT(i)-10\}^2)/2 + 1.8\{MINT(i) - 4.4\}/2)$$

where CHU = corn heat units
i = days over which CHU are calculated
Maxt = maximum daily temperature
Mint = minimum daily temperature.

This method is an improvement on Growing Degree days calculations because it considers both daytime and nighttime temperatures as well as being a quadratic relationship between temperature and growth. The other limitations of Growing Degree days are still inherit in the corn heat unit method. Corn heat units are currently being used to characterize areas of potential production of soybean in Manitoba.

2.2.4 Biometeorological Time Scale

The Biometeorological Time Scale developed by Robertson (1968) is the most complex of the phenological models discussed here. The growth of a plant is considered to be a function of temperature and photoperiod. The rate of crop development within a given phenological stage is given in the Biometeorological Time Scale by:

$$1 = r = \sum_{S_1}^{S_2} \{a_1(L-a_0) + a_2(L-a_0)^2\} \{b_1(T_1-b_0) + b_2(T_1-b_0)^2 + b_3(T_2-b_0) + b_4(T_2-b_0)^2\} \qquad (3)$$

where S_1, S_2 = stages of development
L = daylength
T_1 = maximum temperature
T_2 = minimum temperature
a_1, a_2, b_1, b_2, b_3, b_4 = rate coefficients
a_0, b_0 = critical values of the photoperiod and temperature, respectively.

By using this approach to model phenological growth the Biometeorological Time Scale overcomes many of the weaknesses of Growing Degree Days and Corn heat units. The Biometeorological Time Scale divides the period of growth of a plant into distinct phases, each of which is considered to be different with respect to the plant-environment growth response. Photoperiod is considered to be a factor in determining phenological development. The temperature portion of the model is quadratic and recognizes the contributions of both daytime and nighttime temperature. Critical nighttime and daytime temperatures, however, are assumed to be the same, an assumption which is not totally valid (Robertson, 1968).

2.2.5 Differential Models

Phenological development is not the only plant characteristic in which modelers have interest. Total photosynthesis, dry matter production and seed yield are a few of the other parameters of interest. In order to predict these and other quantities given certain environmental conditions a number of complicated models have been developed. These models usually consist of a series of differential equations which quantify the various processes of growth and development. Two such models are SOYMOD (Meyer et al., 1979) and a similar model developed by Wilkerson et al. (1981).

A flow chart for the SOYMOD model is shown in Figure 5. A series of differential and empirical equations are used to model the production, translocation and storage processes of the plant. These equations are solved using a rectangular integration method with an interval of one hour.

The basic modeling process involves the calculation of photosynthetic production by the plant. This photosynthate is partitioned to the various organs of the plant where it is stored or used for maintenance and growth. The coeffi-

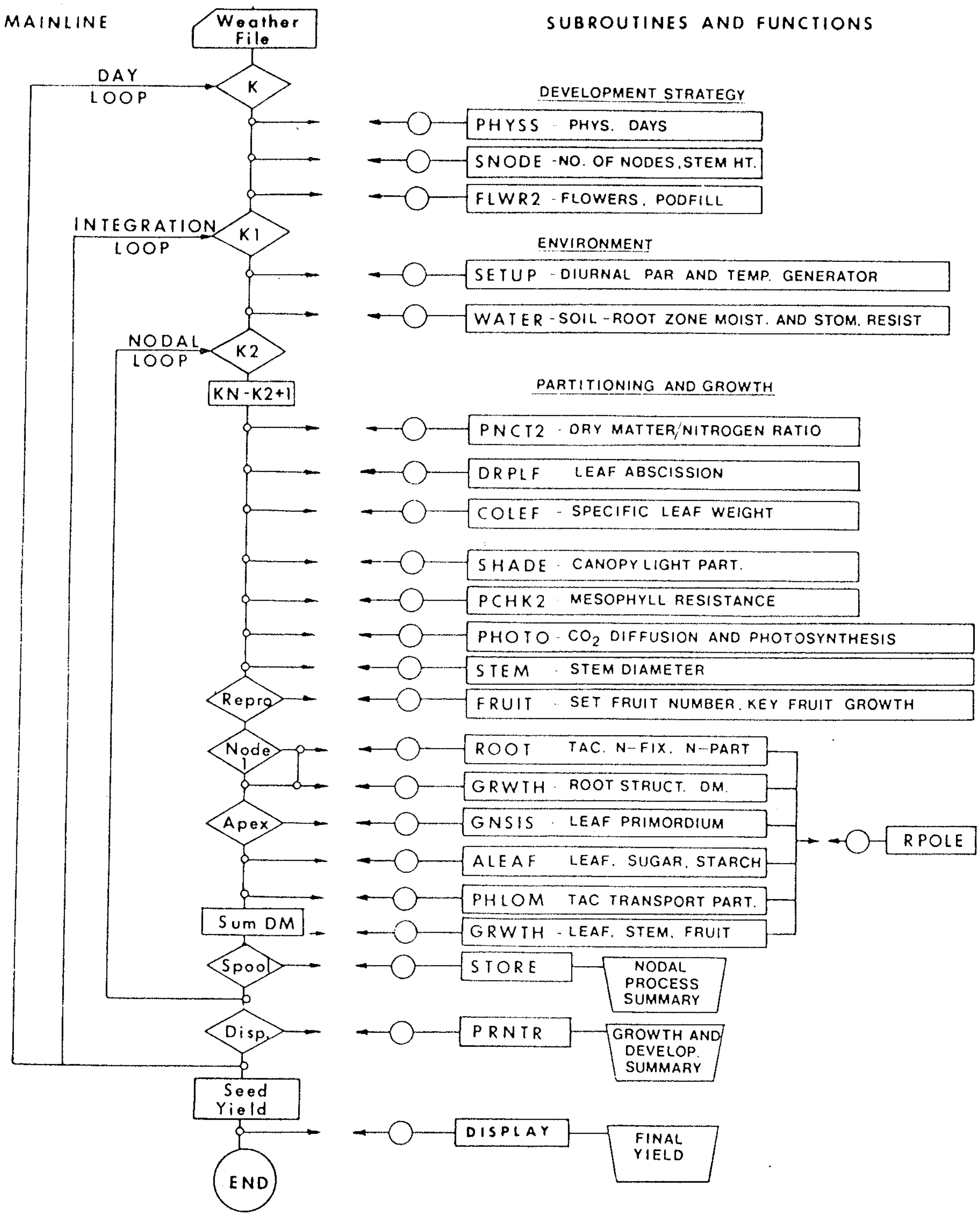

Figure 5: SOYMOD flow chart (after Meyer et al., 1979).

cients of the differential equations determine the proportion of total photosynthate which is allocated to each process. This is shown in the equations used in the model developed by Wilkerson et al. (1981).

$$\frac{dWL}{dt} = \frac{XL(Pa - R_0WT)}{(\emptyset + GR)} - SL - ML$$

$$\frac{dWS}{dt} = XS\frac{(Pa - R_0WT)}{(\emptyset + GR)} - SS - MS$$

$$\frac{dWR}{dt} = XR\frac{(Pa - R_0WT)}{(\emptyset + GR)} - SR$$

where W = mass
Pa = total photosynthate
R_0 = maintenance respiration per unit mass
WT = total mass
($\emptyset$ + G) = respiration cost
S = senescence loss
M = metabolic loss
X = partition coefficient
(R = root; S = shoot; L = leaf)

The partition coefficient, X, determines the relative amount of photosynthate which is allocated to each portion of the plant. This coefficient changes throughout the development of the plant. This change allows the plant to redirect photosynthate according to the stage of development. A series of differential equations also model nitrogen uptake and translocation in the plant.

Phenological sub-models play an important role in differential models. Stages of development must be known in order to define photosynthate partitioning strategies. Because the actual physiological processes determining phenological growth are not exactly known, a stochastic method of prediction must be used. In the SOYMOD model this is achieved by using Robertson's Biometeorological Time Scale. It is very interesting to note that SOYMOD which uses a time interval of one hour to calculate the growth parameter, predicts crop development using a method which is based on daily weather inputs. This leads to some inaccuracies in model prediction (Meyer et al., 1979).

In summary, differential models are complicated models which predict many plant growth parameters. Despite their complexity, these models contain phenological submodels which are similar to those described in the previous section.

Chapter III

METHODS AND MATERIALS

The purpose of this project was to determine the areas of potential soybean production in Manitoba. In order to accomplish this goal, a program was initiated in 1979 to monitor soybean growth at various locations throughout Manitoba. The first two years of data have been published by Falk (1981). In 1981 and 1982, the field program was continued and the data gathered was combined with that collected by Falk (1981) for analysis. This section describes the types of measurements taken during the field program.

3.1 PLOT LOCATION AND DESCRIPTION

Plot locations and descriptions of the first two years of field work were given by Falk (1981) and are summarized in Table 2. A total of nine station years of data were gathered in the first two years.

Site description and location of the subsequent two years are given in Table 3. These sites were established in cooperation with the Manitoba Crop Zonation Trials. Four cultivars of soybeans, McCall, Maple Presto, Maple Amber, and Portage were monitored in 1981. All cultivars except Portage were used in 1982. An additional two station years

TABLE 2

Site location and descriptions for 1979 and 1980.

STATION & YEAR	SOIL TYPE	FERTILIZER kg/ha	HERBICIDE	SEEDING EQUIPMENT
Winnipeg	Riverdale silty clay	none applied	Treflan 1.1 kg/ha	4 row plot seeder
Morden 1979	Morden fine loamy clay	none applied	Treflan 1.1 kg/ha	8 row conventional drill
1980	same as 1979	none applied	Treflan 1.1 kg/ha	4 row plot seeder
Waskada 1979	Waskada clay loam	31 kg/ha N 39 kg/ha P	Treflan 1.1 kg/ha	4 row plot seeder
Brandon 1979	Assiniboine complex	67 kg/ha P 67 kg/ha K 22 kg/ha S	Treflan 1.1 kg/ha	10 row conventional drill
1980	same as 1979	same as 1979	Treflan 1.1 kg/ha Basagran .82 kg/ha (4 app)	same as 1979
Dauphin 1979	Dauphin clay	31 kg/ha N 39 kg/ha P	Treflan 1.1 kg/ha	4 row plot seeder
1st seeding date 1980	Edwards Association	31 kg/ha N 39 kg/ha P	Treflan 1.1 kg/ha	same as 1979
2nd seeding date 1980	Edwards Association	31 kg/ha N 39 kg/ha P	Treflan 1.1 kg/ha	same as 1979

of data for the cultivar McCall was obtained from the study by Senthanathan (1983). Therefore data from thirteen station years of data was collected for Portage, and seventeen station years for McCall and Maple Presto during the four years.

TABLE 3

Site location and descriptions for 1981 and 1982.

STATION & YEAR	SOIL TYPE	FERTILIZER kg/ha	HERBICIDE	SEEDING EQUIPMENT
Woodmore	Pelan sandy loam	31 kg/ha N 39 kg/ha P	1.1 kg/ha Treflan	4 row plot seeder
Teulon	Lakeland clay loam	31 kg/ha N 39 kg/ha P	1.1 kg/ha Treflan	4 row plot seeder
Mariapolis	Pembina clay loam	31 kg/ha N 39 kg/ha P	1.1 kg/ha Treflan	4 row plot seeder
Bagot	Almasippi loamy sand	31 kg/ha N 39 kg/ha P	1.1 kg/ha Treflan	4 row plot seeder

Particular attention was paid to selecting sites which represented the various types of climates found in the agricultural region of Manitoba. The spatial distribution of sites is shown in Figure 6.

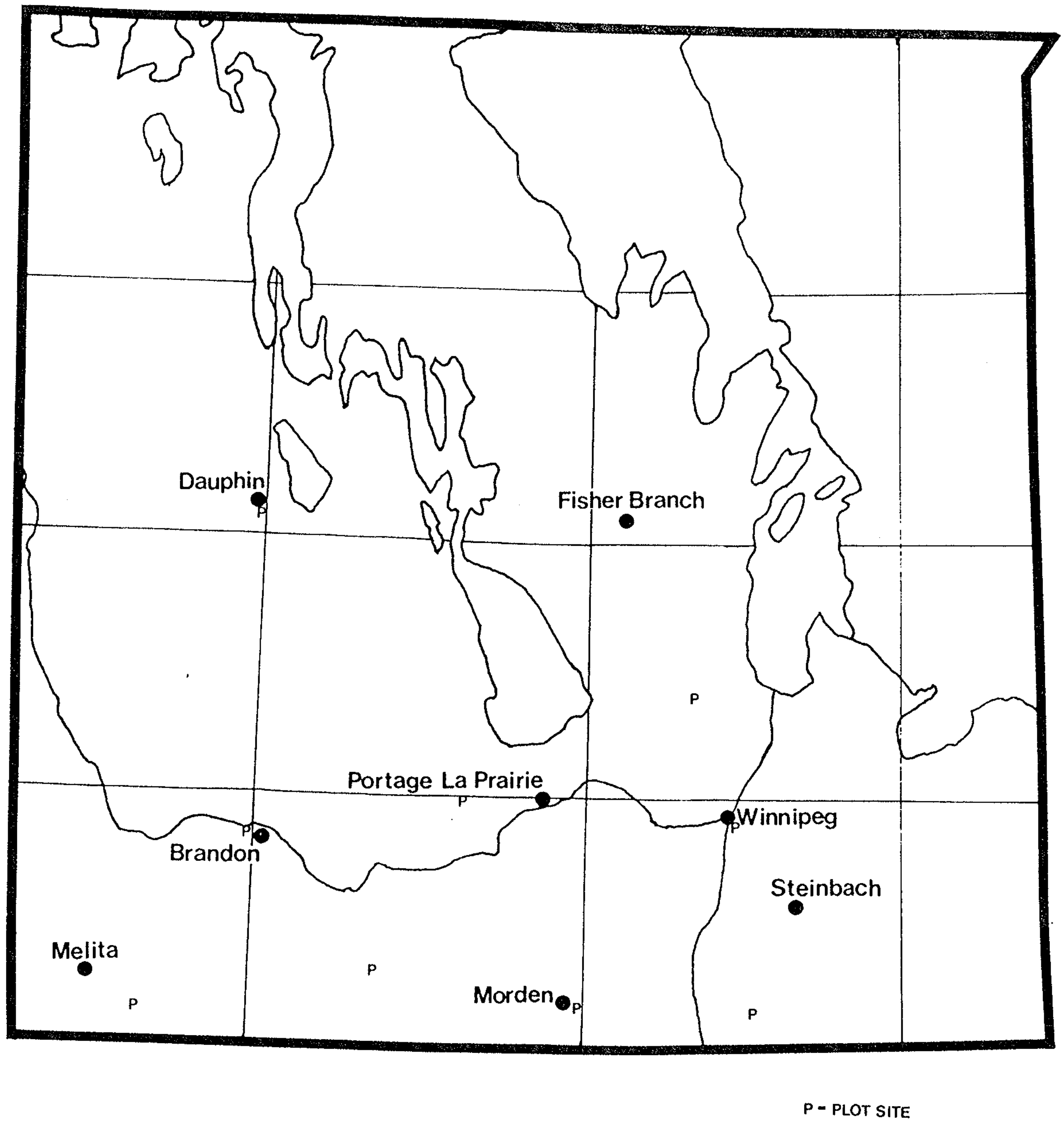

Figure 6: Site locations.

3.2 METEOROLOGICAL MEASUREMENTS

3.2.1 Temperature

Maximum and minimum temperatures were monitored at each site during the growing season (May through September). The temperature data was acquired from two sources.

The first source was on site weather stations which were set up to conform to Atmospheric Environment Service (A.E.S.) specifications. The weather stations consisted of a recording hydrothermograph or thermograph placed in a Stevenson screen. Maximum and minimum temperatures were then read from the instrument chart for each day.

Due to limitations in equipment it was necessary to use existing weather stations in the Atmospheric Environment Service network for temperature data. The A.E.S. stations were located within five miles of the plot site and in most cases were closer. Table 4 shows the origin of the weather data used for each site.

TABLE 4

Weather data source for plot locations.

Site	Source of Weather Data
Winnipeg	A.E.S.
Morden	A.E.S.
Waskada	O.S.W.S.
Brandon	A.E.S.
Dauphin	A.E.S.
Bagot	A.E.S.
Teulon	A.E.S.
Mariapolis	O.S.W.S.
Woodmore	O.S.W.S.

A.E.S. Atmospheric Environment Service
O.S.W.S. On Site Weather Station

3.2.2 Daylength

Daylength values were determined for each site using the formula relating daylength to latitude described by Robertson and Russello (1968). A FORTRAN program was used to calculate the daylength for each site.

3.3 SOIL MEASUREMENTS

3.3.1 Soil Temperature

Soil temperature measurements were taken on a weekly basis throughout the field trials. Two sets of thermocouples were inserted into the soil at each site and the temperature at 2.5, 5.0, 10.0, 20.0, 50.0, 100.0, 150.0 cm were recorded using a hand held potentiometer. Because of problems with equipment and difficulties in thermocouple insertions, the data for soil temperature for the last two years was incomplete.

3.3.2 Soil Moisture

Soil moisture status was monitored at each site at weekly intervals. Determination of the volumetric water content in the top 20 cm was achieved using a physical sampling technique. The sample was dried at 110°C in the laboratory and the volumetric water contents were calculated.

A neutron moisture meter was used to determine the water content of the soil from 20-120 cm. Because of tube insertion difficulties and equipment malfunction the soil moisture data is discontinuous for the four years of the study.

3.3.3 Phenological Measurements

In order to quantify the growth of the soybean plants over the growing season, the phenological development of the plant must be described. The method outlined by Fehr and Caviness (1977) was used in this study. A summary of this phenological classification system is shown in Tables 5 and 6.

TABLE 5

Vegetative stages of soybean development (after Fehr and Caviness, 1977).

STAGE	TITLE	DESCRIPTION
VE	Emergence	Cotyledons above soil surface
VC	Cotyledon	Unifoliate leaves unfolded
V1	First node	Fully developed leaves at unifoliate nodes
V2	Second node	Fully developed trifoliate leaf at node above unifoliate node
Vn	nth Node	n number of nodes on the main stem with fully developed trifoliate leaves

Phenological measurements throughout this study were taken by two researchers (B. Burnett and G. Falk). This was done to minimize the variation due to differences in personal interpretation.

Ten plants per replicate were randomly chosen at the beginning of the growing season. The phenological development of these plants was recorded at weekly intervals. A

TABLE 6

Reproductive stages of soybean development (after Fehr and Caviness, 1977).

STAGE	TITLE	DESCRIPTION
R1	Beginning bloom	One open flower at any node on the stem
R2	Full bloom	Open flower at one of the two upper most nodes on the main stem with a fully developed flower.
R3	Beginning pod	Pod 5mm long at one of the four uppermost nodes on the main stem with fully developed flower.
R4	Full pod	Pod 2cm long at one of the four uppermost nodes on the main stem with a fully developed upper leaf.
R5	Beginning seed	Seed 3mm long in a pod at one of the four uppermost nodes on the main stem with a fully developed leaf.
R6	Full seed	Pod containing a green seed that fills the pod cavity of one of four uppermost nodes on the main stem with a fully developed leaf.
R7	Beginning maturity	One normal pod on the main stem which has reached its mature pod color.
R8	Full maturity	95% of the pods have reached their mature pod color.

replicate was considered to be at a certain stage when 50% of the plants had reached that stage. Because the observations were done on a weekly basis, a plot was rarely at the point of development where exactly 50% of the plants were in a given stage. To overcome the difficulty a method of linear interpolation (described in detail by Falk, 1981) was used to determine the date the plot reached each stage. The dates that each stage of development was reached for each cultivar are given in Appendix A.

3.4 MODEL DEVELOPMENT

The model selected to simulate soybean growth was the Biometeorological Time Scale (BMTS) developed by Robertson (1968). The model assumes that the rate of growth of a crop is a function of temperature and daylength. The rate of growth is given as:

$$r = dM/dt = F(T) * F(L) \qquad (2.1)$$

where r = rate of development
M = degree of maturity
F(L) = non-linear function of daylength
F(T) = non-linear function of temperature

In order to solve for the degree of maturity over a given growth stage, equation (1) must be integrated.

$$\sum_{S_1}^{S_2} r\ dt = M = \sum_{S_1}^{S_2} \{F(T) * F(L)\} = 1 \qquad (2.2)$$

where S_1, S_2 = two consecutive growth stages

Since there is no quantitative value for maturity it is arbitrarily set to a value of one. When a plant has grown from stage S_1 to S_2 then the value of maturity is equal to one. Any value of degree of maturity which is less than one indicates that the stage of development is not complete. The two functions of temperature and daylength are assumed to be quadratic functions and are written in power series form. The resultant equation is:

$$1 = M = \sum_{S_1}^{S_2} \{a_1(L-a_0) + a_2(L-a_0)^2\} \{b_1(T_1-b_0) + b_2(T_1-b_0)^2 + b_3(T_2-b_0) + b_4(T_2-b_0)^2\} \quad (2.3)$$

where S_1, S_2 = stages of development
L = daylength
T_1 = maximum temperature
T_2 = minimum temperature
a_1, a_2, b_1, b_2, b_3, b_4 = rate coefficients
a_0, b_0 = critical values of the functions

This model assumes that there will be different critical values and rate coefficients for each stage of growth of the plant. It is therefore necessary to divide the growth of the plant into distinct growth stages. The stages selected by both Falk (1981) and Major (1975a) were:

1. Planting to emergence (P - VE)
2. Emergence to flower (VE - Rl)
3. Beginning flower to beginning pod (Rl -R3)
4. Beginning pod to maturity (physiological) (R3 - R7)

The growth stages used in this analysis were the same as those used by Falk (1981).

The effect of temperature and photoperiod on the growth of the soybean plant over these stages was assumed to be homogenous. When this assumption is made it is possible to solve equation (2.2) using an iterative regression technique outlined by Robertson (1968). A computer program to solve

Robertson's (1968) equation written in the language FORTRAN was obtained from the Land Resource Research Institute of Agriculture Canada and was modified for use in this analysis by Falk (1981). The rate coefficients as well as the critical values for each stage could then be calculated using the appropriate phenological and meteorological data.

To evaluate the effectiveness of photoperiod in the model a temperature only model can be used (Falk, 1981). Robertson (1968) uses this form of the biometeorological time scale formula to determine the length of time between planting and emergence because photoperiod does not play a role in this stage of development. The temperature only model is derived by setting the photoperiod contribution in equation 2.3 to the value of one. The equation for the temperature only model is:

$$1 = M = \sum_{S_1}^{S_2} \{b_1(T_1-b_0) + b_2(T_1-b_0)^2 + b_3(T_2-b_0) + b_4(T_2-b_0)^2\} \qquad (2.4)$$

This model is related to the corn heat unit equation (Robertson, 1968).

The complete model for the growth of the soybean crop can then be stated as:

$$\sum_{P}^{VE} w + \sum_{VE}^{R1} w + \sum_{R1}^{R3} w + \sum_{R3}^{R7} w = 4 \qquad (2.5)$$

where w = temperature and light quadratic equations
P, VE, R1, R3, R7 = stages of development

3.5 MODEL APPLICATION

A schematic diagram of the general model building and application process is shown in Figure 7. The first stage of analysis was to compare the performance of the model proposed by Falk (1981) with the observed data of the third year. The first two years of observations were then concatenated with the third year's data and a new set of critical values and rate coefficients were calculated. The model using these new coefficients was then compared with the fourth year observations and tested statistically for accuracy in predicting the length of growth stages. Again after this analysis the results were combined and a final calculation of critical values and coefficients were made. These were the coefficients used in the climatological analysis.

The above procedure was repeated for the temperature only model.

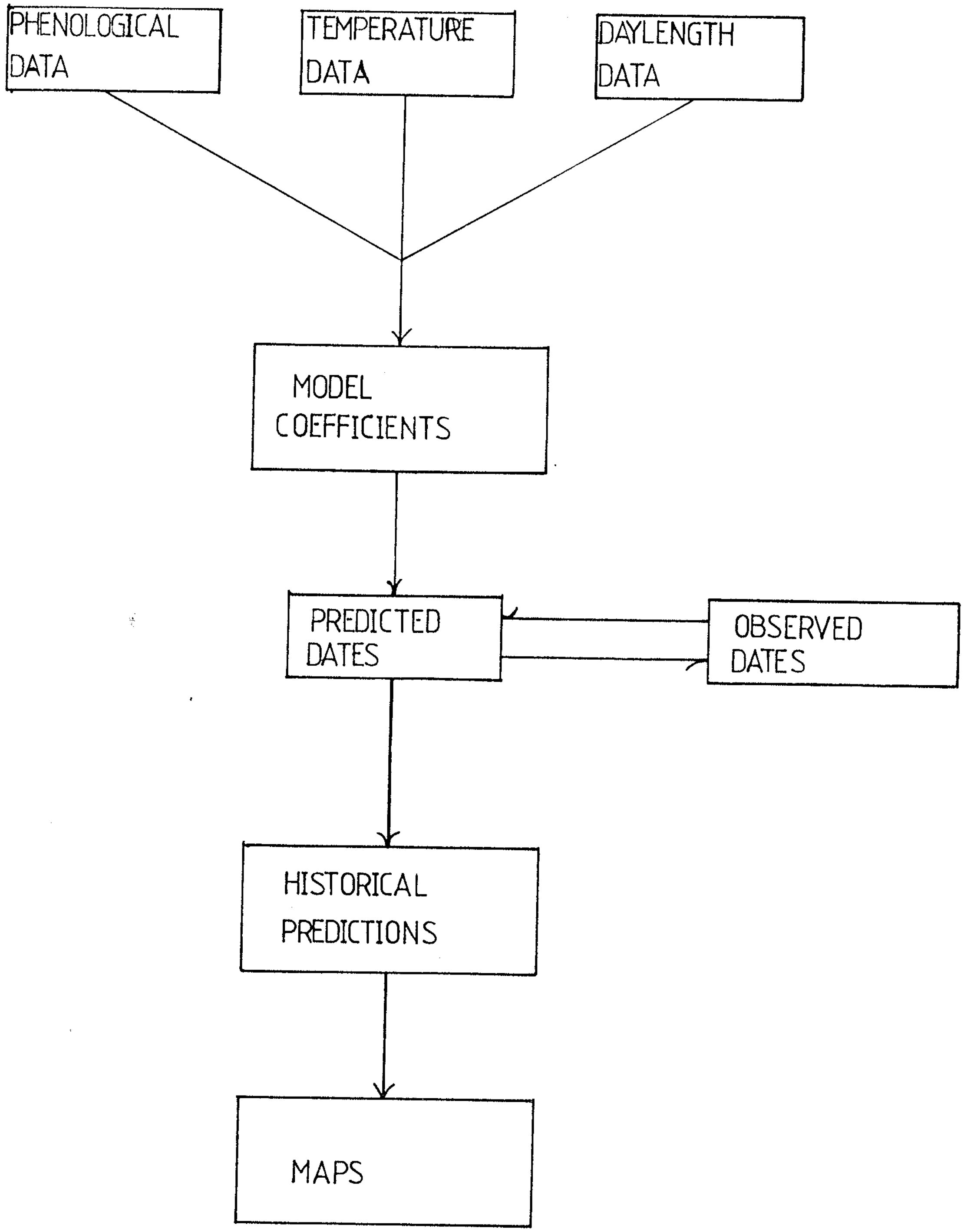

Figure 7: Diagrammatic representation of model building process.

3.6 CLIMATOLOGICAL ANALYSIS

The climatological analysis used weather stations which had recorded weather observations (maximum and minimum temperature) for a minimum of 15 years. A list of the stations used in this analysis are given in Appendix B. The locations of these stations are shown in Figure 8.

The planting dates used in the model were obtained by adding a constant value of 5 days to the planting date for wheat. The planting dates for wheat are available for the years 1948-1978 from Statistics Canada. The method of calculating an actual planting date from this data outlined by Dunlop (1981) was used. The historical weather data and planting dates were then used by the soybean crop growth model to predict the date of maturity for each year. If the predicted maturity date came before the first killing frost (-2.2°C) then that year was said to be a suitable year for growing soybeans. The probability of having a suitable year for soybean production is then given by

$$P(\text{suitable year}) = \frac{\text{number of suitable years}}{\text{total number of years}}$$

The probabilities for all of the stations used in the analysis were then used by SYMAP (Symographic Mapping System) to produce a contour map consisting of contours joining areas of equal probability for the successful production of soybeans.

Figure 8: Locations of stations used in climatological analysis.

Chapter IV

RESULTS AND DISCUSSION

In the previous chapter the model building and application process was described. The results of the model building phase will be discussed by the year of the data used in the development of the model. The complete and temperature only models will be discussed separately. After the model building results have been discussed then the application of the project will be described.

4.0.1 Phenological Observations

The phenological data gathered during the four years were used to calculate the date at which each stage was reached. The complete set of phenological data for the cultivars Portage, Maple Presto and McCall is presented in Appendix A. Tables 7, 8 and 9 show the lengths (in days) of the planting to emergence (PLT-VE), emergence to flowering (VE-R1), flowering to beginning pod fill (R1-R3) and podfill to physiological maturity (R3-R7). The cultivar Maple Presto consistently matured earlier than the other two cultivars. Of the other two cultivars, Portage, appears to mature slightly earlier than McCall. All cultivars took approximately the same time to emerge. Maple Presto has a slightly shorter vegetative growth phase and a substantially shorter reproductive phase.

4.0.2 Seed Yield

Yields for the plot sites are shown in Table 10. The missing data for McCall and Maple Presto is due to unfavourable climatic conditions. Portage yield data was not collected for the years of 1980 and 1981. McCall, in the cases when it reached maturity out yielded Portage and Maple Presto. Portage also showed a yield advantage over Maple Presto at most sites.

TABLE 7

Length of growth stages for soybean cultivar Maple Presto.

		Length of Stage (days)				
Station	Year	PLT-VE	VE-R1	R1-R3	R3-R7	
Winnipeg	1979	12	28	8	39	
Morden	1979	14	26	9	46	
Waskada	1979	18	25	8	33	
Brandon	1979	11	26	8	34	
Dauphin	1979	14	24	13	44	
Morden	1980	17	26	8	37	
Brandon	1980	9	23	12	--	
Dauphin	1980	11	29	18	42	
Dauphin	1980	--	--	14	43	
Woodmore	1981	12	29	15	36	
Mariapolis	1981	8	32	15	34	
Teulon	1981	7	31	12	36	
Winnipeg	1981	7	34	13	36	
Woodmore	1982	11	40	12	38	
Mariapolis	1982	8	40	13	--	
Teulon	1982	7	35	20	--	
Bagot	1982	8	39	16	34	
Average		10.9	30.4	12.6	37.6	91.5

The yield of soybeans is thought to be related to the length of the reproductive growth period (Dunphy et al., 1979; Falk, 1981). There appears to be such a relationship

TABLE 8

Length of growth stages for soybean cultivar McCall.

Station	Year	Length of Stage (days) PLT-VE	VE-R1	R1-R3	R3-R7	
Winnipeg	1979	11	33	14	47	
Morden	1979	14	28	16	48	
Waskada	1979	17	27	13	42	
Brandon	1979	11	32	10	43	
Dauphin	1979	13	35	14	--	
Morden	1980	12	32	12	52	
Brandon	1980	9	27	14	--	
Dauphin	1980	10	38	11	--	
Dauphin	1980	--	--	21	45	
Woodmore	1981	12	29	21	42	
Mariapolis	1981	8	34	20	47	
Teulon	1981	7	33	15	44	
Winnipeg	1981	7	34	17	45	
Woodmore	1982	11	42	21	42	
Mariapolis	1982	7	42	20	--	
Teulon	1982	7	35	24	--	
Bagot	1982	8	43	18	--	
Portage[1]	1981	11	31	17	55	
Portage[1]	1981	11	38	14	--	
Average		10.3	34.1	16.3	46.	106.7

[1] Portage data gathered by A. Senthanathan.

TABLE 9

Length of growth stages for soybean cultivar Portage.

Station	Year	Length of Stage (days) PLT-VE	VE-R1	R1-R3	R3-R7	
Winnipeg	1979	13	35	11	40	
Morden	1979	15	31	13	40	
Waskada	1979	19	31	10	36	
Brandon	1979	11	34	11	36	
Dauphin	1979	15	35	14	--	
Morden	1980	18	29	10	44	
Brandon	1980	9	24	15	--	
Dauphin	1980	10	38	11	50	
Dauphin	1980	--	--	20	43	
Woodmore	1981	12	34	16	40	
Mariapolis	1981	8	39	14	43	
Teulon	1981	7	35	15	37	
Winnipeg	1981	7	41	12	39	
Average		12.0	33.8	13.23	40.7	99.7

TABLE 10

Length of reproductive phase and yields for soybean cultivars Portage, McCall, Maple Presto.

		Cultivar					
		Maple Presto		McCall		Portage	
		Length (days) (R1-R7)	Yield (kg ha^{-1})	Length (days) (R1-R7)	Yield (kg ha^{-1})	Length (days) (R1-R7)	Yield (kg ha^{-1})
Winnipeg	1979	47	1809	61	2559	51	1790
Morden	1979	49	3107	64	4538	53	3929
Waskada	1979	41	864	55	1416	46	1203
Brandon	1979	42	1907	53	1951	47	1786
Dauphin	1979	57	1741	--	--	--	--
Morden	1980	45	2203	64	3689	54	2927
Brandon	1980	--	--	--	--	--	--
Dauphin	1980	53	1510	65	1755	36	1628
Dauphin	1980	--	--	--	--	--	--
Woodmore	1981	51	3056	63	3101	--	--
Mariapolis	1981	49	2363	67	3879	--	--
Teulon	1981	48	2593	59	3512	--	--
Winnipeg	1981	49	2792	62	3669	--	--
Woodmore	1982	50	2489	63	2638	--	--
Mariapolis	1982	--	--	--	--	--	--
Teulon	1982	--	--	--	--	--	--
Bagot	1982	50	2252	--	--	--	--

in the data as the lowest yielding cultivar, Maple Presto, had the shortest reproductive growth phase. Regression analysis using the Statistical Analysis System (SAS) was applied to the yield - reproductive growth phase data to determine if there was a relationship between yield and reproductive phase length. When each cultivar was considered separately it was found that there was no relationship between yield and reproductive phase. Figure 9 shows the relationship between the two variables when the data from all three cultivars is used. The model variables were significantly related (at $P = .01$) but the model's ability to predict was very poor ($r^2 = .28$). This result indicates that the inclusion of another variable to improve the model may be appropriate. The addition of a soil water availability term may have improved the relationship but a lack of continuous soil moisture data prevents the use of a moisture term.

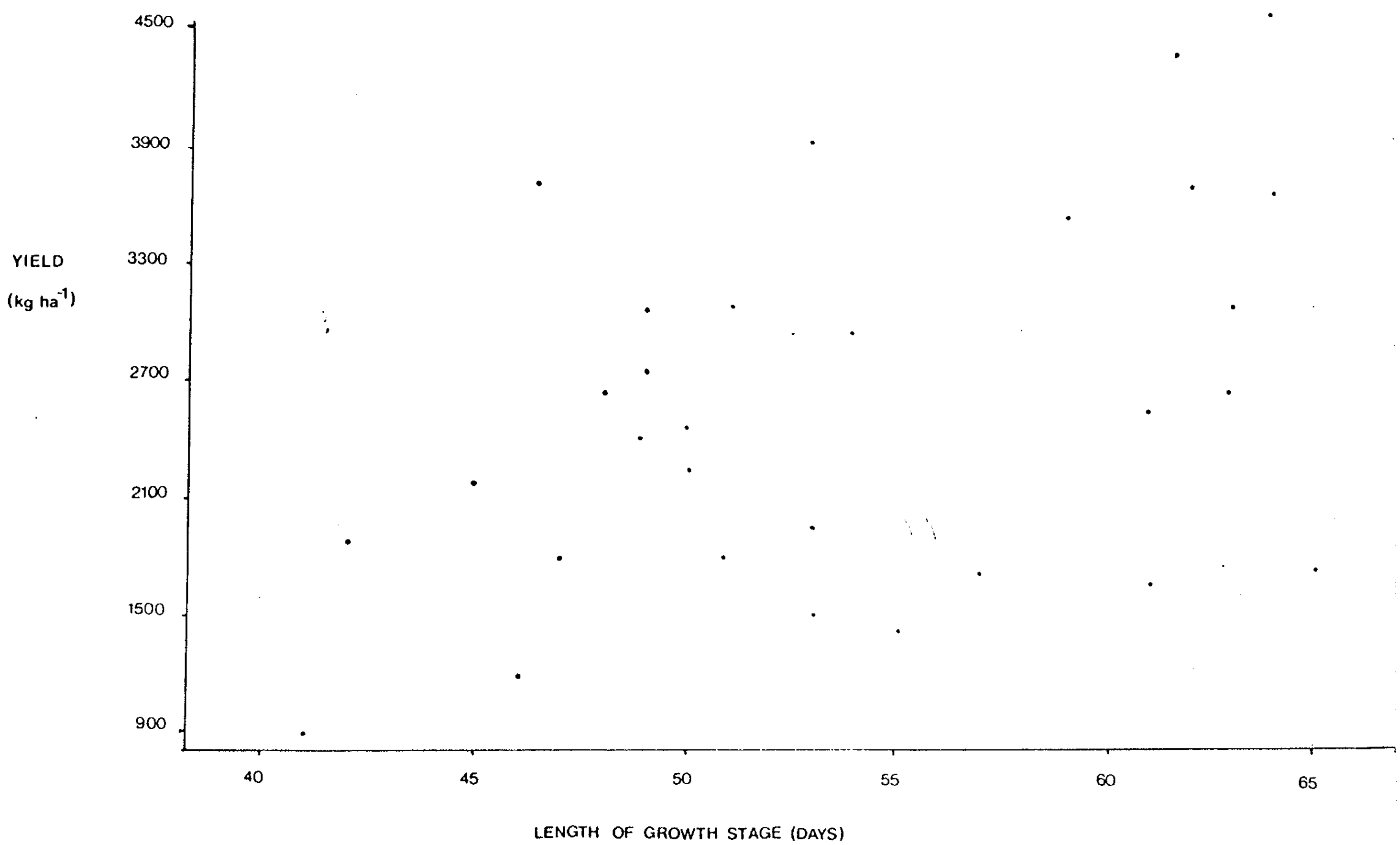

Figure 9: Relationship between yield and length of reproductive phase.

4.0.3 Model Assumptions

Usually in the model building process, several assumptions are made in the model. If these assumptions are not recognized then there is a chance that the model could be misapplied and the result could be poor prediction of crop growth. It is therefore useful to outline the model assumptions before interpreting the model results.

The biometeorological time scale coefficients are determined by a special type of regression analysis. Thus all considerations that must be used in applying and interpreting regression analysis must be followed. The assumption of regression analysis is that the model properly portrays the dependence of the variables upon each other. Specifically in this model the assumption is that growth is a quadratic function of temperature and photoperiod. If this is not the case then the model may not be totally accurate.

When one uses a regression model to predict the dependent variable (in this case growth) several considerations must be acknowledged (Neter and Wasserman, 1974). These considerations are:

1. The conditions in predicted period are similar to those which were in existence during the period from which the model was base. In the case of this particular model this means that the environmental conditions (i.e., fertility, disease, moisture, pest) in a predicted year were similar to the conditions in the locations that the data was acquired.

2. The regression model is only valid for the range of values of the independent variable that were encountered in the experimental period. As a result of this the proposed model should only be applied to temperatures and photoperiods which are similar to those of the research sites.
3. There is no physical significance to the coefficients developed in regression analysis. Thus, one must be very cautious in interpreting the regression equation as if it was an empirical equation. This is particularly important in the interpretation of base temperatures.

4.1 TEMPERATURE - PHOTOPERIOD MODEL COEFFICIENT DETERMINATION.

Falk (1981) calculated a set of coefficients for soybeans using two years (nine station years) of data. The prediction ability of this model was tested using the third year of data. The results are shown in Table 11.
The model adequately predicts Maple Presto growth in the vegetative growth period and the pod to maturity stage.

The McCall coefficients did a poor job of predicting growth at all stages. For Portage, the vegetative phase was the only growth period which was predicted accurately.

The reasons for poor prediction of the independent growth data are two-fold. The first reason is that the length of the growth stage being modeled determines the accuracy which can be attained. It is more difficult to obtain an accurate

TABLE 11

Differences between predicted and actual dates. Second year model.

Site	Year	Difference (Days) Maple Presto (VE-R1)	(R1-R3)	(R3-R7)	McCall (VE-R1)	(R1-R3)	(R3-R7)	Portage (VE-R1)	(R1-R3)	(R3-R7)
Woodmore	1981	2	-7	3	5	-8	-7	0	-7	-6
Mariapolis	1981	2	-4	5	5	-6	-7	-2	5	-7
Teulon	1981	1	-3	-3	5	-1	22	6	-2	-2
Winnipeg	1981	-2	-4	-2	2	-4	-7	-2	7	-6
Average		.75	-4.50	.75	4.25	-4.75	.25	.50	1.75	-5.25
Root Mean Square Error		1.8	4.7	3.4	4.4	5.4	11.7	3.3	5.6	5.6

model for a short growth period than for a longer one (Falk, 1981). This is shown in Table 11 as the shortest period, flowering to pod-fill, has the largest difference between predicted and estimated dates in McCall and Maple Presto. The limitations of regression analysis, especially in predicting values using limited data, plays an important role in determining the accuracy of the model.

The best way to improve a model's predicting ability is to increase the range of the independent variables. In this case, two more years of data were collected and analysed with the first two years.

4.1.1 Third Year Model

The model coefficients which were developed using the first three years of data are shown in Table 12. The values for a_0 and b_0 correspond to the critical values of daylength and temperature. It must be emphasized that there is no specific physical meaning implied by the coefficients. For instance, the "base temperature" for the pod filling to maturity phase is given as -20.28°C. The equation was developed with data that did not include temperatures that were close to -20°C. The temperature relationship in this case is linear with a very low value for the slope. This leaves the intercept (critical value) a considerable distance from the data points and results in an unreasonable base temperature. The same is true for the base daylengths. For instance, the base daylength for Maple Presto in the flowering to pod-fill (R1-R3) stage is 21.5 hours, well above the maximum daylength for sites in the agricultural region of Manitoba. Falk (1981) noted a relationship between cultivar and base temperature and photoperiod. The base daylength for McCall is smaller than the base for Maple Presto in the flowering to pod-fill stage. This would result in a longer flowering to pod-fill stage for McCall.

The ability of the third year model to predict the phenological data over the three years is shown in Table 13. The new coefficients do a better job of predicting the four 1981 plot sites than the second year coefficients.

TABLE 12

Temperature - photoperiod model coefficients - Third year model.

Cultivar Stage	AO	A1	A2	BO	B1	B2	B3	B4
Maple Presto								
VE - R1	.6601E 01	.1765E-02	-.1467E-03	.4117E 01	.5974E 00	-.2137E-02	.2159E-01	-.8213E-02
R1 - R3	.2512E 02	-.3360E-01	.0000E 00	.1228E 02	.2197E-01	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1757E 02	-.1833E-01	-.3324E-02	.1074E 02	.1294E 00	-.3212E-02	.0000E 00	.0000E 00
McCall								
Ve - R1	.1907E 02	-.6669E-03	.0000E 00	.5016E 01	.1729E 01	-.4650E-01	.9477E 00	.6928E-01
R1 - R3	.1823E 02	-.2739E 00	.0000E 00	.7067E 01	.5510E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1275E 02	.4550E-03	-.1307E-03	.1043E 02	.1069E 02	-.3768E 00	.0000E 00	.0000E 00
Portage								
VE - R1	.5933E 01	.1737E 00	-.7426E-02	.7383E 01	.1348E-01	-.2829E-03	.0000E 00	.0000E 00
R1 - R3	.1122E 02	.8740E 01	-.9751E 00	.7608E 00	.1658E-03	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1693E 02	-.1794E 00	-.3630E-01	-.2028E 02	.2790E-02	.0000E 00	.0000E 00	.0000E 00

TABLE 13

Differences between predicted and observed dates. Third year temperature - photoperiod model.

Site	Year	Difference (Days)								
		Maple Presto			McCall			Portage		
		(VE-R1)	(R1-R3)	(R3-R7)	(VE-R1)	(R1-R3)	(R3-R7)	(VE-R1)	(R1-R3)	(R3-R7)
Winnipeg	1979	2	1	-1	0	0	-1	-1	-1	1
Morden	1979	-1	0	-5	0	-4	-6	-2	-2	-2
Waskada	1979	-1	-1	2	4	0	1	1	0	1
Brandon	1979	-3	1	0	-4	2	-	-3	0	2
Dauphin	1979	1	-4	-3	-2	-1	-	-2	-2	-[1]
Morden	1980	-1	3	1	-1	4	0	-1	3	-1
Brandon	1980	0	0	-	1	-1	-	1	-1	-
Dauphin	1980	0	1	-1	-5	3	-	-1	2	-2
Dauphin	1980	-	-3	-3	-	-3	1	-	8	-2
Woodmore	1980	0	-6	0	-1	-7	-3	0	-3	-2
Mariapolis	1981	0	-2	3	0	-3	-4	0	0	-4
Teulon	1981	-1	-2	-3	2	0	0	3	-3	-1
Winnipeg	1981	-5	-4	-2	-2	3	-4	-4	0	-3
RMSE		1.9	2.8	2.5	2.5	3.1	3.0	2.0	2.8	2.1

[1] Dash indicates no data for that site.

4.1.2 Fourth Year Coefficient

Table 14 shows the difference between actual and predicted values for the fourth year of data.

TABLE 14

Differences between predicted and actual dates. Third year model.

Site	Year	Difference (Days)					
		Maple Presto			McCall		
		(VE-R1)	(R1-R3)	(R3-R7)	(VE-R1)	(R1-R3)	(R3-R7)
Woodmore	1982	2	6	-1	4	-7	5
Mariapolis	1982	3	-2	-	-1	-3	-
Teulon	1982	1	3	-	0	-2	-
Bagot	1982	-4	-4	2	2	1	-
Portage[1]	1981	-	-	-	3	-2	-
Portage	1982	-	-	-	-1	-3	-
RMSE		2.7	4.05	1.6	2.8	3.6	

[1] Independent data.

The third year model does a reasonable job of predicting the independent data. Again the most difficulty was encountered when predicting the flowering to pod-fill (R1-R3) stage. An early fall frost resulted in very little data for the pod-fill to maturity stage.

The fourth year coefficients are shown in Table 15. Even though the third year coefficients did a reasonable job of predicting the fourth year of data, the change in coefficients between the third and fourth year models was quite large. This has to do with the complexity of the curve fitting process in the iterative regression (see Appendix C). The fourth year model was eventually applied to the historical weather data.

TABLE 15

Temperature - photoperiod model coefficients - Fourth year model.

Cultivar Stage	A0	A1	A2	B0	B1	B2	B3	B4
Maple Presto								
PLT - VE								
VE - R1	.2143E 02	-.5649E-02	.0000E 00	.6012E 01	.6520E-01	.0000E 00	.0000E 00	.0000E 00
R1 - R3	.2820E 01	-.3079E-01	.0000E 00	.1200E 02	.1574E-01	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1167E 02	-.1188E-00	-.2081E-01	.7027E 01	.1366E-01	-.2071E-03	.0000E 00	.0000E 00
McCall								
PLT - VE								
VE - R1	-.3644E 01	.5893E-01	-.2584E-02	.3998E 01	.9503E-02	-.2209E-03	.3154E-01	-.1710E-02
R1 - R3	.2770E 02	-.5684E-01	.0000E 00	-.2397E 00	.3673E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1275E 02	.4550E-03	-.1307E-03	.1043E 02	.1069E 02	-.3768E 00	.0000E 00	.0000E 00

4.1.3 Temperature Only Models

A growth model considering temperature only can be made by modifying the biometeorological time scale (Robertson, 1967). This modified equation is somewhat like the corn heat unit equation. The temperature only model is useful in two ways. Firstly, it can be used to model the planting to emergence stage, an important part of the climatic analysis. Secondly, the model can be used to compare its prediction ability with that of the temperature photoperiod model. This will give an indication of the contribution of daylength to the prediction ability of the model.

Table 16 shows the coefficients for the temperature only model developed after the third year. The differences between predicted and observed data is shown in Table 17. When this data is compared with that of the third year temperature - photoperiod model, it is apparent that the temperature only model is not quite as accurate. This is to be expected as the inclusion of an extra variable, in this case, photoperiod, will increase the prediction ability of the model. The fourth year model coefficients are shown in Table 18. The PLT - VE stage will be used in the climatological analysis.

TABLE 16

Temperature only model coefficients - Third year model.

Cultivar Stage	b_0	b_1	b_2	b_3	b_4
McCall					
PLT - VE	.9483E 01	.1212E-01	-.3211E-03	.0000E 00	.0000E 00
VE - R1	.4323E 01	.2429E-02	-.4115E-04	.0000E 00	.0000E 00
R1 - R3	-.9498E 01	.1967E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	-.8156E 02	.2095E-03	.0000E 00	.0000E 00	.0000E 00
Maple Presto					
PLT - VE	.1149E 02	.1097E-01	-.3503E-03	.0000E 00	.0000E 00
VE - R1	-.3551E 03	-.1371E-02	.3865E-05	.0000E 00	.0000E 00
R1 - R3	.1104E 02	.6210E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1155E 02	.3499E-02	-.1006E-03	.0000E 00	.0000E 00
Portage					
PLT - VE	.1386E 02	.1996E-01	-.8155E-03	.0000E 00	.0000E 00
VE - R1	.1231E 02	.4351E-02	-.1353E-03	.0000E 00	.0000E 00
R1 - R3	.1093E 01	.3270E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.4863E 01	.1932E-02	-.3091E-04	.0000E 00	.0000E 00

TABLE 17

Differences between predicted and observed dates. Third year temperature model.

Site	Year	Difference (Days)											
		Maple Presto				McCall				Portage			
		(PLT-VE)	(VE-R1)	(R1-R3)	(R3-R7)	(PLT-VE)	(VE-R1)	(R1-R3)	(R3-R7)	(PLT-VE)	(VE-R3)	(R1-R3)	(R3-R7)
Winnipeg	1979	1	4	5	6	7	-4	-6	-7	1	-2	-1	1
Morden	1979	-2	5	4	4	1	-1	-7	-11	-2	1	-2	0
Waskada	1979	-8	5	5	11	-4	-1	-5	-7	-9	0	1	1
Brandon	1979	-1	4	5	10	2	-7	-2	-7	-1	-3	0	3
Dauphin	1979	-4	6	0	2	2	-11	-2	-	-4	-5	-2	-
Morden1	980	-4	5	6	7	5	-7	-2	-17	-2	4	3	-6
Brandon	1980	0	7	3	-	4	-2	1	-	1	7	-1	-
Dauphin	1980	-1	2	3	3	3	-10	1	-	0	-5	2	-5
Dauphin	1980	-	-	0	2	-	-	-11	-5	-	-	-8	-1
Woodmore	1981	0	4	-1	9	4	2	-12	-6	10	-5	-3	-2
Mariapolis	1981	2	3	0	11	6	0	-7	-10	2	-1	0	-3
Teulon	1981	2	0	2	7	6	-5	-5	-10	3	-2	-3	-1
Winnipeg	1981	2	-2	1	8	6	-5	-7	-11	2	-8	0	-2

TABLE 18

Temperature only model coefficients - Fourth year model.

Cultivar Stage	b_0	b_1	b_2	b_3	b_4
Maple Presto					
PLT - VE	.1286E 02	.2016E-01	-.8129E-03	.0000E 00	.0000E 00
VE - R1	.6033E 01	.1933E-02	.0000E 00	.0000E 00	.0000E 00
R1 - R3	.1309E 02	-.6872E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	.1026E 02	-.3361E-02	-.9438E-04	.0000E 00	.0000E 00
McCall					
PLT - VE	.1145E 02	.1491E-01	-.4485E-03	.0000E 00	.0000E 00
VE - R1	.4137E 01	.2360E-02	-.3850E-04	.0000E 00	.0000E 00
R1 - R3	-.5303E 01	.2093E-02	.0000E 00	.0000E 00	.0000E 00
R3 - R7	-.8156E 02	.2095E-03	.0000E 00	.0000E 00	.0000E 00

4.1.4 Climatological Analysis

The model of crop growth development then was applied to a historical weather data base to determine the areas of potential soybean production. This analysis deals only with the climatological factors involved in soybean production. Other factors such as soil type and fertility are not taken into account. Yield, an important consideration in the production of soybeans was not used as criterion. The fourth year coefficients for McCall and Maple Presto and the third year coefficients for Portage were used to model soybean growth. For each weather station, historical planting dates for wheat were used as a base seeding date. A constant value of 5 days was added to this date to calculate the seeding date for soybeans. Predicted maturity dates were then compared with the date of the first killing fall frost. If the fall frost date came before the expected maturity date then the year was considered to be unsuitable. Probabilites were then calculated for each station and were mapped using SYMAP. The results of the symap procedure are shown in Figures 10, 11 and 12.

When these figures are compared with a corn heat unit map of Manitoba (Dunlop, 1981) a number of observations can be made. The 80% probability contour of Maple Presto follows approximately the 2300 corn heat unit isoline. The McCall and Portage 80% contours are very close to the 2500 corn heat unit isoline. The 2300 (Maple Presto) and the 2500 (McCall) corn heat unit areas are currently recommended for production of these soybean cultivars.

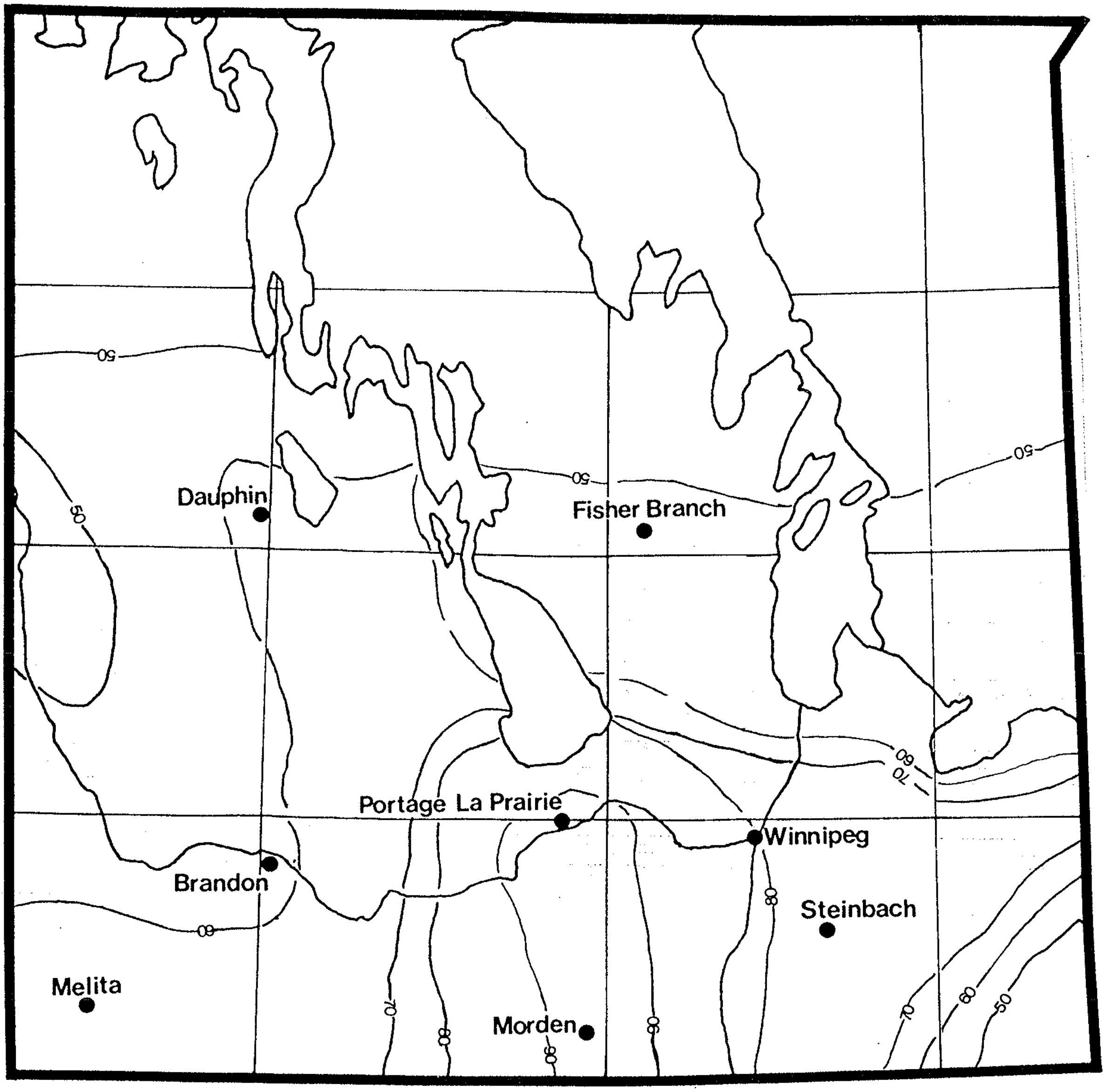

Figure 10: Probability of McCall maturing before first killing frost.

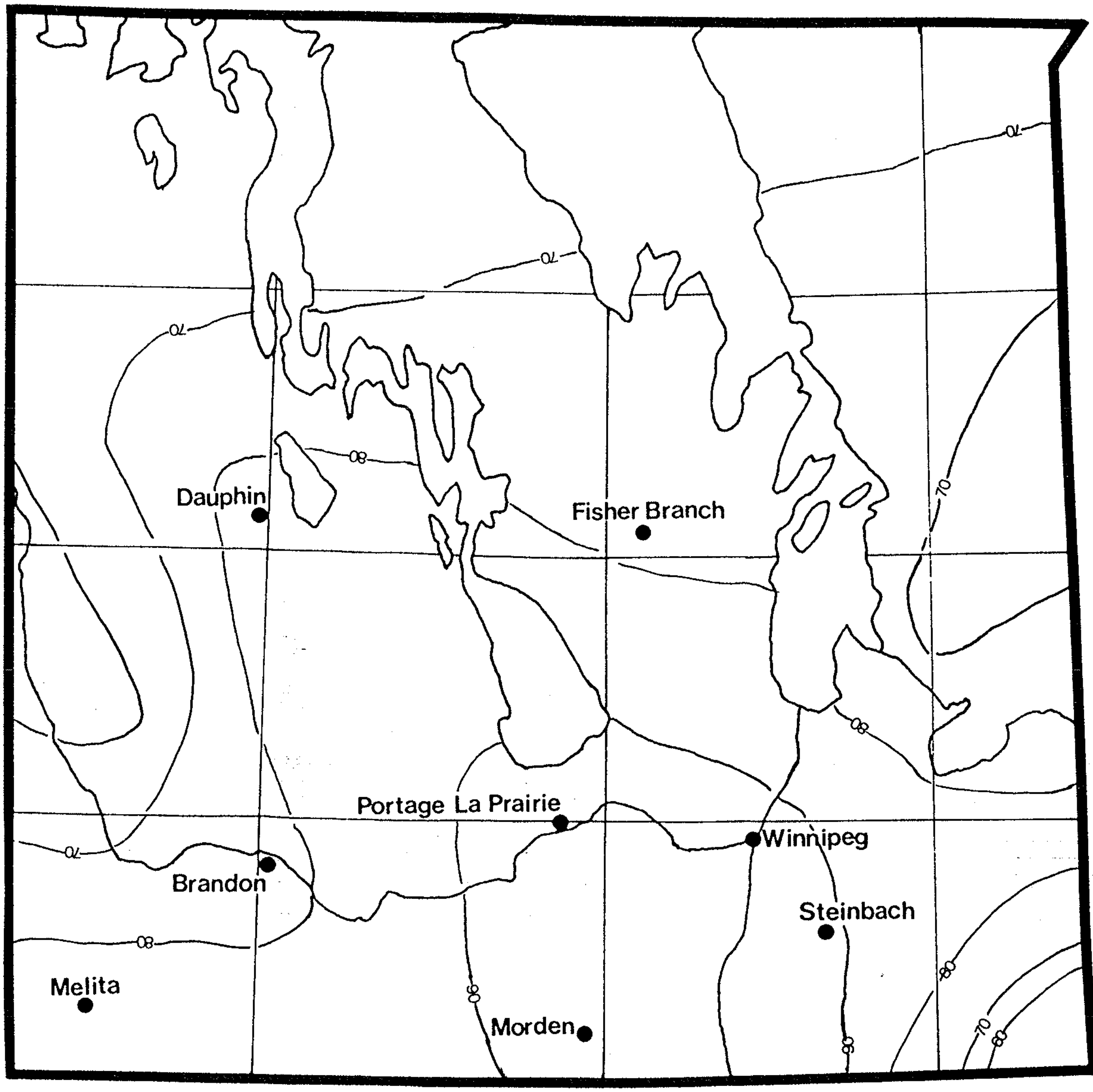

Figure 11: Probability of Maple Presto maturing before first killing frost.

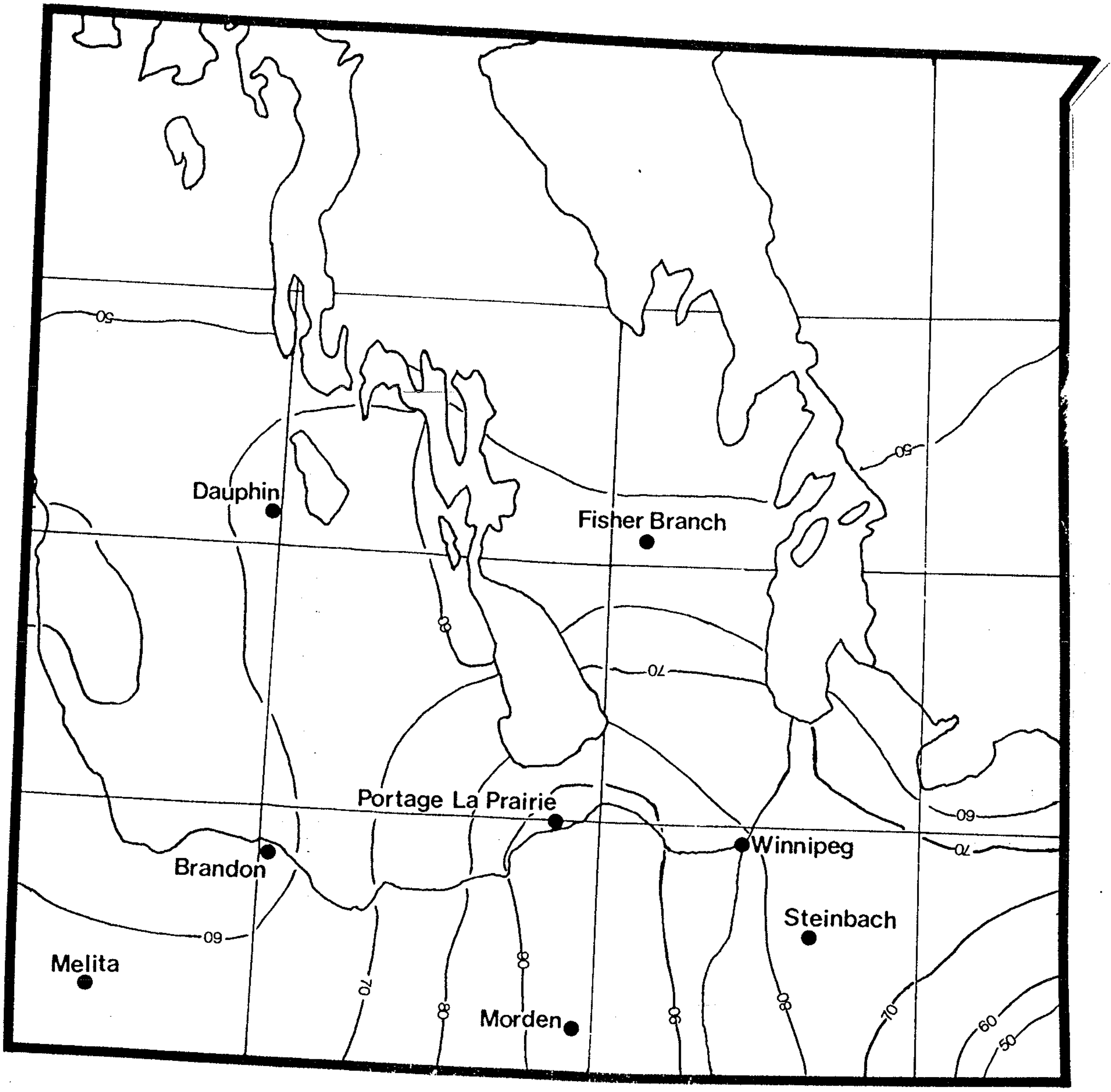

Figure 12: Probability of Portage maturing before first killing frost.

Maple Presto is the most adaptable cultivar to Manitoba's climate. Most of the agronomic area of Manitoba has a 70% chance of successfully growing soybeans. The yield of the Maple Presto may not be enough for economic production. The other two cultivars show a significant yield advantage but are very limited in the area in which they can be grown. The Carman - Portage - Winkler region appears to be the most suitable (>90% probability of maturing) for the production of Portage and McCall cultivars. Other areas in South Central Manitoba may be suitable, but growing these cultivars outside of this region has a high level of risk.

Chapter V

CONCLUSIONS

The biometeorological time scale proved to be an effective method of predicting soybean development. Of the two soybean growth models developed, the temperature - photoperiod model proved to be the most accurate.

The model proposed by Falk (1981) using nine station years of data did not predict soybean development very well. When the third year of data was incorporated into the model, the predicting ability became better. In predicting the fourth year growth stage lengths, the model had the highest root mean square error in the Maple Presto R1-R3 stage. The third year model had the most difficulty in predicting short growth stages. Planting to emergence was modelled by a temperature only model. The performance of the planting to emergence model was good.

The photoperiod contribution to the model was evaluated by using a temperature only model. The temperature only model consistently had higher root mean square errors in predicting the data from the first three years. The highest root mean square error of 9.2 occurred in the McCall R1-R3 stage using the temperature only model.

A final model was derived from the four years of phenological measurements. This model was used in the analysis of the historical weather data. The results of the historical weather analysis indicate that Maple Presto is the most suited to Manitoba's climate. A large portion of the agricultural land in Manitoba has a greater than 80% probability of maturing Maple Presto soybeans before the first killing frost in the fall. McCall and Portage have a significantly smaller area suited for their production. The 80% probability area for McCall is located in the south central portion of the province, specifically the Morden - Portage - Winnipeg region. Production of these cultivars outside this region is risky.

The historical analysis does not take into account yield potential. The yield potential of Maple Presto is significantly lower than McCall. Further study should be done on the relationship between the environment and yield of soybeans. New cultivars, which show potential for production in Manitoba, should be analysed in a similar manner to determine the potential area of production.

LIST OF REFERENCES

Beuerlein, J. E. and J. W. Pendleton. 1971. Photosynthetic rates and light saturation curves of individual soybean leaves under field conditions. Crop Sci. 11:217-219.

Boyer, J.S.. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflowers at various leaf water potentials. Plant Physiol. 46:233-235.

Bramlage, W. J., C. A. Leopold and D. J. Parrish. 1978. Chilling stress to soybeans during imbibition. Plant Physiol. 61:526-529.

Brown, D. M. 1962. Soybean ecology I. Development - temperature relationships from controlled environmental studies. Agron. J. 52:493-495.

Brown, D. M. and L. J. Chapman. 1962. Soybean ecology II. Development - temperature - moisture relationships from field studies. Agron. J. 52:496-499.

Burris, J. S., O. T. Edje and A. H. Wahab. 1973. Effects of seed size on seedling performance in soybeans II. Seedling growth and photosynthesis and field performance. Crop Sci. 13:207-210.

Burris, J. S. and K. H. Knittle. 1975. Partial reversal of temperature dependent inhibition of soybean hypocotyl elongation by cotyledon excision. Crop. Sci. 15:461-462.

Burris, J. S., A. H. Wahab and O. T. Edje. 1971. Effects of seed size on seedling performance in soybeans. I. Seedling growth and respiration in the dark. Crop Sci. 11:492-496.

Ciha, A. J. and W. A. Brun. 1975. Stomatal size and frequency in soybeans. Crop Sci. 15:309-313.

Doss, B. S., B. W. Pearson and H. T. Rodgers. 1974. Effect of soil water stress at various stages on soybean yield. Agron. J. 66:297-299.

Dunlop, S. 1981. An agroclimatology of southern Manitoba. M. A. Thesis. Department of Geography, University of Manitoba.

Dunphy, E. J., J. J. Hanway and D. E. Green. 1979. Soybean yields in relation to days between specific developmental stages. Agron. J. 71:917-920.

Edwards C. J. and E. E. Hartwig. 1971. Effect of seed size upon rate of germination in soybeans. Agron. J. 63:429-430.

Elgi, D.B.,J.E. Leggette, and J.M. Wood. 1978. Influence of soybean seed size and position on the rate and duration of filling. Agron. J. 70:127-130.

Elgi D.B. and I.F. Wardlaw. 1980. Temperature response of seed growth characteristic of soybeans. Agron. J. 72:560-564.

Emmerson, B. N., H. C. Minor. 1979. Response of soybeans to high temperature during germination. Crop Sci. 19:553-558.

Falk, G. 1981. Environmental factors affecting soybean growth in Manitoba. M. Sc. Thesis. Department of Plant Science, University of Manitoba.

Fehr, W.R. and C.E. Caviness. 1977. Stages of soybean development. Special Report 80, Cooperative Extension Service, Iowa State University, Ames IA.

Fehr, W. R., J. S. Burris and D. F. Gilmar. 1973. Soybean emergence under field conditions. Agron. J. 65:740-742.

Fontes, L. A. N. and A. J. Ohlrogge. 1972. Influence of seed size and population on yield and other characteristics of soybeans. Agron. J. 64:833-836.

Garner, W. W. and H. A. Allard. 1920. Effect of relative length of day and night and other factors of the environment on growth and reproduction in plants. J. Agric. Res. 18:553-606.

Gilman, D. F., W. R. Fehr and J. S. Burris. 1973. Temperature effects on hypocotyl elongation of soybeans. Crop Sci. 13:246-249.

Gordon, A. J., J. D. Hesketh and D. B. Peters. 1982. Soybean photosynthesis in relation to maturity classification and stage of growth. Photosynthesis Res. 3:81-83.

Gourdon, F. and C. Planchon. 1982. Responses of photosynthesis to irradiance and temperature in soybean, Glycine max. Photosynthesis Res. 3:31-42.

Grabbe, D. F. and R. B. Metzer. 1969. Temperature induced inhibition of soybean hypocotyl elongation and seedling emergence. Crop Sci. 9:331-333.

Hadas, R. and D. Russo. 1974. Water uptake by seeds as affected by water stress, capillary conductivity, and seed soil contact. Agron. J. 66:643-647.

Hatfield, J. L. and D. B. Elgi. 1974. Effect of temperature on the rate of soybean hypocotyl elongation and field emergence. Crop Sci. 14:423-426.

Heatherly, L. G. and W. J. Russell. 1979. Effect of soil water potential of two soils on soybean emergence. Agron. J. 71:980-982.

Hesketh, J. D., D. L. Myhre and C. R. Willey. 1973. Temperature control of time intervals between vegetative and reproductive events in soybeans. Crop Sci. 13:250-254.

Hicks, D. R. 1978. Growth and Development. In: Soybean Physiology, Agronomy and Utilization. Norman, Ed., Academic Press. pp. 17-44.

Hill, R. W., D. R. Johnson and K. H. Ryan. 1979. A model for predicting soybean yield from climatic data. Agron. J. 71:251-256.

Hobbs, P.R. and R. L. Obendorf. 1972. Interaction of initial seed moisture and imbibitional temperature on germination and productivity of soybean. Crop Sci. 12:664-667.

Hofstra, G. 1972. Response of soybeans to temperature under high light intensities. Can. J. Plant Sci. 52:535-543.

Hopper, N. W., J. R. Overholt and J. R. Martin. 1979. Effect of cultivar, temperature and seed size on the germination and emergence of soyabeans. Ann. Bot. 45:301-308.

Hume, D. J. and A. K. H. Jackson. 1981. Pod formation in soybeans at low temperatures. Crop Sci. 21:933-937.

Hunter, J. R. and A. E. Erickson. 1952. Relation of seed germination to soil moisture tension. Agron. J. 44:107-109.

Johnson, D. R. and V. D. Leudders. 1974. Effect of planted seed size on emergence and yield of soybeans. Agron. J. 66:117-118.

Johnson, D. R. and D. J. Major. 1979. Harvest index of soybeans as affected by planting date and maturity rating. Agron. J. 71:538-541.

Kao, C. H. 1980. Retardation of senescence by low temperature and benzyladenire in intact primary leaves of soybeans. Plant and Cell Physiol. 21:339-344.

Kilen, T. C. 1979. A temperature sensitive miniature soybean. Crop Sci. 19:405-406.

Knittle, K. H. and J. S. Burris. 1979. Effect of downward force on soybean hypocotyl growth. Crop Sci. 19:47-51.

Knittle, K. H. and J. S. Burris. 1979. Soybean hypocotyl growth under field conditions. Crop Sci. 19:37-41.

Knittle, K. H., J. S. Burris and D. C. Erbach. 1979. Regression equations for rate of soybean hypocotyl elongation by using field data. Crop Sci. 19:41-46.

Knypl, J. S. and K. M. Janas. 1979. Increasing low temperature resistance of soybean by exposure of seeds to water saturated atmosphere. Biologia Planterium 21:291-297.

Littlejohns, D.A. and J.W. Tanner. 1976. Preliminary studies on the cold tolerance of soybean seedlings. Can. J. Plant Sci. 56:371-375.

Major, D. J. 1980. Photoperiod response characteristics controlling flowering of nine crop species. Can. J. Plant Sci. 60:777-784.

Major, D. J., D. R. Johnson, J. W. Tanner and I. C. Anderson. 1975. Effects of daylength and temperature on soybean development. Crop Sci. 15:174-179.

Major, D. J., D. R. Johnson and V. D. Luedders. 1975. Evaluation of eleven thermal unit methods for predicting soybean development. Crop Sci. 15:172-174.

Martineau, J. R., J. H. Williams and J. E. Specht. 1979. Temperature tolerance in soybeans. II. Evaluation of segregating populations for membrane thermostability. Crop Sci. 19:79-81.

Mayer, A. M. and A. Poljakoff-Mayber. 1981. The germination of seeds. Third edition. Pergamon Press, Oxford.

Meyer, G. E., R. B. Curry, J. G. Streeter and H. J. Mederski. 1979. SOYMOD/OARDC. A dynamic simulator of soybean growth, development and seed yield. I. Theory structure and validation. Research Bulletin Ohio Agricultural Research and Development Center. 36 pp.

Neter, J. and W. Wasserman. 1974. Applied linear statistical models. Richard D. Irwin Inc. Homewood, Ill.

Nissly, C.R., R.L. Bernard, and C.N. Hittle. 1981. Variation in photoperiod sensitivity for time of flowering and maturity among soybean strains of maturity group III. Crop Sci. 21:833-837.

Obendorf, R. L. and P. R. Hobbs. 1970. Effect of seed moisture on temperature sensitivity during imbibition of soybean. Crop Sci. 10:563-566.

Patterson, D. T., M. M. Peet and J. A. Bunee. 1977. Effect of photoperiod and size at flowering on vegetative growth and seed yield of soybean. Agron. J. 69:631-635.

Polson, D. E. 1972. Day-neutrality in soybeans. Crop Sci. 12:773-776.

Read, D. J. and E. M. Bartlett. 1972. The physiology of drought resistance in the soybean plant. The relationship between drought and growth. J. of Appl. Ecol. 9:487-499.

Robertson, G. W. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. Int. J. Biometeor. 12:191-223.

Robertson, G. W. and D. A. Russello. 1968. An astrometeorological estimater for estimating time when sun is at any elevation, elapsed time between the same elevations in the morning and afternoon and hourly and daily values of solar energy, Qo. Ag. Met. Tech. Bul. 14. Agmet. Section. Canada Department of Agriculture. Ottawa, Canada.

Salisbury, F.B. and C.W. Ross. 1977. Plant Physiology. Second Edition, Wadsworth Publishing Co. Inc., Belmont.

Siammy, C. and C. E. Lamotte. 1976. Anomalous temperature dependence of seedling development in some soybean cultivars. Plant Physiol. 58:786-789.

Schmid, J. and E. R. Keller. 1980. The behavior of three cold tolerant and a standard soybean variety in relation to the level and the duration of cold stress. Can. J. Plant Sci. 60:821-829.

Sediyama, T. and J. R. Wilcox. 1980. Response of soybean populations to inbreeding under two photoperiods. Crop Sci. 20:499-501.

Senthanathan, A. 1983. Response of soybeans to annual crop windbreaks in Manitoba. M.Sc. Thesis, Department of Plant Science, University of Manitoba.

Stone, J.A. and H.M. Taylor. 1983. Temperature and the development of the taproot and lateral roots of four indeterminate soybean cultivars. Agron. J. 75:613-618.

Smith, T. J. and H. M. Camper, Jr. 1975. Effects of seed size on soybean performance. Agron. J. 67:681-684.

Tekrony, D. M., D. B. Elgi and G. Henson. 1981. A visual indicator of physiological maturity in soybean plants. Agron. J. 73:553-556.

Thomas, J. F. and C. D. Raper, Jr. 1976. Photoperiodic control of seed filling in soybeans. Crop Sci. 21:667-672.

Thomas, J. F. and C. D. Raper, Jr. 1983. Photoperiod and temperature regulation of floral initiation and anthesis in soya bean. Ann. Bot. 51:481-489.

van Schaik, P. H. and A. H. Probst. 1958. Effect of some environmental factors on flower production and reproductive efficiency in soybeans. Agron. J. 50:192-197.

Wann, W. and C. D. Raper, Jr. 1979. A dynamic model for plant growth: Adaptation for vegetative growth of soybeans. Crop Sci. 19:461-467.

Waterer, J. 1982. Effect of temperature on soybean emergence. Unpublished B. Sc. Thesis. University of Manitoba. 26 pp.

Whigham, D. K. and H. C. Minor. 1978. Agronomic characteristics and environmental stress. In: Soybean Physiology, Agronomy and Utilization. Norman, Ed. Academic press. p. 45-69.

Wilkerson, G.G., J.W. Jones, K.S. Boote, K.T. Ingram and J.W. Mishoe. 1981. Modelling soybean growth for crop management. ASAE paper No. 81-1801., ASAE St Joseph, MO.

Wilson, H.K. 1928. Wheat, soybean and oat germination studies with particular reference to temperature relationships. J. Am. Soc Agron. 20:599-619.

Williat, S. T. and R. G. Struss. 1979. Germination and early growth of plants studied using neutron radiography. Ann. Bot. 43:415-422.

Zeevaart, J. A. D. 1976. Physiology of flower formation. Ann. Rev. Plant Physiol. 27:321-348.

Appendix A

DATES[1] THAT EACH PHENOLOGICAL STAGE WAS REACHED FOR EACH VARIETY

Portage

STATION		PLT	VE	VC	V1	R1	R2	R3	R4	R5	R6	R7	R8
Winnipeg	1979	144	157	162	170	192	196	203	206	212	225	243	249
Morden	1979	149	164	164	173	195	200	208	215	223	234	248	256
Waskada	1979	145	164	165	172	195	199	205	211	220	229	241	248
Brandon	1979	158	169	170	178	203	208	214	219	227	237	250	256
Dauphin	1979	159	174	176	182	209	215	223	232	247	257	0	0
Morden	1980	130	148	148	153	177	182	187	193	205	217	231	241
Brandon	1980	179	188	189	192	213	221	228	240	253	0	0	0
Dauphin	1980	159	169	175	183	207	211	218	226	237	251	268	0
Dauphin	1980	138	0	0	163	189	200	209	216	228	242	252	270
Woodmore	1981	146	149	160	176	192	204	208	215	222	233	248	0
Mariapolis	1981	151	159	163	168	198	205	212	217	222	233	255	0
Teulon	1981	153	160	167	174	195	203	210	215	220	232	247	0
Winnipeg	1981	151	158	164	174	199	205	211	218	223	234	250	0

McCall

STATION		PLT	VE	VC	V1	R1	R2	R3	R4	R5	R6	R7	R8
Winnipeg	1979	144	155	161	168	188	193	202	206	214	226	249	0
Morden	1979	149	163	164	171	191	198	207	216	224	237	255	0
Waskada	1979	145	162	164	171	189	193	202	209	221	230	244	248
Brandon	1979	158	169	169	178	201	205	211	217	225	237	254	262
Dauphin	1979	159	172	176	182	207	212	221	231	247	258	0	0
Morden	1980	130	142	146	153	174	180	186	194	207	217	238	245
Brandon	1980	179	188	189	193	215	221	229	244	256	0	0	0
Dauphin	1980	159	169	175	184	207	211	218	228	240	253	0	0
Dauphin	1980	138	0	0	163	187	192	208	219	230	242	252	271
Woodmore	1981	146	158	160	176	187	203	208	214	222	239	250	0
Mariapolis	1981	151	159	163	170	191	205	211	217	223	242	258	0
Teulon	1981	153	160	167	173	193	203	208	213	220	238	252	0
Winnipeg	1981	151	158	163	174	192	204	209	214	223	241	254	0
Woodmore	1982	146	160	162	173	199	208	220	228	238	247	262	0
Mariapolis	1982	151	165	165	172	200	211	220	228	0	0	0	0
Teulon	1982	162	175	177	185	204	218	228	242	248	0	0	0
Bagot	1982	146	160	161	169	197	206	215	224	230	0	0	0
Portage	1981	148	159	162	172	190	000	207	000	221	247	262	0
Portage	1982	143	154	158	170	197	000	211	000	224	247	000	0

Maple Presto

STATION		PLT	VE	VC	V1	R1	R2	R3	R4	R5	R6	R7	R8
Winnipeg	1979	144	156	162	168	184	188	192	198	205	214	231	237
Morden	1979	149	163	164	171	189	192	198	207	213	223	238	246
Waskada	1979	145	163	164	170	188	192	196	200	206	217	229	237
Brandon	1979	158	169	169	177	195	199	203	207	212	223	237	245
Dauphin	1979	159	173	176	182	197	203	210	216	229	242	254	262
Morden	1980	130	147	148	152	173	178	181	187	194	206	218	225
Brandon	1980	179	188	189	191	211	218	223	230	239	255	0	0
Dauphin	1980	159	170	175	184	199	205	210	217	233	245	252	0
Dauphin	1980	138	0	0	163	182	190	196	205	215	232	239	252
Woodmore	1981	146	158	160	176	187	198	202	206	213	221	238	0
Mariapolis	1981	151	159	163	168	191	201	206	210	217	226	240	0
Teulon	1981	153	160	167	173	191	197	203	207	211	220	239	0
Winnipeg	1981	151	158	163	173	192	202	205	209	214	220	241	0
Woodmore	1982	146	160	162	173	197	203	209	219	224	230	247	256
Mariapolis	1982	151	165	168	177	199	206	212	220	226	232	0	0
Teulon	1982	162	172	177	186	204	210	224	230	239	246	0	0
Bagot	1982	146	160	161	169	193	204	209	218	224	231	243	249

[1] Dates are given as days into the year, i.e., Jan 1=1.

Appendix B

LATITUDE, LONGITUDE AND ELEVATION OF WEATHER STATIONS USED IN THE CLIMATOLOGICAL ANALYSIS

STATION NAME	NUMBER	LAT.	LONG.	ELEV.(ft.)	YEARS
Baldur	5010140	49 19	99 20	1400	1963-1980
Bede	5010180	49 22	100 56	1450	1956-1980
Birtle	5010240	50 23	100 49	1707	1904-1980
Brandon	5010480	49 55	99 57	1337	1949-1980
Brandon CDA	5010485	49 52	99 58	1200	1890-1980
Camp Shilo	5010540	49 49	99 39	1253	1954-1960
Carberry	5010548	49 52	99 21	1263	1962-1980
Cypress River	5010640	49 33	99 05	1232	1904-1980
Deloraine	5010760	49 11	100 30	1642	1965-1980
Deloraine 2	5010761	49 10	100 24	1750	1954-1980
Hamiota	5011240	50 11	100 37	1700	1930-1980
Melita	5011720	49 20	101 00	1450	1936-1960
Minnedosa	5011760	50 16	99 50	1700	1966-1980
Oakner	5012054	50 04	100 36	1650	1965-1980
Pierson	5012080	49 11	101 14	1538	1946-1980
Portage La Prairie A	5012320	49 54	98 16	867	1952-1980
Portage La Prairie 2	5012322	49 59	98 18	851	1963-1983
Rivers A	5012440	50 01	100 19	1553	1938-1970
Roblin	5012471	51 12	101 27	1735	1969-1980
Rossburn	5012500	50 46	100 48	1936	1956-1980
Russell	5012520	50 47	101 16	1837	1957-1971
Somerset	5012720	49 37	100 15	1350	1912-1969

Strathclair	5012796	50	24	100	24	1905	1962-1980
Virden	5012960	49	51	100	56	1451	1958-1980
Waskada	5013120	49	02	100	45	1540	1959-1980
Altona	5020040	49	06	97	33	813	1948-1980
Boissevain	5020320	49	14	100	03	1680	1912-1980
Deerwood	5020720	49	24	98	19	1110	1952-1980
Dugald	5020810	49	53	96	39	843	1962-1980
Emerson	5020880	49	00	97	12	792	1942-1980
Grayville	5021160	49	30	98	10	930	1925-1980
Killarney	5021480	49	11	99	40	1625	1969-1980
Morden CDA	5021848	49	11	98	05	992	1918-1980
Morris	5021920	49	21	97	22	778	1915-1980
Ninette	5022040	49	24	99	37	1363	1948-1980
Petersfield	5022070	50	19	96	59	730	1960-1980
Pilot Mound P O	5022125	49	12	98	54	1557	1957-1980
Roland	5022480	49	25	98	00	875	1951-1980
Selkirk	5022630	50	09	96	53	739	1963-1980
Sprague	5022760	49	02	95	38	1072	1915-1980
Steinbach	5022780	49	32	96	41	880	1956-1980
Winnipeg A	5023160	49	54	97	14	786	1938-1960
Arborg	5030080	50	55	97	20	746	1960-1980
Beausejour	5030155	50	04	96	13	900	1859-1980
Beausejour 2	5030160	50	07	96	30	781	1961-1980
Gimli	5031038	50	37	96	59	730	1971-1980
Gimli A	5031040	50	38	97	03	725	1943-1971
Pinawa WRNE	5032162	50	11	96	03	875	1963-1980
Pine Falls	5032164	50	34	96	13	750	1959-1980
Dauphin A	5040680	51	06	100	03	999	1942-1980

Eriksdale	5040895	50	52	98	10	877	1959-1980
Gilbert Plains	5040985	51	06	100	28	1325	1958-1980
Grass River	5041140	50	31	98	58	885	1958-1980
Neepawa A	5042000	50	14	99	30	1273	1945-1962
Neepawa CSC	5042003	50	14	99	28	1210	1962-1969
Neepawa Water	5042005	50	13	99	28	1210	1969-1980
Swan River	5042800	52	06	101	16	1115	1937-1980

Appendix C

GUIDELINES FOR THE USE OF ITERATIVE REGRESSION PROGRAM

The iterative regression program requires initial or seed values in order to find a solution to the biometeorological time scale formula. The relation of these values is important because they help determine the effectiveness and efficiency of calculating the regression coefficient. The problem of selecting initial coefficients is easy if the biometeorological time scale has been used to analyse the growth of the crop previously. It is then a simple matter of using these coefficients developed in the previous study which should be adequate for use as the initial coefficients. Problems arise however when either there has been no previous coefficient determination or the previously determined coefficients were developed under dissimilar environmental conditions. After using the trial and error method of selecting seed coefficients it became apparent that an estimation procedure could be used to determine appropriate initial coefficients. The procedure is as follows:

1. Run the iterative regression program using dummy coefficients. The program will calculate the mean daylength, maximum temperature, minimum temperature and growth period for the particular crop development phase.

2. Estimate appropriate daylength and minimum temperature base values for the particular growth phase. (Exactness is not required as this is just an estimation procedure).
3. Calculate the average daily growth rate by using the reciprocal of the mean days to complete the growth stage.
4. Assume that daylength and temperature contribute equally to daily growth. This means that the daily contribution to growth by temperature and daylength is equal to the square root of the average daily growth rate. Using this assumption one can arbitrarily set the coefficients to the equation so that the average daily growth is close to that of the data. In order to estimate the temperature portion of the equation 50% of the temperature contribution can be assumed to come from the minimum temperature and 50% from the maximum temperature.

Even if these starting coefficients are carefully chosen there is no assurance that the program has determined the best set of coefficients. A number of program runs are usually necessary to be sure that a set of coefficients are the appropriate ones. Experience dictates that the following procedures should be used to test the particular coefficients.

1. Check the program's coefficients which occurred after each iteration. Note all of the points when the base

temperature or daylength changes substantially to the next iteration. The other coefficients of interest are those which are the best choice, lowest coefficient of variation for the program run.

2. The base temperatures of the coefficients that have been selected by the previous procedure are those of interest. This is because of the nature of the quadratic terms.

In a typical quadratic equation there are two critical points of the function. The base temperature or daylength which has been calculated by the program corresponds to only one of these critical values. It is necessary therefore to use the other critical point to see if the one chosen by the program was appropriate. If the wrong critical point was used the iterative analysis might not have determined the proper coefficients. To solve this problem the critical of the sets of coefficients determined to be of interest (in step 1) should be changed. An approximation procedure that can be used to calculate the other critical values:

1. Subtract the critical value and the mean daylength or temperature.
2. Change the sign of this value to the opposite (eg. negative to positive, positive to negative).
3. The initial value is then calculated by adding the changed value to the mean daylength or temperature.

By inserting this value into the equation from which these new values were calculated and changing the appropriate sign of the equation a new equation can be established. This new coefficient can then be used in the iterative analysis. Comparisons then can be made between the coefficients of the various program runs to determine which set was the most appropriate.

As long as the initial values are reasonable estimates the program, in theory, should converge to the best set of coefficients. The iterative procedure however, is not dealing with a mathematical function, but with a statistical relationship. A statistical relationship is used because of the variability of the data. In this iterative analysis one assumes that there is one set of critical values which will give a "best fit". Because of the variability of these data there may be many critical values which will give a best fit in relation to the values around itself. This however, does not ensure that there is elsewhere a set of critical values which will be even better. In other words, the program will give the best fit coefficients for the set of critical values which it used during the iterations. If the iterations did not include a point close to the actual critical values (the ones which will give the absolute best fit) then the critical values derived by the program will be incorrect.