

The Climatic Environment for Agriculture in the North:  
A Case Study of the Pasquia Land Settlement Project  
In Northern Manitoba

by

Janet Halpin

A thesis  
presented to the University of Manitoba  
in partial fulfillment of the  
requirements for the degree of  
Master of Arts  
in  
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Winnipeg, Manitoba, 1985

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THE CLIMATIC ENVIRONMENT FOR AGRICULTURE IN THE NORTH:  
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IN NORTHERN MANITOBA

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JANET HALPIN

A thesis submitted to the Faculty of Graduate Studies of  
the University of Manitoba in partial fulfillment of the requirements  
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This work is dedicated to my family, in particular my daughter Claire. She is my source of inspiration and comic relief and she makes all things possible.

## ABSTRACT

This study investigates the climatic environment for agriculture in the north. The Pasquia Land Settlement Project near The Pas, Manitoba is studied in terms of the frost-free season, thermal factors and moisture availability as they affect crop growth.

A program to calculate the biometeorological time scale for wheat development is applied, using climatological station data for 1955-83. A degree-day program for estimating alfalfa growth to cutting time is used for the site. The dates of reaching each developmental stage derived from these programs provide input to a soil moisture budgetting procedure to estimate water use. The dates associated with crop development and the water use for the 29-year period are analysed statistically to study the probabilities for frosts, time to maturity and water deficit at critical times during the season.

There is sufficient energy to mature wheat, but spring and fall conditions make timing a critical factor. In spring wet fields and risk of frost can delay seeding. In fall decreasing energy and ample precipitation create a problem for drying crops before onset of cold weather. The degree-day program for forage predicted one cutting in the summer. The decrease of energy and the frost risk make a second cutting inadvisable. The results of the soil moisture budgetting procedure indicate that there is ample water for crop growth, with a deficit in only a few years.

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## Chapter One

## INTRODUCTION

1.1 HISTORICAL BACKGROUND

The Pasquia Land Settlement Project is situated within the Saskatchewan River Delta, bounded on the north and southeast by the Carrot and Pasquia Rivers respectively, and on the west by the Saskatchewan-Manitoba boundary. The area is at the northern fringe of agriculture of the Great Plains (figure 1.1).

A frequently expressed concern regarding agriculture in this region relates to economic viability. This is controlled by its geographical position in human/economic and physical terms. Although the purpose of this research is to investigate the climatic environment for agriculture, some comment must be made in reference to the position of The Pas area within the context of the agricultural community. This illustrates the fact that environmental factors are not alone in militating against successful agriculture in the region.

Troughton (1982) states that all agricultural areas of Canada have undergone three distinct phases of development: early development, rapid expansion and adjustment. Manitoba settlement began in 1810 with the arrival of the Selkirk Settlers and grew slowly till about 1870 when Manitoba entered Confederation. In 1869 Rupert's Land was handed

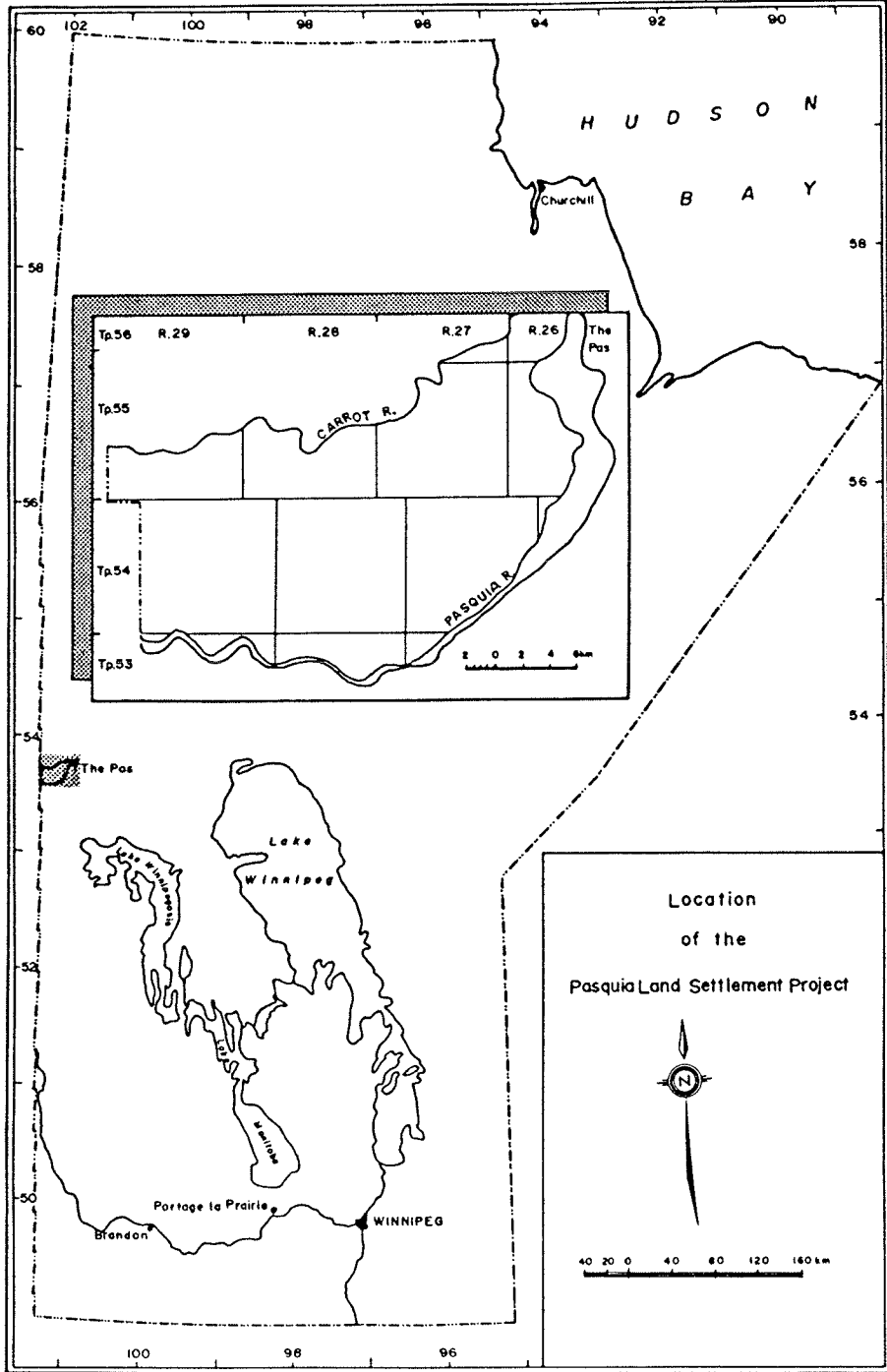


Figure 1.1: Location of Study Area

over to Canada, and in 1871 British Columbia entered Confederation with the demand that a railroad be built and settlement of the prairies take place to connect it physically to the rest of the Dominion. The railroad was completed in 1886, followed by consolidation of branch lines along the way. By 1896 immigration and expansion in the Prairies had begun. At the turn of the century, wheat varieties which were suited to a short growing season were developed. There was also an increase in immigration, promoted by the federal government's Dominion Lands Act.

Although The Pas area was first important as a fur trade and transportation centre, agriculture of various types and intensity has been practised there for a long period of time. The levees of the Carrot and Pasquia rivers were used to grow vegetables, grain and livestock. The first permanent agricultural settler arrived from Quebec in 1810. In 1915 another group of settlers came into the area from Quebec, but they were forced to leave after three successive years of spring flooding (Hopkins & Smith 1982).

In 1900 lots had been surveyed along the Carrot River. A surveyor, G.G. Horsey, reported in 1923 that the area had great agricultural potential. However, settlement of the prairies was taking place at that time and good agricultural land was available elsewhere. Consequently, development of The Pasquia area for agriculture was not a priority.

The economic depression of 1930 to 1940 was accompanied in the Prairies by several years of below average rainfall.

Farms were abandoned and immigration slowed because the homesteaders were not in a position to cope with lower produce prices and drought conditions. A change in government policy brought about the passage of the Prairie Farm Reclamation Act in 1935. The purpose was to provide assistance to prairie lands and to the farming population. While the Prairies suffered through a long dry period, the land in the Pasquia area was used extensively for hay and pasture land, and in some cases for grain production.

It appears that impetus for development in this marginal region was always tied to conditions elsewhere in the country. A soil reconnaissance survey of the Pasquia region was carried out in 1946. It was reported (Ehrlich et al., 1960) that the Pasquia area was poorly drained, peaty, and subject to periodic flooding. Some of the land was considered unsuitable for agriculture due to stoniness or salinity, but other parts could be suitable for farming if adequate surface drainage were provided. After the war years, there was a need for agricultural land as the economy recovered. In 1953, development of the Pasquia area was undertaken by joint projects of the Prairie Farm Rehabilitation Project and the Manitoba Lands Branch. Canals and drainage ditches were constructed.

The agricultural economy of the 1970's reflected a position of significant mechanization and electrification, made possible by the universal availability of fossil fuel.

Along with an increase in mechanical technology, requiring fewer workers to work the land with large machinery, there was also an increase in chemical technology. The use of pesticides and fertilizers fulfilled two purposes: the reduction of labour and the increase of productivity. The growing dependence on fossil fuels and petroleum products lead to the world energy crisis of the early seventies. Agricultural productivity is dependent on a fossil fuel subsidy in the form of fertilizers and pesticides. In the north, the situation was worse due to the high transportation costs related to movement of supplies in and produce out of the region.

A conference called "The North Feeding the North", was held in The Pas in 1980 (Province of Manitoba, 1981). This addressed the issues of making the northern area more self-sufficient. Experts and lay people in the agricultural sector discussed the potential of the north in terms of self-sufficiency. It was generally agreed that:

"...the future of agricultural development in northern Manitoba appears to be very limited. It is limited not so much because of the lack of adequate land base or climatic hazards ... as it is for reasons of economics and the reluctance of government to risk such development."

Smith, from "The North Feeding the North", 1982, p. 38

## 1.2 AGRICULTURAL ENVIRONMENT

There are important considerations necessary for successful agriculture. Temperature, moisture, nutrients and light are required in sufficient quantities. These environmental requirements are related to the genetic make-up of the crop and may change throughout the growing season in response to physiological development of the crop.

In southern agricultural regions one or more factors may be limiting. There may be deficiencies in some years depending on the natural variability of the climate. For example, the region may suffer from an excess or deficit of moisture in some years or at critical times in the season. The soil may lack nutrients or have physical attributes such as stoniness or drainage problems which make agricultural activity difficult or impossible. There is usually enough energy and light available to grow crops.

In the north the amount and timing of the environmental elements are more critical. The total amount of energy is less, although the longer daylength during the summer can lessen the difference and can speed physiological development of the crop. In the Pasquia area, a combination of cool temperatures and abundant moisture has delayed soil development. Many of the soil profiles consist of weathered mineral horizons with layers of peat on the surface, in locations where the ground has not been disturbed. The organic constituent, which is important for providing nutrients to vegetation, is poorly developed in these soils.

### 1.3 OBJECTIVES OF THE STUDY

The objective of this study is to evaluate the climatic environment of the Pasquia region. The interaction of the climate with the soils and the ability to support agricultural production has been studied.

Specific knowledge of the climatic requirements of an agricultural crop can be applied to study various facets of production. One can:

1. evaluate an area for its potential to support a species which has not been grown there before, as an alternative or adjunct to several years of field trials,
2. change the variables to test the crop's response to changes which cannot easily be duplicated in the field or laboratory, or
3. based on previous knowledge and current meteorological data, predict yield and harvest time.

The present study has focused on the first aspect, that is, to evaluate the location in terms of the potential for agriculture. The risks of crop loss associated with the variable climate and the short growing season were studied by modelling crop growth based on historical meteorological data. The response of the crop to meteorological conditions throughout the season were tested statistically to evaluate the risks of damage to the crop caused by overall adverse weather.

In this study, the climatic environment was considered as a unit. The mathematical model of wheat growth calculated response of the crops to a combination of day length, day and night temperature and energy from the sun. While those factors are related to physiological response, the moisture status has an effect on potential yield. Adequate moisture is more important during vegetative growth and grain filling periods than during the ripening stage. The combination of physiological development and yield accumulation require that the climatic requirements for optimal growth be present at the appropriate times.

#### 1.4 ORGANIZATION OF THESIS

Chapter One has provided a brief introduction to the problem. The historical development of The Pas region in parallel with development of the country as a whole was briefly outlined. The general findings of the recent "North Feeding the North" conference were discussed in terms of the overall feasibility of development. The suggestion was made that development has been related not only to environmental factors but also to economic or policy matters. This implied that the failure of successful agriculture in the northern areas is not only related to environmental factors. The environmental relationship to agriculture can therefore be studied with the knowledge that if economic factors were different the climatic requirements would be valid.

A review of the fundamental climatic factors which control the climatic environment is in Chapter Two. Radiation balance, temperature and moisture are presented in terms of 1) theoretical background, 2) effect on plant growth and 3) particular conditions of these elements in a northern environment which are different from more southerly regions.

Chapter Three contains a discussion of the crops used in this analysis. The phenological growth stages and the climatic requirements of a forage crop and a common wheat (Marquis) crop are described. A description of the study area demonstrates its place as a transition area of marginal use for agriculture, and how in a marginal area small fluctuations in the climatic environment can be critical in terms of productivity.

The methodology is presented in Chapter Four. It is shown that the basic climatic elements are important not only for the primary role they play in defining the environment for growth, but also in the impact on specific developmental processes of the crop. Potential evapotranspiration, net radiation availability, frost free season, consumptive water use by plants are a result of interactions of energy and matter in the environment. Crop development toward maturity is essentially a function of the genetic makeup of the plant. Environmental requirements change through the life cycle. The statistical estimation procedure is described which integrates genetic requirements

of the crop at various development stages with the meteorological conditions at that time. Consumptive water use in agriculture is related to the atmospheric demand for water, the water requirements of the plant at each stage, and the ability of the soil system and root system to provide moisture from the soil in response to the demand. A soil moisture budgetting procedure which attempts to model this is described.

Chapter Five contains the results of the estimation procedures and the statistical analysis of the duration of developmental stages. The statistical probabilities of risks of frost prior to harvest and of significant water deficit during critical growth stages are presented. A discussion of problems for agriculture which are related to the serious climatic constraints in the north are discussed.

Chapter Six contains the conclusion and suggestions for future research in this area. It includes evidence in the form of crop yields over several years that indicate that successful agriculture is possible in this northern area despite the critical climatic situation. Suggested research includes determining the risk factors associated with field workdays in the spring and fall, as timing in a short season can determine the success or failure of the operation. The ideal nature of this location for research related to possible carbon dioxide induced warming is investigated.

## Chapter Two

### CLIMATIC ELEMENTS

#### 2.1 INTRODUCTION

The climatic environment for agriculture comprises many interrelated facets. The meteorological conditions, physical structure and vegetation interact to form the framework for growth. Before an understanding of the interactions can be attempted, one must know the importance of individual elements which provide the foundation of the climatic environment.

The radiation budget defines the amount of energy available for energetic processes. It consists of both shortwave radiation (0.3 to 5  $\mu$ ) and longwave ( $>5 \mu$ ) radiation. Energy also can be advected into a region. However, since a part of this advected energy is incorporated in the change in radiative flux density, it will not be considered separately. The total available energy is utilized mainly as sensible and latent heat energy exchange between the earth and atmosphere.

The seasonal variation of insolation contributes to the long term temperatures of the location. The temperature determines the growing season and provides lower, optimum and upper critical thermal constraints for vegetation as it progresses through its life cycle.

Water, whether it be the precipitation process, soil moisture storage or that used in evaporation, is an important element in the climatic environment of a location. The moisture regime serves as a temperature regulator. As well, water is required for translocation of photosynthate and as a structural part of vegetation.

This chapter discusses the importance of the climatic elements as they relate to agriculture. Furthermore, it elucidates how these elements become critical in a marginal northern setting.

## 2.2 RADIATION

Except for small amounts of energy originating from the earth's molten core (geothermal energy), nuclear reactions and gravitational potential, all energetic processes on the earth are ultimately powered by solar radiation. The Stephan-Boltzmann law relates the intensity of energy ( $I$ ) radiating from a surface to the fourth power of the absolute temperature ( $T$ ) of the radiating body, i.e.  $I = e s T^4$  ( $e$  is emissivity and  $s$  is the Stephan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ Wm}^{-2}$ )). Wien's Displacement Law states that the wavelength of maximum emission of energy is inversely proportional to the fourth power of the absolute temperature. These laws explain the difference in wavelength spectrum and intensity of radiation emitted by the sun (surface temperature  $6000^\circ\text{K}$ ,  $0.001 - 3$  microns), and the earth ( $285^\circ\text{K}$ .,  $3 - 100$  microns). Thus, although the

radiation spectrum is actually a continuum, the wavelengths of emission of the sun and the earth are essentially mutually exclusive. The radiation energy which originates from the sun is referred to as shortwave radiation, and that from the earth-atmosphere system as longwave.

### 2.2.1 Insolation

The amount of energy received at the top of the atmosphere on a plane perpendicular to the direction of the sun's rays is taken to be approximately  $1375 \text{ Wm}^{-2}$ . This value is the solar constant.

The actual amount of energy received at the top of the atmosphere is a function of the zenith angle ( $z$ ), the angle between incident radiation and the normal to the plane. The zenith angle is dependent upon 3 factors:

1. geographical latitude, angle  $\varphi$
2. solar declination, angle  $\delta$
3. Hour angle (0 at solar noon), angle  $H$

Therefore

$$\cos z = \sin\varphi * \sin\delta - \cos\varphi * \cos\delta * \cos H$$

The total incoming radiation incident at the surface of the earth ( $K_d$ ), is a proportion of the amount received at the top of the atmosphere. Incoming radiation can be scattered, reflected, transmitted or absorbed by the atmosphere.  $K_d$  is depleted by atmospheric constituents including ozone, water (vapour, liquid and solid), and

various aerosols. As well, the path length through the atmosphere, depending on the season and latitude, contributes to the depletion of the solar beam.

#### 2.2.1.1 Estimation of Insolation

Unfortunately, while insolation is of utmost importance in energy processes at the surface, it is not measured on a regular basis at most climatological stations. Therefore mathematical and empirical formulae have been developed to estimate insolation from readily available measurements.

Angstrom (1924) first developed a model for estimation of global shortwave radiation,  $K_d$ , on a surface. It was of the form

$$K_d = K_o(a + b.n/N)$$

where  $K_o$  is the optimum energy receipt at the site on a completely clear day,  $n$  is bright sunshine duration, and  $N$  is variously interpreted as either 1) maximum duration of sunshine ever recorded for that day at that site, or 2) duration of period of solar zenith angle  $< 87$  degrees, because the Campbell-Stokes sunshine recorder is not sensitive to low intensity radiation at low sun angle (Hay, 1979; Edwards & Lyons, 1982). The constants "a" and "b" are linear regression coefficients. Use of  $K_o$  requires that  $K_d$  actually be measured at that location for a sufficient period of time to have observations of  $K_o$  for each day.

Therefore, most equations of this type incorporate the theoretical value  $K_A$  - Angot's Value, the amount of energy falling on the surface of the atmosphere at that latitude. This allows extrapolation to locations where  $K_d$  has never been measured and requires only the measurement of bright sunshine duration.

In studies related to estimation of  $K_d$ , there has been a focus on the interpretation of the regression coefficients  $a$  and  $b$ , in terms of their variability and significance. The intercept of the regression line ( $a$ ), is representative of a lower threshold value - the amount of  $K_d$  reaching the sensor on a completely overcast day. Therefore it depends on the level of diffuse radiation. The slope of the regression line,  $b$ , is related to the attenuation of direct radiation as it passes through the atmosphere. Ideally, " $b$ " reflects the rate of change in  $K_d/K_A$  for a unit change in  $n/N$ .

There is controversy in the literature regarding the significance of " $b$ ". Davies, (1965), working in West Africa, reported it as an index of latitudinal gradient. Glover and McCulloch (1958) used daily observations to compute yearly values for " $a$ " and " $b$ " based on data from stations from 358S to 518N. They stated that " $b$ " shows no dependence on either path length or on latitude. They concluded that for purposes of application " $b$ " should be assigned a mean value of 0.52. They found that " $a$ ", the threshold value, has a

marked dependence on latitude, and derived an equation of the form

$$a = 0.29 \cos \phi$$

where  $\phi$ =latitude, useful over the latitude range 0 - 60°. No reasons, other than empirical goodness-of-fit, were presented in support of this formula. Graham (1978), suggested that variations in "b" could be associated with maritime or continental influences. Although no justification was presented for that statement, it was possibly related to difference of transmission quality of moist and dry air.

Rietveld (1978) compared a series of regression coefficients from many sources and concluded that the intercept is linearly related to and the slope curvilinearly related to  $n/N$ . His method provides an accurate way of estimating  $K_d$  for locations for which measurements are not available. Coefficients derived for stations having similar climatological conditions could be used with local bright sunshine data. Particularly when mean sunshine duration is less than 0.4 of potential, Rietveld's method is up to twice as accurate as using latitudinal or global estimates of "a" and "b".

Driedger and Catchpole (1970) investigated the seasonal trends in the relationship between bright sunshine duration and radiation receipt, for Winnipeg Airport. They found

that throughout the year the intercept and slope were inversely related. They stated that "...any process that elevates the receipt of solar radiation on sunless days may, in this linear relationship, tend to reduce the magnitude of b." This was also observed by Davies (1965) who noted that as "b" was reduced by increased cloudiness, "a" increased with greater reflections.

Recently, Hay (1979) has used a more physically-based formula to improve the accuracy of prediction. He utilized monthly mean values of daily radiation receipt for a variety of locations in Western Canada, ranging from maritime to continental and from mid-latitude to sub-Arctic. He reported a correlation coefficient of 0.905, as opposed to 0.624 using the traditional formula with the same data. His formula includes terms for ground albedo, cloud base albedo, and transmissivity of the air. It was intended to correct for multiple reflections in continental high latitude locations during the late winter months, such as when photoperiod is increasing but there is still snow on the ground (Catchpole, 1975).

### 2.2.2 Longwave Radiation

Radiation absorbed at the surface is either stored, transferred to the air as sensible heat or as latent heat, or is radiated by the surface at wavelengths determined by Wien's Law. At the same time, the atmosphere is radiating electromagnetic energy in an amount related to its

temperature both towards the surface (reradiation) and towards space (out of the system). Solar radiation impinges on the surface only during day, i.e. when the sun is above the horizon. Terrestrial and atmospheric long wave radiation occur twenty four hours per day and constitute continual fluxes of energy. As with insolation from the sun, the wavelengths and amounts of energy emitted are a function of temperature and emissivity. Emission of longwave energy is generally highest during the day when warmest temperatures are found. As well, overall long wave radiation loss is higher during the summer months, rather than the other seasons, because of the overall warmer temperatures.

Longwave radiation ( $L_{up}$ ) can be calculated from the surface temperature, using the relationship

$$L_{up} = e s T^4 .$$

"e" is the emissivity of the material, s is the Stephan-Boltzmann constant, and temperature is in degrees Kelvin. Because measurement of surface temperature is not commonly carried out, longwave radiation from the surface can be estimated using a variety of empirical or physically based formulas. A common example of a longwave radiation estimation formula is that of Brunt (1934, cited in Mather, 1974).

$$L^* = s T^4 (0.56 - 0.08 e^{1/2}) (1 - a_c)$$

estimates the net longwave balance at the surface on a daily basis. Net longwave emission is the difference between incoming and emitted longwave radiation. "e" is the water vapour pressure, "a" is a constant depending on cloud type and "c" is the cloud cover in tenths. Water vapour and clouds absorb radiation in the longwave bands. If there is a significant amount of water vapour or cloud cover, the loss of longwave from the surface will be less. The major problem with Brunt's formula is that it requires several measurements and observations which may not be generally available. Vapour pressure and cloud cover may not be measured at a site. Alternatively, an estimation for longwave radiation may not always be necessary. An estimation of this amount is usually included in a formula to estimate net radiation.

### 2.2.3 Net Radiation

Net radiation,  $Q^*$ , is derived from the shortwave and longwave radiation balance, i.e.:

$$\begin{aligned} Q^* &= K_d - K_u + L_d - L_u \\ &= K^* + L^* \end{aligned}$$

It is the amount of energy remaining at the surface after inputs and outputs are accounted for.

Just as the shortwave flux and longwave flux vary according to cloudiness and other meteorological conditions, so the net radiation is subject to variation. The proportion

of net radiation to incoming solar radiation varies mainly due to surface albedo and surface temperature. If the albedo is high the net solar radiation amount is low. Similarly, when the surface temperature is high, the outward longwave flux will be higher than for a cool surface. As well, atmospheric humidity and cloud conditions affect the longwave balance and therefore the net radiation balance. Clouds maintain the vertical temperature profile and also serve to absorb and counterradiate longwave energy.

Actual measurements of net radiation rarely exist for most locations. Therefore, as with short wave radiation, workers have attempted to devise empirical and/or theoretical estimation procedures for this quantity.

Linacre (1968) presented a formula to estimate net radiation amount on a daily basis.

$$Q^* = K_d(1-a) - 16 * 10^{-4} (0.2 + 0.8 n/N) * (100 - T^{\circ}\text{C.})$$

Here  $a$  is albedo,  $T$  is daily mean temperature and  $n/N$  (bright sunshine duration) is an approximation of the cloudiness. Although clouds of different types have specific effects on the absorption and transmission of radiation,  $n/N$  is a good approximation due to the ease of measuring this parameter. The daily mean temperature ( $T^{\circ}\text{C.}$ ) is the average surface temperature during the day and night periods.

#### 2.2.4 Relevance to Agriculture

The radiation budget determines the amount of energy available at the surface to do work. Energy is mainly required for change of state of water, sensible heating of the ground and atmosphere, and a small amount in specific wavebands is required for photosynthesis and various other plant development processes.

The range of wavelengths emitted by the sun are related to specific developmental factors in the plant. Absorption of different wavebands changes through the life cycle of the plant. Annual plants which are actively growing absorb strongly in .4-.5 and .61-.7 micron bands, but as they begin to ripen the absorptivity drops off considerably. Perennial continuous cover forage plants absorb photosynthetically-active radiation throughout the season.

#### 2.2.5 Relevance to Northern Site

In low latitude areas, the incoming shortwave radiation balance dominates the surface energy budget. However, in northern latitudes, the insolation is not necessarily the major source of energy. As air advection transports heat northwards to energy deficient areas, downward longwave radiation represents an enhancement of temperature in the lower troposphere (Miller, 1981). In Europe, the annual variation in  $L_d$  is small near coastal areas but large inland, such as in the interior of the U.S.S.R. (Rudnev,

1980, cited in Miller). Thus the advection of heat in the summer months would increase the energy of a northern inland area. In a low-Arctic site adjacent to Hudson Bay, Rouse and Bello (1983) observed that the shortwave flux accounted for at most 41% of incoming energy flux, with the rest coming from earthward sky radiation. Under cloudy conditions the net radiation is fairly constant due to the cushioning effect of the cloud on the temperature profile. In their study, Rouse and Bello found that  $L_d$  did not vary more than + or - 10%, while  $K_d$  varied by as much as + or - 50%. As well "Kd accounted most for variation in surface temperature from period to period and between one surface and another".

### 2.3 THERMAL ENVIRONMENT

Net radiant energy is utilized primarily in sensible heat and latent energy transfers between the surface and the atmosphere. Sensible heat transfers determine the temperatures at and above the surface. The latent energy transfer is related to evaporation of moisture from the surface and from the crops, depending on the atmospheric demand for moisture and on the moisture content of the surface.

#### 2.3.1 Temperature

The result of the seasonal progress of the sun's path from 23.5°S. to 23.5°N. can be observed in the wave of temperature from cold or cool in the winter season to warm

or hot during the summer months. Superimposed on the seasonal regime are the daily fluctuations. These fluctuations depend on the meteorological conditions associated with the passage of synoptic scale features.

During the warmer part of the year is the "frost-free season" which has been variously defined as above 0°C. or above -2.2°C. Although the commencement, duration and end of this season can be defined statistically, the periods vary annually, again due to the varying meteorological conditions.

### 2.3.2 Frost-Free Season

For agricultural production in an area to be feasible, the growing season must be of sufficient length to permit successful maturation and harvest of the crop. The growing season is defined as the number of days between the last occurrence of a killing frost in the spring and the first killing frost in the fall.

The first statistical treatment of frost hazard as a farming risk was undertaken by Reed and Tolley (1916), in which they studied frost series for a multitude of points in the United States. Previously only the mean dates of frost were used to describe growing season limits. This practice effectively set a 50% risk limit, which is too high for profitable farming. Extreme dates of frost occurrence had also been used, but no attempt was made to establish causes for extreme values or to define the frequency distribution

of frost dates. Knowledge of the incidence of radiation frost would allow farm operators to protect their crops by various management techniques. Reed and Tolley utilized the Chi-square test to determine that dates of spring and fall frost were normally distributed. Thus confident predictions based on probability theory could be made for frost risk. They were the first to produce maps of risk factors for frost for the United States.

### 2.3.3 Relevance to Agriculture

Thom and Shaw (1958) reviewed the prospects for defining the growing season statistically, as the work of Reed and Tolley had not been effectively translated into general practice. They used more powerful and modern statistical methods to test for normality of freeze data for the state of Iowa. They found that the dates of freeze were normally distributed, so that confident estimates of frost risks can be made.

These workers also questioned the use of the freezing point of water as a freeze "in contrast to 'killing frost' which is defined non-numerically as the frost or freezing condition which kills the staple vegetation in the vicinity of the observing station". (Thom and Shaw, 1958:251). Vegetation is frost-damaged by the expansion of water in the tissues as they freeze. Hayter & Proudfoot (1978) suggested that  $-2.2^{\circ}\text{C}$ . is appropriate as a killing frost temperature for cereal crops, as the plants desiccate during the

ripening stage, reducing potential for frost damage.

Sly et al. (1971,1974) developed a technique to estimate normal dates of critical temperatures near freezing from readily available climatic data. This eliminated the necessity of using daily temperature records. The technique was concerned more with meso- and macro- climatic factors than with local factors related to site and aspect. Prediction might seem poor for particular farms but it is known that freezing conditions can vary greatly in a small area due to site differences. While estimates of critical dates were in error by about three days, the method was appropriate for regional land use planning.

The method used multiple regression techniques, where variables were added until they caused an insignificant change in the coefficient of variation and standard error of estimate. Variables considered included elevation of the station, January mean minimum temperature, range (mean maximum temperature minus mean minimum temperature) on the date of occurrence of frost, warming in spring or cooling in fall during the 30 days prior to the date of occurrence of frost, difference between July and January mean minimum temperatures, and difference between the July mean maximum and the January mean minimum temperatures.

#### 2.4 MOISTURE

Water is recognized, along with temperature, as a primary influence on vegetation distribution. Not only is

water necessary as a constituent of plant material, but nutrients from the soil are transported upward and photosynthate downward in water solution. Transpiration, while being a passive response to a vapour pressure gradient when the stomata are open, regulates the temperature of the leaves during the day.

The basic equation of the hydrologic cycle is

$$P = E + G + R.$$

Water enters the system as precipitation (P), or by irrigation. The water can evaporate (E) from the soil surface, from the vegetation or from a free water surface. Water can leave the system as runoff (R) along the surface or in subsurface flow to a stream channel. The moisture can remain in storage (G) in the soil or deep in the ground.

#### 2.4.1 Precipitation

Precipitation, occurring as rain, snow or dew, is the main mechanism, in the absence of irrigation, by which moisture is delivered to the ground. It is stored in the soil and made available to growing vegetation. The timing and amount of precipitation is highly variable and there are extreme variations of amount of precipitation over quite small areas. Adequate moisture supply requires that precipitation amount and distribution be appropriate to its demand by plants.

Treidl (1978) summarized precipitation normals for the Prairie provinces. There is a summer maximum of precipitation in the Prairies. He found that the data fit the assumption that monthly precipitation totals follow a normal distribution (Kendall, et al, 1968, cited in Treidl).

#### 2.4.1.1 Relevance to Agriculture

The general finding of Treidl's work was that in the prairies mean temperatures decrease from southwest to northeast while rainfall increases from southwest to northeast. The significance of this temperature-precipitation relationship is very important to agriculture, particularly in the north. In a region where the absolute amount of precipitation is relatively large, less energy (as reflected in low mean temperatures) is available to evaporate moisture. Cooler temperatures would be an advantage in an area of precipitation deficit, by maintaining the moisture supply over a longer period. However, in a region which receives adequate or surplus rainfall, a mechanism is needed to dispose of excess moisture. In the North, energy availability decreases sharply in August, while moisture supply does not (see figure 5.2).

According to Treidl (1978), The Pas experienced fewer dry spells (periods between precipitation events) than the average for the Prairies. In April, May and June the dry spells were longer than the Prairie average. This would

assist in drying fields to permit field work and seeding in the spring. However, the July to October data indicated that dry spells were fewer than the Prairie norm and did not last as long. Rains in the post-ripening stage of grain crops are not welcome because the crop must be dried and harvested. There is little atmospheric demand for moisture at that critical time for agriculture. The following table shows the differences in dry spell durations for locations on the Prairie provinces.

Table 2.1: Duration of Dry Spells for Selected Prairie Locations

Location	Apr	May	Jun	Jul	Aug	Sep	Oct
Winnipeg	4.3	3.8	2.8	3.3	3.7	4.1	4.5
The Pas	6.5	5.0	3.6	3.4	3.9	4.4	5.4
Russell	6.7	5.3	3.5	3.9	4.5	6.2	5.8
Prairies	5.6	4.6	3.3	3.8	4.2	5.1	6.4

values in days, after Treidl, 1978; p.359

#### 2.4.2 Evaporation

A climatic classification based on vegetation distribution was developed by Linsser (in 1867, 1869, cited in Mather, 1974), which accounted for plant response to heat and precipitation. Koppen's climatic classifications of the world were also based on temperature and precipitation distribution. However, it is not merely the precipitation amount which is of importance in vegetation studies, but the path the moisture takes once it enters the soil system.

Modern approaches to the problem have recognized the importance of evaporation in delineating the climatic resources of a region. As early as 1900, Warington (cited in Penman, 1963), discussed the transpiration ratio of plants - the ratio of water transpired to dry matter produced - and considered it to be a biological phenomenon, controlled by the plant. Difficulties were encountered in establishing which plants were more or less wasteful in water consumption, and in how water use was related ultimately to yield. The actual relationship between the transpiration ratio and the climate were suggested by Leather (1910, cited in Penman):

"The water requirement has been shown to be profoundly affected by the atmospheric conditions. The water requirement of the same crop varies greatly according to the period of the year in which it is grown. Similarly, the same crop will give a widely differing water requirement when grown in different regions during the same period."

Finally, Thornthwaite, using empirical data and plot experiments and Penman using theoretical concepts of the physics of evaporation, arrived at a common idea that "when a full crop cover is kept plentifully supplied with water, the rate at which the water is transpired is dictated primarily by the weather, with plant and soil factors playing only secondary roles" (Penman, 1963:34). This rate is frequently referred to as potential evapotranspiration.

Viewed as a purely physical phenomenon, water in the soil passes in liquid state into the root system, up to the

leaves and into the stomata, which during the day are open to permit entry of atmospheric  $\text{CO}_2$  into the cells. Water exits the plant system as water vapour, requiring an energy input of approximately 540-590 cal./gm. for evaporation, depending on temperature. Evaporation, then, requires a source of energy and a vapour pressure gradient and is enhanced by wind speed (Rosenberg, 1974). (The wind decreases the depth of the laminar boundary layer between the stomatal opening and the turbulent layer, thereby increasing the vapour pressure gradient and reducing resistance to vapour flow.)

It is relatively easy to measure potential evapotranspiration. One can place a large pan of water at the location of interest and measure free water evaporation by the difference of water levels at the beginning and ending of the measurement period. Evapotranspiration can also be measured, albeit with greater difficulty, by using a lysimeter. A large mass of soil and representative vegetation is isolated within the lysimeter. Sensitive weighing instruments installed under the lysimeter measure changes in mass related to evapotranspiration and to moisture recharge.

#### 2.4.2.0. Estimation of Evapotranspiration

While potential evapotranspiration is determined by atmospheric conditions, actual evapotranspiration is often less than the potential due to limitations imposed by soil

factors, such as moisture content and rate of water movement to the evaporating surface. Stage of growth of vegetation affects root distribution and moisture usage in the plant tissues. As well, when temperature is high and moisture is limited, transpiration will be slowed by closure of stomata on leaf surfaces. It is difficult to measure actual evaporation.

There are mathematical methods for estimating actual evaporation. Atmospheric demand for water is dependent upon energy supply to evaporate moisture and upon maintenance of a vapour pressure gradient from the surface to the atmosphere. The mathematical methods utilize these mechanisms. The energy balance approach is a procedure whereby available energy is partitioned into various processes. An aerodynamic approach models the vertical movement of sensible heat and water vapour by turbulent diffusion. Combination approaches make use of factors involving the energy supply and vertical gradients.

#### 2.4.2.1 Energy Balance Method

One can consider evaporation as an energetic process. Net radiation is partitioned into evaporation, sensible heating, ground heat storage and miscellaneous energy sinks such as photosynthesis. That is

$$Q^* = Q(E) + Q(H) + Q(G) + Q(M)$$

respectively. Penman (1956) postulated that on a daily basis the heat balance can be assumed to be composed of energy for sensible heating of the air and energy for evaporation. Ground heat storage and miscellaneous processes such as photosynthesis would be insignificant at this time scale. The allocation of energy to Q(E) is found from

$$Q(E) = -(D_a * L * M / P) * K(V) * de/dz$$

where  $D_a$  is air density,  $M$  is relative molecular weight of water with respect to air,  $L$  is latent heat of vapourization,  $P$  is barometric pressure,  $K(V)$  is the eddy diffusivity of water vapour, and  $de/dz$  is the vertical water vapour pressure gradient.

The amount of energy allocated to Q(H) is found from

$$Q(H) = -(D_a * C_a * K(H) dT/dz$$

where  $D_a$  is the density of air,  $C_a$  is the specific heat of air at constant pressure,  $K(H)$  is the eddy diffusivity of heat ( $\text{cm}^{-2} \text{sec}^{-1}$ ), and  $dT/dz$  is the temperature lapse with height. One assumes that the exchange coefficients for water vapour and heat are the same. Bowen (1926, cited in Rosenberg, 1974) developed the Bowen Ratio,  $Q_H/Q_E$ , that is

$$B = Q(H)/Q(E) \\ = ((P * C_P) / (L * M)) * (K(H) / K(E)) * ((dT/dz) / (de/dz))$$

The exchange coefficients are assumed to be equal, and B can be estimated by

$$B = 0.27*(T(\text{surface}) - T(\text{air})) / (e(\text{surface}) - e(\text{air}))$$

#### 2.4.2.2 Aerodynamic Method

The aerodynamic method of determining potential evaporation relates to the gradient of vapour pressure with height. The basic factor is that net vertical flux of water vapour from an evaporating surface results from turbulent diffusion from the surface to the air. Thornthwaite and Holzmann (1942, cited in Rosenberg, 1974), estimated evaporation using gradients of water vapour and wind profile.

$$PE = Da * k^2 * \frac{(e(2) - e(1)) * (u(2) - u(1))}{(\ln(z(2)/z(1)))}$$

Here, "k" is von Karman's Constant, approximately 0.4. "z" refers to the vertical distance above the surface and relates to the logarithmic profile of wind with altitude. This method requires that temperature and wind be measured at the two levels simultaneously.

#### 2.4.2.3 Combination Method

Combination methods involve mathematical factors which combine energy balance and aerodynamic methods. Their

advantage is that they can be used to estimate evapotranspiration from measurements at a single height. Based on field observations in England, Penman (1956) developed an equation to estimate free water evaporation using elements associated with aerodynamic and energy balance methods.

The turbulent exchange coefficients were replaced by a term for the horizontal wind speed. The vapour pressure profile values were replaced by the slope of the saturated vapour pressure curve at air temperature. The equation was of the form

$$\text{Pot. ET} = \frac{mH + 0.27 * E(a)}{m + 0.27}$$

"m" is the slope of saturation vapour pressure curve at mean temperature (Ta) and 0.27 is the psychrometric constant. "H" is an approximation of net radiation in terms of the amount of water it could evaporate (mm day<sup>-1</sup>).

$$E(a) = 0.35(es - ed)(1 + (9.8 \times 10^{-3})u(2)) \text{ where}$$

es is mean daily saturated vapour pressure at water surface, determined by surface temperature, ed is mean vapour pressure of the air, and u(2) is wind velocity in miles/day measured at 2 metres above the free water surface.

Baier and Robertson (1965) have developed equations to estimate potential evapotranspiration. Their equations

incorporate empirical relationships involving meteorological data, but which are based on the theoretical concepts of Penman.

$$PE = -53.39 + .337T_{max} + .531T_r + .0107KA + .0512Kd \\ + .0977(u(2)) + 1.77(ew - es), \text{ where}$$

$T_{max}$  is an approximation of surface temperature,  $T_r$  (temperature range) is related to the change in saturation vapour pressure through the day, wind run accounts for ventilation of the crop canopy and maintenance of the vapour pressure gradient, and  $(ew - es)$  is the vapour pressure deficit.

This equation gives a good estimate ( $r = .86$ ) of potential evaporation but the meteorological data input is not usually available for most stations. An equation involving fewer meteorological variables, although with less accuracy ( $r = .68$ ), is currently in wide use. It is of the form:

$$PE = -87.03 + .928T_{max} + .933T_{range} + .0486KA.$$

Once potential evaporation is known or estimated, actual evaporation can be determined as a percentage of the total possible. The effect of soil characteristics and plant development stage on actual water use will be discussed in Chapter Four.

## Chapter Three

### STUDY AREA AND CROPS

#### 3.1 INTRODUCTION

This chapter examines the agricultural crops studied in this analysis and the attributes of the site which are important to the analysis. Because the soil type is important to storage and availability of moisture to the growing crops, two soils within the Pasquia Project are included in the study. A forage crop and a common wheat crop are described in terms of the developmental stages and their demands on the climatic environment.

#### 3.2 THE PASQUIA LAND SETTLEMENT PROJECT

The Pasquia Land Settlement Project is a small agricultural region in northern Manitoba, near The Pas (53°58' Lat., 101°06' W. Long.). The region is situated within the Saskatchewan River delta, bounded on the north and southeast by the Carrot and Pasquia Rivers respectively, and on the west by the Saskatchewan-Manitoba boundary (figure 1.1). The area is considered to be at the northern agricultural fringe of the Great Plains. In a marginal area small fluctuations in the climatic environment can be critical in terms of productivity.

According to Smith (Province of Manitoba, 1981), the

Province of Manitoba as a whole contains  $54.8 \times 10^6$  hectares of land. However, a "combination of climatic, soil and terrain characteristics leave only about 10% which is suitable for crop production."

The Pasquia Project is located on a tip of the Hudson Bay Lowlands. The area contains about  $0.2 \times 10^6$  hectares of land of highly variable quality for agriculture. The soils are regosolic, alluvial clay material laid down by the Saskatchewan River Delta. Much of the region is topographically depressed, with the result that large parts of the land are poorly to imperfectly drained. In the natural state, much of the soil was overlain by peat deposits of variable depth. The nature of the alluvium, ranging from clays and silts (extremely fine-textured) to coarse sands with gravel banding, increases the problem of drainage in addition to making cultivation with machinery difficult.

### 3.2.1 Climatic Aspects

Heat energy availability, as it affects growing degree days, frost free season and soil temperature, is important to agriculture. In comparing The Pas ( $53^{\circ}58'N$ . Lat.) to Brandon ( $50^{\circ}$  Lat.), Fraser (Prov. of Manitoba, 1981) indicated that while mean temperatures are lower at The Pas, the difference is less in the summer. For example, Brandon is  $4^{\circ}C$ . warmer in winter, but only  $1^{\circ}C$ . warmer in the summer. For the May to September season as a whole, the

difference is only 1.5°C. Other climatic attributes of The Pas area of importance to agriculture are, according to Fraser:

1. that the moisture supply is adequate,
2. available light is similar to that in the South, and
3. violent hazards are less frequent than in the South.

### 3.2.2 Soils

Soil factors important to plant growth include natural fertility, temperature, moisture storage and availability, salinity and drainage. In general, soil development in the region has been inhibited by cool temperatures and waterlogged soils (Hopkins & Smith, 1982). Many soils are characterized by peat deposits of variable thickness. While the soils in this area present many management problems, they can be productive when steps are taken to improve drainage and fertility.

"The yields recorded herein for the two stations in the Pasquia Area indicate wide differences in the natural productivity of the better drained LePas clay soil type and the formerly poorly drained and some-what salinized Pasquia soil type that is now in the process of reclamation. However, the results obtained in the fertilizer trials indicate that the yields on the poorly drained sites can be increased substantially and satisfactorily when the land is drained and certain management practices are adopted."

J.H. Ellis, Agricultural  
Consultant, Field Crop  
Recommendations for 1961  
(Ellis, 1961a)

Detailed descriptions of the two soil types used in the

analysis, taken from the Report of Detailed Soil Survey of The Pasquia Area, No. 11, (1960) can be found in Appendix 2. Briefly, site 1 is Le Pas Clay, of clay to silty clay texture, moderately calcareous, with moderately good surface drainage. This soil covers approximately 7500 hectares of the settlement area. Site 2 is fine sand with a thin surface clay layer, with bands of fine textured soil within. These soils suffer from variable degrees of salinity. The salinity has been somewhat ameliorated in recent years by improvement of drainage and lowering of the water table. This soil type occupies approximately 1200 hectares of the Pasquia region.

### 3.3 CROPS USED IN THE ANALYSIS

The crops to be analysed are a common wheat and a forage crop, alfalfa. These are described in Principles and Practices of Commercial Farming (University of Manitoba, 1977) as cool-season, long-day crops, and would appear to be well-suited to the northern environment.

#### 3.3.1 Wheat

Wheat is an annual crop which has a characteristic life cycle in which half of the cycle is spent in vegetative growth and half in flowering and ripening. Several stages in the life cycle of wheat can be identified. Each stage has a different requirement for light, moisture and temperature. It is these requirements which make the

interaction with climatic elements so important on a yearly and long-term basis.

Principles and Practices of Commercial Farming identify 12 distinct stages in the life cycle of common wheat, beginning with the seed and ending with fully ripe, dry grains. Robertson (1968), in field tests to determine dates for achieving phenological stages, identified 6 stages from planting of the seed to ripening, (followed by a period of drying). These stages are comparable (table 3.1). The six stages identified by Robertson represent growth stages having homogeneous meteorological requirements. In general, the vegetative parts of the cycle differ from the reproductive stages in their requirements for temperature (minimum, maximum and optimum), amount of light (intensity and photoperiod), nutrition, moisture and genetic factors.

In terms of progress toward maturity, the dominant factors are temperature and photoperiod. Higher temperatures increase the rate of biological activity, including photosynthesis and respiration. In agriculture, an effort is made to maximize net production. During vegetative growth, wheat responds positively to daylength duration. However, during ripening there is a negative response to daylength duration.

Clearly as important as progress toward maturity is the production of final yield. Yield potential is strongly related to moisture availability. Moisture deficit can have a more or less damaging effect on final yield depending on

Table 3.1: Development Stages of Wheat

Physiological and Anatomical Stages of Wheat Plants (University of Manitoba, 1977)	Homogeneous Stages Used For Purposes of Modelling Response to Meteorological Conditions (Baier & Robertson 1968)
Seed	Seed
Seedling	Emergence
Tillering Jointing	Vegetative growth Jointing *
Boot	
Heading	Heading
Filling Milk Soft Dough	Soft Dough
Hard Dough	Ripe - Hard Dough (Could still depress grains with fingernail)
Mature Seed	**
Fully Ripe	***

\* First recognizable stage of floral initiation, Friend et al., 1963

\*\* approximately 35% water content

\*\*\* approximately 12-15% water content

when in the growth cycle the deficit occurs. According to Doorenbos et al. (1979), "slight water deficit in the vegetative stage may have little effect on crop development or may hasten maturation. The flowering period is most sensitive to water deficit. A loss in yield during flowering cannot be recovered by adequate water supply later". This is because water deficit interferes with pollen formation and fertilization, so reducing the number of heads per plant as well as the number of grains per head. There is also an affect on root development. If the deficit occurs early, the root development will extend further into the soil system. However, if the deficit occurs after root extension has occurred, the roots may not cover enough area to draw moisture from the soil. Once the grains have begun to fill, water deficit may affect final yield by reducing grain weight or even shrivelling grains if combined with hot, dry winds. Doorenbos et al. (1979) stated however, that wheat can usually withstand a soil water deficit of about 50% of total available water without damage. A deficit of more than 80% leads to significant reductions in yield.

### 3.2.2 Alfalfa - Forage Crop

Forage crops "include all crops whose vegetative or seed components are eaten by livestock" (University of Manitoba, 1977:133). In addition to the use of forage as feed for livestock, forage crops promote soil conservation

and improvement. Forage crops can improve soil structure and organic matter content. In the north, legume crops are used especially to improve the nitrogen content of the soil.

Alfalfa is a leguminous, continuous cover crop. Once planted it requires a period of about 3 months to become established. The root development becomes quite extensive and deep. A soil water deficit of up to 50% of available water can be tolerated without adverse reaction by the crop. However, alfalfa is fairly sensitive to salinity (table 3.2, from Doorenbos et al., 1979):

Table 3.2 Decrease in Alfalfa Yield Due to Soil Salinity

mmhos Eec	% loss of yield
2.0	0
3.4	10%
5.4	25%
8.8	50%
15.5	100%

At the North Feeding the North conference, Tsukomoto (Province of Manitoba, 1981) stated that alfalfa is well-adapted to the northern environment. As well, comments in Field Crop Recommendations for the Pasquia Project (Ellis, 1961a), indicate clearly the role that this crop can play in the agriculture and in the land improvement of the region.

"Perhaps the most important conclusion that can be drawn... is that alfalfa has proved to be a highly successful forage crop where patchy growth of cereals and other non-legumes have indicated a deficiency of available nitrogen or where a natural surface cover of peat has been removed by burning, and where the soils show some degree of salinity and alkalinity...It becomes more and more apparent that agricultural land use in this area should be built up around the growing and utilization of alfalfa and alfalfa-grass mixtures in a diversified system of culture, and that a fallow grain system of mono-culture should be avoided."

Field Crop Recommendations for 1961.

## Chapter Four

### METHODOLOGY

#### 4.1 INTRODUCTION

This chapter discusses the statistical estimation procedures used to model development and water use of agricultural crops. The interrelationship between the atmospheric conditions and the genetic requirements of the crops are discussed. The statistical analysis to evaluate the risks of frost hazard, the probabilities of development duration and risks of water stress are described.

The maturation process is related to both astronomical and meteorological conditions. These include photoperiod, insolation, temperature and water. The optimum conditions are not the same at all stages of the life cycle. Similarly, the water requirements of the crop vary throughout the life cycle. For instance, during vegetative growth, water is required for the translocation of photosynthate as well as for transpiration and maintenance of turgidity. After flowering the need for moisture decreases as water content of the plants drops from 80% to less than 20% by maturity (Doorenbos et al., 1979, University of Manitoba, 1979). The ability of the root system to extract available water is also related to the stage of development (extent of root development) and to previous moisture conditions (extent of roots in deep soil layers).

Present methods of dealing with this problem entail a variety of statistical and mathematical approaches (Baier, 1976; Baier et al., 1976). Terjung and Louie (1973) note that the methods range in a continuum from simple empirical regression models to "deterministic crop growth models based upon the transfer of energy and mass within a multi-layered crop canopy... and which often include the partitioning of photosynthate within crop storage sites". The degree of complexity of the model is necessarily related to the balance between accuracy and detail, which require exact measurements of instantaneous values, and ease of application with fairly simple calculations. Issues of importance when choosing an appropriate model were summarised by LeDuc et al. (1980). They include:

- 1) the needs of the user in terms of objectives of the model and the size of the study area.
- 2) the sensitivity of the model. For a single field the input data must be appropriate for that field, while for estimating for a larger area the data requirements are not as specific but the results will be generalized over the study area.
- 3) timeliness. For yield predication, meteorological data is required on a daily basis while for feasibility studies, historical data from climatological stations is adequate.

4) cost. In general, for more detail and accuracy, more frequent observations are required, resulting in greater expense.

Gommes (1983) has prepared a variety of programs ranging from rainfall probability analysis, calculation of potential evaporation, solar radiation and daylength, to a modified crop-specific soil moisture budgetting procedure for use on a programmable pocket computer. These were based "not on recent technological benefits nor any intentional choice but rather on the availability of certain machines to the author in Dar es Salaam." At the other end of the continuum, Terjung and Associates (Hayes et al., 1982) have compiled from a variety of models a composite crop yield model for worldwide international food production. Subroutines deal with differences of soil type, salinity, water table depth, field size, wind regime, photoperiod, crop development stage, percolation losses, runoff, leaching requirements and fertilizer effects. (Hayes, et al., 1982). There are also models which use detailed equations to study the energy budget of leaves in plant canopies, related to long- and short-wave radiation exchange, latent and convective energy exchange, and carbon dioxide exchange (Lemon, 1967; Terjung and Louie, 1973; Miller, 1981).

#### 4.2 WHEAT - BIOMETEOROLOGICAL TIME SCALE

Robertson (1968) has developed a biometeorological time scale for wheat which utilizes "readily available climatic

data, knowledge of physical relationships between various environmental factors and of the physiological relationships between crop responses and its environment". The general equation for rate of development (r), or progress to maturity (dM/dt) is of the form

$$r = dM/dt = F(1)L * F(2)T \quad \text{where}$$

L is daylength, T is maximum and minimum temperature, and the F's are non-linear functions dependent on the developmental stage of the crop. As the basis for using this type of relationship, Robertson postulated that a good mathematical model of crop development should:

1. "Consider the reponse to temperature as being non-linear and allow for lower and upper critical limits as well as an optimum value
2. Consider the response to photoperiod also as a non-linear function, allowing for the three cardinal points.
3. Consider the response to day and night temperatures separately.
4. Integrate the influence of these three factors over fairly short phenological periods during which physiological processes are relatively uniform.
5. Make use of temperature at least on a daily basis so that extreme conditions may be considered and not masked by any averaging procedure." (Robertson, 1968 p. 193).

The empirical constants used in this model were

generated from controlled field trials with Marquis Wheat from 1953-1957. The model was tested with independent data from the same stations for 1958-1963, and with data from Buenos Aires, Argentina. The Buenos Aires trials were considered a powerful test of the model, due to the great latitudinal and temperature differences from the other stations used. Table 4.1 lists the stations used in the model development. The model predicted that crop responses were related to photoperiod and temperature variations. The strength of the results indicated that the numerical coefficients used to estimate development are representative of the genetic factors of the plants, and are independent of the environment (Robertson, 1968).

Table 4.1: Location of stations providing data for development of Crop Development Model for Marquis Wheat, using Biometeorological Time Scale (from Robertson, 1968:203)

<u>Location</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Elevation</u>
Harrow	42°02'N	82°53'W	190 m.
Ottawa	45°24'N	75°43'W	79
Normandin	48°51'N	72°32'W	136
Kapusking	49°25'N	82°23'W	223
Swift Current	50°16'N	107°44'W	820
Lacombe	52°28'N	113°45'W	843
Beaverlodge	55°11'N	119°22'W	758
Fort Vermilion	58°23'N	116°03'W	277
Fort Simpson	61°52'N	121°21'W	130
Buenos Aires	34°35'S	28°29'W	23

#### 4.2.1 Application to The Pasquia Project

In the present study, Robertson's model was used to determine the overall potential for growing wheat in a specific climatic environment. Actual dates of planting were available for only 8 years - 1957-1964. 4 situations were used for the development model:

- I A climatic estimation program was used to determine a planting date based on temperature, field moisture and precipitation. The criteria were (1) at least 5 consecutive days with maximum temperatures greater than 0°, (2) the top zone of the soil at less than 90% of field capacity, and (3) there should be precipitation not in excess of 2.5 cm on the planting day (Dunlop, 1981). This was considered appropriate for southern Manitoba.
- II Planting was assumed to have taken place on the date following which the chance of killing frost was less than 25%, regardless of whether or not precipitation occurred on that day.
- III Planting was assumed to have taken place on the date following which the chance of killing frost was less than 10%, regardless of whether or not precipitation occurred on that day.
- IV Planting date was the actual planting day for the eight years (1957-1964) when variety trials were undertaken in the Pasquia project.

V Planting date was set as for I, using data from 1957-64, for use as a comparison with IV.

Situation I assumed a soil moisture status of field capacity every spring at the beginning of May. It also assumed that there would be no excess water on the fields at the beginning of the season. Because the Pasquia Project is a topographically depressed location, with an overall problem of excess moisture, the assumptions of soil moisture content are questionable. The modelling of crop development and soil moisture budget done under this scenario should be considered "theoretical or idealized". A target date of May 7 was established for drainage of free water from third order drains in order that seeding take place as early as possible in the Pasquia Project (Bell, 1971).

#### 4.3 FORAGE - DEGREE DAYS

A soil moisture based simulator of forage yield was developed by Selirio and Brown (1979). The object of their research was to provide a means of estimating yield from available meteorological information for a crop insurance scheme. Actual measurement of yields is hampered by the variety of harvest methods (dry hay, haylage, grass silage) as well as the difficulty of measuring pasture yields. Developed for Southern Ontario, the SIMFOY program begins computation of yield accumulation after March 15 on the first day which is preceded by 5 days with mean temperature

greater than 5°C. The program accumulates "degree days" (daily maximum temperature minus a base value of 5°C.) up to 550 - when flowering begins and the crop is first cut. At the same time, daily soil moisture extraction is calculated using the Versatile Soil Moisture Budget. After cutting, the soil moisture extraction rate is reduced to allow for regrowth and after 10 days the accumulation of degree days begins for the second cutting.

Wallis et al. (1983) studied the relationship between growth and transpiration for estimating hay yield in the Peace River Region (55°56'N.). They attempted to relate growth to temperature and moisture limitations in that northern setting. Their model allowed for a reduction of yield potential associated with senescence related to low temperature and/or moisture deficit.

In the present study, no attempt is made to model forage yield. The purpose of this portion of the analysis is to derive approximate dates of full field cover and cutting for use in the Versatile Soil Moisture Budget. Therefore, only the degree day accumulation to flowering upon attainment of full field cover in the spring is used.

There are problems associated with using the degree day program for the Pasquia Project. The model was developed for Southern Ontario, where the range of photoperiod throughout the growing season is much less than in northern Manitoba. As well, only degree day totals were considered. The relationships between photoperiod and day and nighttime

conditions were not modeled. Nighttime temperature is known to be important in the production of protein as a proportion of dry weight. The model is used here mainly to investigate soil moisture availability. Estimated growth stages in terms of degree days accumulation are utilized to set the plant water use parameters for the Versatile Soil Moisture Budget. The model begins on April 15, at the end of the winter period when snow cover is receding.

#### 4.4 VERSATILE SOIL MOISTURE BUDGET

The Versatile Soil Moisture Budget (Baier, Dyer & Sharp, 1979; Baier & Robertson, 1965) is a computerized procedure to estimate soil moisture usage and recharge, using climatological station data and knowledge of soil and plant characteristics. The soil profile is divided into 6 zones of varying moisture capacity. Daily soil moisture status of these zones is estimated from precipitation and evapotranspiration amounts.

Water availability in the root zone is estimated using constants which reflect soil physical properties (Z) and plant development stage. The plant related coefficient (K) is essentially a consumptive use factor. It integrates the effect of root extent, which is species specific and related to antecedent moisture conditions, and to aerial development and leaf area index.

The equation developed by Baier and Robertson

(1965,1979) is of the form:

$$AE(i) = \text{Sum } (K(j) * (S(j,i-1) / Cj * Z(j)) * PE(i))$$

where:

AE(i) = actual evapotranspiration for the day (i),  
summed over all the zones

K(j) = plant consumptive use coefficient, for each  
soil zone (j)

S(j,i) = available moisture in the zone at the start  
of the day

C(j) = capacity for available water in each zone (j)

Z(j) = adjustment factor for soil drying curve

PE(i) = potential evapotranspiration for the day

Potential evaporation is estimated using an empirical formula which is related to temperature and to incoming solar radiation at the top of the atmosphere:

$$PE = -87.03 + 0.928 * Tmax + 0.933 * Trange + 0.486 * KA.$$

The drying curves used are dependent on the type of soil. For a clay soil, water is considered to be readily available to approximately 70% of capacity, (Baier et al., 1979) then decreases. For a sandy soil, they suggest that water is readily available to 30% of capacity, then decreases rapidly. The root contact model of Herkelrath et al. (1983.a & .b) supports the use of curvilinear response

to soil drying at the point when roots begin to lose contact with the soil at drying. This would be more pronounced in a clay soil which tends to undergo shrinkage on drying, whereas shrinkage would be less pronounced in a sandy or silty soil. The moisture content of various levels in the soil column can be highly variable if the physical properties of the soil change with depth. It is often useful to know the moisture content of a particular depth. For example, the moisture content of the surface zone must be suitable for seed germination. Similarly, the moisture content of the top zone is of importance for tractability - the strength to withstand the weight of heavy machinery (Dyer & Baier, 1979). The Z coefficients are set each day depending on the soil moisture content of the zone at the end of the previous day.

Plant rooting characteristics are specific to the type of crop, and can be used with confidence regardless of soil type. According to Miller (1977:207) if ample moisture is available at the beginning of the season, root development will be concentrated at the top of the soil profile. Consequently, if dry conditions follow later in the season, the lower roots will not be extensive enough to take advantage of soil moisture stored in the lower levels. The Versatile Soil Moisture Budget allows for lower root zones to extract a larger proportion of moisture from the soil after the heading stage of wheat, when plant demand for water is critical. The K coefficients are set according to

the stage of development of the crop. These dates are derived from the crop development programs.

#### 4.4.1 Problems With Assumptions of Soil Moisture Status

There were several major problems associated with a study of this type. The analysis assumed that the fields were at field capacity on May 1 of each year. While it is certainly reasonable to assume that the fields would not be at less than field capacity, the usual case is an excess of standing water on the fields (Bell, 1971). Also, one of the characteristics of the budgetting procedure is that in episodes of excess rainfall, a logarithmic equation predicts the amount of runoff from the field, based on antecedent moisture content in the top zone. Due to the absence of slope and the naturally poor drainage on these lands, it is likely that a large rainfall would remain ponded on the field and either evaporate or slowly infiltrate over a few days.

Finally, in the absence of actual soil moisture measurement to compare with the estimated amounts, it is difficult to make more than general qualitative conclusions on the soil moisture status of these fields.

#### 4.5 STATISTICAL ANALYSIS

The development estimation programs and soil moisture budgetting programs are carried out for each year from 1955 to 1980 inclusive. The results are in the form of series of

twenty nine dates or amounts derived from the programs.

The dates of attainment of phenological stages and the amount of moisture remaining in the soil at different times in the season are then analysed statistically. They are used to determine the probabilities related to development by certain dates and moisture availability at critical times. For the biometeorological time scale, dates of attaining each stage (planting, emergence, jointing, heading, soft dough and ripe), and the intervals between each stage are calculated. For the degree day forage growth program, the dates derived include date when full cover is reached, date of cutting, and date when crop has again reached full cover. From the water budgetting procedure, the results consist of the proportion of total water available present at the end of each stage, for the 29 years.

#### 4.5.1 Probability

The basis for the statistical analysis of the derived values is the normal probability distribution. For each set of values:

$$Y(i) = \mu + e(i)$$

That is, each individual observation,  $Y(i)$ , from the population consists of the mean of the population,  $\mu$ , plus or minus an amount due to random fluctuation and natural

variability,  $e(i)$ . The normal distribution contains a structural part,  $\mu$ , and a distributional part

$$e \sim N(0, \sigma^2) .$$

In the population from which the observations are taken, the random component follows a normal distribution with mean=0 and variance =  $\sigma^2$ . This relationship is such that a distribution function can specify cumulative probabilities of an event taking place, or of an observation falling under a certain value (Steel & Torrie, 1980).

$$\text{Prob}(Y \leq Y(i)) = P(Y=0) + P(Y=1) + \dots P(Y=Y(i))$$

First and last frost dates for the period 1943 to 1980 are analysed using the normal probability distribution to determine dates on which the risk of killing frost in the Pasquia Project is at a certain level. For crop growth, the sets of twenty nine derived values are used to determine cumulative probabilities of dates on which each phenological stage is reached as well as duration of intervals between stages. The amount of moisture remaining in the soil following attainment of each stage is also evaluated using the normal probability distribution, to study the probability of moisture content dropping the level at which it is readily available.

#### 4.5.2 Statistical Analysis Program

The PROC UNIVARIATE program (SAS Institute Inc., 1982) was used to calculate the probabilities associated with frost hazard, development time of crops and amount of moisture available. The program is used to calculate a variety of descriptive statistics of the sample, such as the mean, median, range (lowest to highest), quartiles and deciles. The program is also used to confirm that the samples follow a normal distribution.

## Chapter Five

## RESULTS AND DISCUSSION

5.1 INTRODUCTION

The growth of vegetation is influenced by the interactive effect of climatic, astronomical and soil factors. The response of the crop to the environment is related to the requirements of the crop itself at each particular developmental stage. Conditions which are appropriate for one crop may be inadequate or too extreme for another. In this chapter, the results of the crop development models and soil moisture budget are discussed. The responses of the annual and the perennial crop to two different soil moisture regimes are contrasted.

5.2 CLIMATIC ELEMENTS5.2.1. Radiation

A measurement of insolation provides an initial indication of energy available at the site. Insolation data are available from three climatological stations in Manitoba, as follows:

<u>Station</u>	<u>Latitude</u>	<u>Years Available</u>
Winnipeg A	49°54'N.	1949 to present
The Pas A	53°58'N.	1972 to present
Churchill A	58°45'N.	1949-1961 and 1964 to present

Long term mean daily insolation is displayed in Figure 5.1. The latitudinal difference in insolation is most pronounced during the winter period when the northern sites experience very short daylength periods. All the sites experience similar weather patterns which would affect the transmission of light through the atmosphere. The smaller difference in insolation among the three stations in the summer is related to the longer daylength in the more northerly sites. The troughs in the curves are possibly related to the seasonal migration of the Arctic Front (Graham, 1978; Ripley, 1974).

Insolation is depleted by reflection from the surface. Long wave flux, an important component of the energy budget, was not measured. However, as indicated previously, the long wave flux, mainly representing energy advected into the deficit region by southerly air masses, enhances the energy supply of the northern region to some extent. Uncertainty of the actual amount of the short and long wave energy balance makes it difficult to estimate net radiation accurately. Estimated daily mean net radiation for The Pas is shown on figure 5.2 (insert at back) although there is uncertainty of the actual amount of net energy available.

### 5.2.2 Temperature

The thermal characteristics represent an indication of the amount of energy available. The mean daily maximum, and minimum temperatures are shown in figure 5.2. Temperature is

Winnipeg	1949 to 1980
The Pas	1972 to 1980
Churchill	1964 to 1980

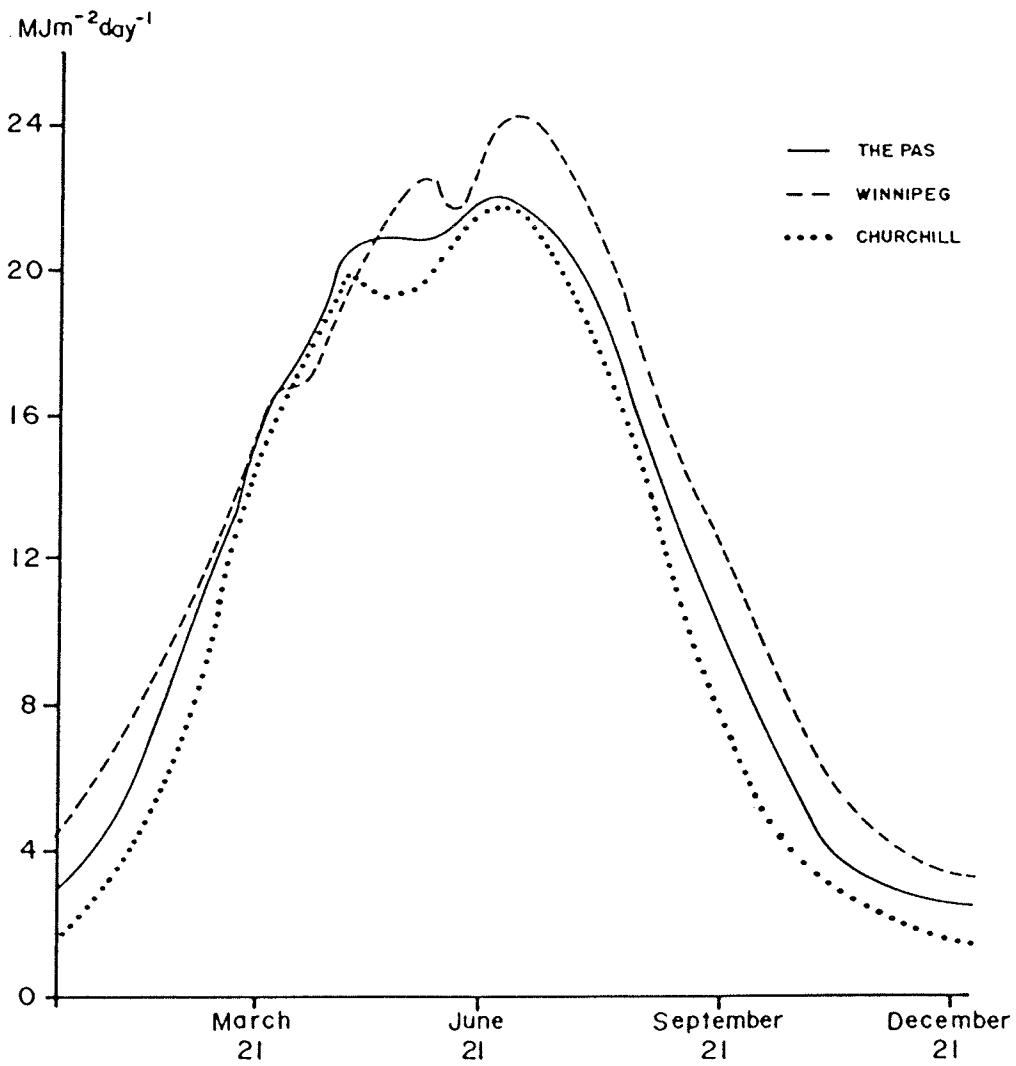


Figure 5.1: Daily Mean Insolation for Three Sites in Manitoba

used, in the absence of radiation measurements, as a substitute in modelling plant interaction with the energy supply. The times of the 10% and 25% risk of killing frost (figure 5.2) comprise an additional element of the thermal and radiative environment of the growing season in the Pasquia Area.

It is evident that, after the month of July, the energy availability decreases significantly. However, the long term precipitation normals for the region indicate that precipitation is expected regularly throughout the growing season. The analysis shows that the precipitation regime is of utmost significance, due to its role in continually depleting the energy available for heating to evaporation.

### 5.2.3 Frost Free Season

Tables 5.1, 5.2 and 5.3 illustrate the statistical analysis of the length of the frost free season and of the expected dates of the last spring and first fall frosts. The mean length of the  $-2.2^{\circ}$  frost free season is 136 days. However, the extreme variability of the climate in these latitudes (st.dev. 16.7 days) effectively reduces the season of above  $-2.2^{\circ}$  to at least 124 days on 75% of the occasions or at least 114 on 90% of the occasions. If  $0^{\circ}\text{C}$ . is used as a critical temperature, then the growing season is even shorter: 96 days 90% of the time and at least 107 days 75% of the time.

The mean date of the last  $-2.2^{\circ}$  spring frost (table

Table 5.1: Statistical Analysis of Frost Free Season  
The Pas, 1943-1980

	Level of Frost	
	-2.2°C.	0.0°C.
number of years	38	38
mean	136 days	115 days
St.Dev.	16.7	13
C.V.	12.2	11.3
* 90%	114 days	96 days
75%	124	107
50%	136	112
25%	148	124
10%	159	135
Shortest	109 days	95 days
Longest	173 days	148 days

\* Percentages are probabilities that the frost free season will last at least the number of days indicated.

Table 5.2: LAST SPRING FROST, The Pas, 1943-1980

		Level of Frost	
		-2.2°C.	0°C.
no. of years		38	38
mean	day	136 (May 16)	148 (May 28)
St.Dev.		10 days	9.5 days
C.V.		7.4	6.4
* 90%	day	120	136
75%		130	139
50%		136	148
25%		142	155
10%		148	160
earliest		113 (April 23)	126 (May 6)
latest		159 (June 8)	167 (June 16)

Table 5.3: FIRST FALL FROST, The Pas, 1943-1980

		Level of Frost	
		-2.2°C.	0°C.
No. of years		38	38
mean	day	272 (Sept. 29)	262 (Sept. 19)
St.Dev.		11.6 days	10 days
C.V.		4.3 %	3.8 %
* 10%	day	258	248
25%		264	255
50%		268	262
75%		280	270
90%		288	277
earliest		252 (Sept. 9)	245 (Sept. 2)
latest		301 (Oct. 28)	285 (Oct. 12)

\* Percentages indicate probabilities of frost after that date for the spring and before that date for the fall

5.2) is May 16 and the standard deviation is 10 days. To reduce the risk of late spring frost to 25% or less, the earliest date of seeding is May 22. To reduce the risk of late spring frost to 10%, the earliest seeding date would be May 28. The mean date of the first  $-2.2^{\circ}$  fall frost (table 5.3) is September 29, (standard deviation of 12 days). There is a 25% risk of frost before September 21, and a 10% risk of a frost before September 15.

### 5.3 CROP DEVELOPMENT MODELLING

This section relates to crop development toward maturity. The interaction of the plant genetical attributes determines in part the effect of the thermal and daylight regime on its development. Energy and moisture factors are interrelated. In fact the availability of moisture at critical times in the crop development has important consequences to final yield. However, this portion of the analysis is particularly concerned with the question of evaluating maturing of crops within a short and highly variable growing season.

#### 5.3.1 Wheat: Progress Toward Maturity

As discussed in Chapter Three, five situations were investigated using the program to estimate biophothermal units to maturity. Situations I, IV and V are "natural" in that they either incorporate a formula to use actual meteorological and soil conditions to estimate date of

planting (I and V), or actual dates of planting are set in to the program (IV). Situations II and III are "forced" in that an arbitrary date of planting is selected to investigate the performance of the crop under particular conditions.

The results of the analysis are presented on the tables and figures as follows:

Table 5.4: Comparison of Mean dates of reaching phenological stages, under the 5 conditions

Table 5.5: Probable dates of reaching each stage (5.5a-5.5e)

Table 5.6: Probable duration (in days) of each stage (5.6a-5.6f)

Figure 5.2: Probable durations of period of planting to ripening for all situations, set into the constraints of the growing season

Figure 5.3: Comparison of modelled wheat growth for 1957-1964

Appendices: Tables of derived dates and durations on A.2.3-A.2.7 a yearly basis, for each situation

The most critical periods considered in this analysis occur in the springtime, when the crops are seeded, and in the fall, when the mature crops are harvested. Since the growing season in the northern location is short and

Table 5.4

Mean Dates of Attainment of Phenological Stages,  
From Different Methods of Setting Planting Date

	Climatic Estimator	Actual Dates	25% Risk	10% Risk
P	134	145	142	148
E	145	154	151	157
J	166	174	171	175
H	191	196	194	198
S	215	221	219	223
R	229	235	233	238
P-E	11 days	9 days	9 days	9 days
E-J	22	20	20	19
J-H	25	22	23	22
H-S	24	25	25	25
S-R	14	14	14	15
P-R	95	90	91	90

P - date of planting  
 E - emergence of plants from ground  
 J - jointing  
 H - heading  
 S - soft dough  
 R - Ripe

(Categories as per Robertson, 1968)

Table 5.5: Probable dates of attainment of phenological stages. Percentages indicate probability that the stage will have been reached by that date.

Table 5.5.a: Probable date of Planting

%	I Climatic Estimator n=29	II 25% Risk Day=142 n=29	III 10% Risk Day=148 n=29	IV Actual 1957-64 n=8	V Climatic Estimator 1957-64
90%	142			151	138
75%	136			150	137
50%	131			145	134
Mean	134			145	133
25%	127			143	130
10%	126			135	127
St.Dev.	9.32			5.19	3.84
C.V.	6.97			3.58	2.89

Table 5.5.b: Probable date of Emergence

%	I Climatic Estimator n=29	II 25% Risk Day=142 n=29	III 10% Risk Day=148 n=29	IV Actual 57-64 n=8	V Compare 57-64 n=8
90%	152	153	159	160	151
75%	149	152	158	158	150
50%	142	151	156	154	144
Mean	145	151	157	154	145
25%	140	150	156	152	140
10%	136	148	155	148	138
St.Dev	8.44	1.73	1.35	3.93	4.80
C.V.	5.83	1.14	0.86	2.54	3.32

Estimation of Attainment of Phenological Stages  
Statistical Analysis: Dates of Transition

Table 5.5.c: Probable date of Jointing

	I	II	III	IV	I
90%	172	175	179	178	172
75%	170	172	176	177	170
50%	165	171	175	175	166
Mean	166	171	175	174	167
25%	162	169	174	171	163
10%	158	168	173	168	162
St. dev	7.32	2.57	2.20	3.38	4.40
C.V.	4.40	1.51	1.25	1.94	2.40

Table.5.5.d: Probable date of heading

	I	II	III	IV	V
90%	199	199	201	201	198
75%	194	196	200	199	196
50%	189	193	198	197	190
Mean	191	194	198	196	191
25%	187	192	195	192	188
10%	185	190	194	191	184
St.Dev	6.12	3.38	3.08	3.52	4.97
C.V.	3.20	1.74	1.55	1.80	2.60

Probable dates of attainment of phenological stages:

Table 5.5.e: Probable date of attaining soft dough stage

	I	II	III	IV	V
90%	222	226	230	227	222
75%	218	222	228	225	219
50%	213	217	222	222	212
Mean	215	219	223	221	214
25%	210	216	219	216	210
10%	208	213	218	214	207
St.Dev.	6.36	4.65	5.11	4.73	5.13
C.V.	2.96	2.13	2.29	2.14	2.40

Table 5.5.f: Probable date of ripening

	I	II	III	IV	V
90%	237	242	248	242	235
75%	232	238	243	240	234
50%	227	232	236	236	226
Mean	229	233	238	235	228
25%	224	228	232	230	224
10%	222	226	229	225	223
St.Dev	6.00	6.04	7.26	5.70	5.15
C.V.	2.62	2.59	3.05	2.43	2.26

Table 5.6: Probability of durations (in days) of intervals between phenological stages

Table 5.6.a: Probable duration of interval between Planting and Emergence

	I	II	III	IV	V
90%	15	11	11	13	17
75%	13	10	10	10	13
50%	11	9	8	9	11
Mean	11	9	9	9	12
25%	9	8	8	8	9
10%	8	6	7	7	8
St.Dev.	2.68	1.73	1.35	1.77	2.83
C.V. (%)	24.3	19.5	15.6	18.9	24.6

Table 5.6.b: Probable duration of interval between Emergence and Jointing

	I	II	III	IV	V
90%	25	23	20	24	25
75%	23	22	20	21	24
50%	22	20	19	20	22
Mean	22	20	19	20	22
25%	20	18	18	17	20
10%	18	17	17	17	19
St.Dev.	2.35	1.97	1.50	2.33	2.30
C.V.	10.8	9.9	8.0	12.0	10.5

Table 5.6.c: Probable duration of interval between Jointing and heading

	I	II	III	IV	V
90%	29	28	26	26	29
75%	27	26	24	24	26
50%	26	23	23	22	25
Mean	25	23	22	22	24
25%	21	22	20	20	22
10%	19	19	19	18	20
St.Dev.	3.65	2.94	2.74	2.75	2.83
C.V.	14.8	12.6	12.3	12.4	11.5

Table 5.6.d: Probable duration of interval between Heading and Soft Dough Stage

	I	II	III	IV	V
90%	28	26	32	29	25
75%	25	26	27	26	24
50%	24	24	25	25	23
Mean	24	25	25	25	23
25%	23	23	23	23	22
10%	22	22	22	21	21
St.Dev.	1.91	2.65	3.31	2.49	1.25
C.V.	7.9	10.7	13.0	10.1	5.4

Table 5.6.e: Probable duration of interval between Soft Dough and Ripening

	I	II	III	IV	V
90%	18	18	19	16	16
75%	15	16	18	15	16
50%	13	14	14	14	14
Mean	14	14	15	14	14
25%	12	12	12	12	13
10%	11	11	11	11	11
St.Dev.	2.53	3.23	3.39	1.73	1.77
C.V.	18.7	22.9	23.0	12.4	12.7

Table 5.6.f: Probable duration of interval between Planting and Ripening

	I	II	III	IV	V
90%	104	100	100	99	102
75%	100	96	95	94	101
50%	95	90	88	90	95
Mean	95	91	90	90	95
25%	89	86	84	84	90
10%	86	84	81	82	86
St.Dev.	7.62	6.04	7.26	5.88	6.02
C.V.	8.0	6.6	8.1	6.6	6.4

variable, it is important for farmers to make the most advantageous use of the time span in terms of thermal and energy conditions. The four situations considered different timing of planting based on spring conditions.

#### 5.3.1.1 Spring Conditions

Using Situation I, the planting date and beginning of water budgetting were estimated using a climate and soil moisture based formula. Two factors make this approach to modelling plausible. The planting dates correspond well with actual planting dates of wheat crops used in the development of the biometeorological time scale (Robertson, 1968) (table 5.7). The average duration of phenological stages and the average time span from planting to attainment of stages (table 5.8) are very comparable. As well, the climatic estimation formula was used successfully for conditions in southern Manitoba (Dunlop, 1981).

Unfortunately, as Figure 5.2 shows, in many cases emergence occurs when the risk of a  $-2.2^{\circ}$  frost and certainly a  $0^{\circ}$  frost are greater than 25%. Furthermore, due to poor drainage conditions locally in the post thaw period, it is common for water to still be on the fields during the first week of May. It is therefore unreasonable to expect that field work could begin by this early date.

The approach in Situation IV, in which only the 8 years for which known planting dates were used, provides a more accurate representation of wheat growing conditions in the

Table 5.7

Comparison of Mean Planting Dates Estimated for  
The Pasquia Project and at Stations Used in  
Developing the Model (Robertson, 1968)

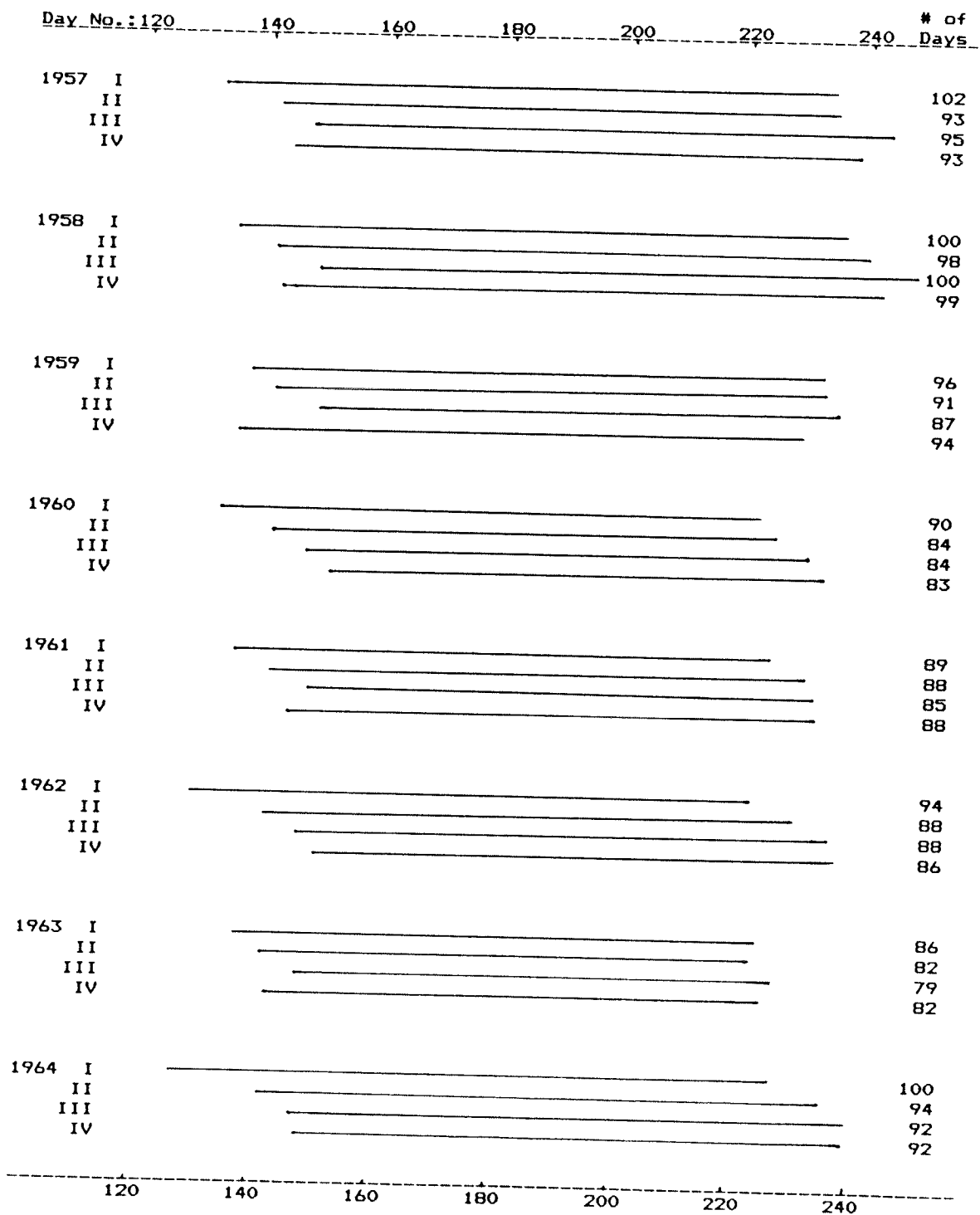
Station	Latitude	Mean Planting Date
Lacombe, Alberta	52°28'	139 (May 19)
Beaverlodge	55°11'	130 (May 10)
Fort Simpson, NWT	61°52'	141 (May 21)
Pasquia Project	53°43'	134 (May 14)

Table 5.8

Average Number of Days Between Stages,  
From Model Development (Robertson, 1968),  
Compared to Situation I Using Pasquia Data

	Planting to End of Stage		Average Span	
	Model	I	Model	I
Planting-Emergence	9	11	9	11
Emergence-Jointing	29	33	20	22
Jointing-Heading	55	58	26	25
Heading-Soft Dough	80	82	25	24
Soft Dough-Ripe	95	96	15	14

Figure 5.3: Comparison of Modelled Wheat Development, 1957-1964  
Using Biometeorological Time Scale



Pasquia Project. Under the constraints of a short growing season and spring field water problems, farmers would be expected to seed their fields at the earliest and most opportune time. These years, from 1957 to 1964, overlap with the years in which the phenological data were collected to develop and test the biometeorological time scale (1953 to 1965). Therefore, the wheat grown in the Pasquia Project would have been comparable and the crops would have been responding in relatively the same manner as those used in the model development. Situation V comprises phenological data derived using the same 8 years, 1957-1964, but setting the planting date with the climatic estimator formula, for the purpose of comparison. Although the results are comparable to that found in the stations used in developing the model, the local conditions clearly make the use of the same planting formula unsuitable in this case.

#### 5.3.1.2 Fall Conditions

The frequent comment during years of variety trials in the Pasquia Project was that seeding must take place as early as possible in order that harvesting can occur before adverse weather conditions commence in the fall. Therefore, the length of time to develop and mature the crop must be considered in terms of the estimated time of ripening.

In Situation I, crop ripening was commonly estimated to occur in late July or early August, much before a frost would be expected. For example, for the year 1963 the model

estimated the ripening of the wheat crop 63 days prior to the days on which a frost of  $-2.2^{\circ}\text{C}$ . occurred. However, it is unlikely that a crop sown that early would survive due to the freezes expected in the late spring.

It would appear that the best dates to use to study the climatic environment at the end of the growing season would be the dates derived from situations II and III, which are similar to the results using actual planting dates. Graphic portrayal of the results in figure 5.2 along with tables 5.5.a-.f and 5.6.a-.f indicate that the best representation of actual conditions is found by setting the planting date to the date following which the risk of frost is less than 25%. Particularly with reference to figure 5.2, the dates of crop ripening for May 22 seeding and actual seeding dates are similar.

However, if one looks only at results of the modelling for the years 1957-1964 (figure 5.3), it is found that the estimated dates of ripening when the crop is planted on May 22 are much earlier than those predicted using actual planting dates. The differences in date of ripening over the eight year period are least when using May 28 as the planting date (table 5.9). Thus the analysis shows that the best representation of wheat development is found with the latest date of planting. For 1960 to 1964 there are also harvest dates available. If one allows a few extra days for drying and for the possibility of precipitation during the post ripening period, III and IV are found to estimate

fairly well the actual wheat growth in the years tested. In 1960, grain was harvested at Station 2 on August 25, the estimated date obtained using the programs for May 28 planting and for actual planting dates. Harvesting was on September 1-3 at Station 1.

Table 5.9: Comparison of Modelled Dates of Ripening when Planting Date was Known with Situations where Planting Date was Estimated.

Year	Date of Ripening	Difference (in days)		
		I	II	III
1957	238	-4	-3	+5 *
1958	242	-7	-2	+6
1959	229	+4	+4	-6
1960	234	-11	-8	+2
1961	233	-8	-2	0
1962	237	-14	-7	+1
1963	225	-1	-1	-2
1964	240	-13	-4	0

\* Negative sign means ripening date was earlier, positive means ripening date was later than for situation where actual planting dates were used

The consequence of the best representation of actual conditions being estimated with the latest planting situation is that it allows a very small margin of safety at the end of the season in which to dry and harvest the crop. The risk of precipitation at the end of the season is quite high.

### 5.3.2 Forage: Degree Days

The degree-day program for forage growth was used to establish reasonable dates to set into the Versatile Soil Moisture Budget. This was done in order to study the difference between water use by an annual crop which grows from the bare ground and reaches a more or less full cover and a perennial crop which is assumed to extract water by a well-developed rooting system throughout the growing season. Therefore, the forage degree day program assumed that a previously planted field of alfalfa was on the field in the spring and, following a period of attainment of full field cover, began to develop vegetatively until the flowering and cutting stage (tables 5.10, 5.11). Following this a brief period of regrowth and adjustment was budgetted for, then the same rate of growth and addition of degree days was carried out for the remainder of the season. In several instances (indicated by asterisks in the tables of dates in Appendix A.2.7) the program indicated that the forage had reached sufficient development for a second cutting. However, the growing season is extremely variable and in most cases the date of predicted cutting was followed within several days by the first fall frost below  $-2.2^{\circ}\text{C}$ .

Dates of cutting predicted by the program ranged from July 9 to August 9, with standard deviation of 11.6 days. Evidence from field crop reports of the Pasquia Project indicate that sampling of forage crops took place within a highly variable time period. In 1957 forage was sampled for

Table 5.10

Forage: Statistical Analysis of Phenological Dates Determined Using Degree Days

%	Begin	Full	Cut	End
90	146	176	221	290
75	140	162	214	274
50	133	155	206	266
Mean	133	156	205	269
25	125	146	196	261
10	122	142	190	257
St.Dev	8.7	11.4	11.6	12.4
C.V.	6.55	7.35	5.63	4.60

Table 5.11

Forage: No. of Days to Each Stage of Growth

%	Begin to Full C	Full Cover to Cutting	Cutting to End of Season
90	54	55	90
75	32	52	72
50	21	50	64
Mean	23	50	64
25	12	47	51
10	5	45	43
St.Dev.	14.9	3.4	15.9
C.V.	65.13	6.94	24.80

hay on July 12 at Station 2, in 1960 sampling was done on June 29, and in 1963 on August 15.

#### 5.4 VERSATILE SOIL MOISTURE BUDGET

In addition to the direct use of the crop development programs to study the crops within the agricultural season in the Pasquia Project, the dates of attainment of phenological stages of development were used to set the coefficients for consumptive use of water. The tables A.2.8 to A.2.11 in the Appendix show probabilities of the extent of soil moisture deficit for each stage of development of wheat grown on the two soil types. Station 1, Le Pas Drained Phase clay soil, was assumed to have 260 mm of available soil water. (University of Manitoba, 1977). The soil drying curve in the budgetting procedure provided for ready extraction of moisture down to 70% of capacity, with a decrease in water availability below this level. Station 2, Pasquia Drained, saline phase, a sandy soil, was assumed to have 240 mm of available water (University of Manitoba, 1977). Soil water is more readily available over a larger range of soil moisture content in a sandy soil (Baier et al., 1979; Gardner, 1960). A soil drying curve which provided for readily available moisture down to 30% of capacity was used to budget water use on this soil. For both soil drying curves, an exponential decrease of availability was used below the level of readily available soil moisture.

The water deficits shown are profile totals for each

stage, although six zones of the soil profile were modelled for each situation on a daily basis. There are no soil moisture data to verify the results, so it would not be meaningful to include modelled amounts for each zone.

#### 5.4.1 Wheat: Water Use

At the beginning of growth the wheat plants extract very little moisture from the soil. The consumptive use increases as the plants develop a root system to extract moisture from the soil and as the aerial extent of the plants present a larger surface for transpiration. Following the soft dough stage of development, consumptive use drops as the seeds ripen and the vegetative parts of the plant dry. Post-ripening water use is similar to that for a bare soil. Tables 5.12.a to 5.12.e present the soil moisture availability at the end of each phenological stage estimated for wheat grown on a clay soil and on a sandy soil.

For both clay and sandy soils in the Pasquia Project there is very little chance of an overall moisture shortage early in the season (table 5.12.a). Within both profiles the content is close to field capacity. This can be misleading because, while the total amount of water available is high, deficit conditions can exist for the plants if the surface of the soil is dried out following a dry spell. Similarly, the analysis shows that by the jointing stage there is adequate moisture in both soil types, according to the moisture budgetting procedure (table 5.12.b).

Table 5.12.a: Proportion of Total Soil Moisture Available on Emergence of Wheat.

	Station 1 Clay Soil	Station 2 Sandy Soil
* 10%	.97	.96
25%	.94	.93
50%	.92	.91
Mean	.93	.92
75%	.93	.89
90%	.90	.89

\* The percentages indicate the percent probability that the soil will contain at least that proportion of total available moisture at that stage.

Table 5.12.b: Proportion of Total Soil Moisture Available upon Attainment of Jointing Stage

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.96	.91
25%	.89	.87
50%	.84	.79
Mean	.86	.81
75%	.82	.76
90%	.81	.74

Table 5.12.c: Proportion of Total Soil Moisture Available On Attainment of Heading Stage

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.90	.86
25%	.79	.68
50%	.71	.53
Mean	.75	.60
75%	.69	.52
90%	.66	.46

Table 5.12.d: Proportion of Total Soil Moisture Available on Attainment of Soft Dough Stage

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.74	.56
25%	.70	.43
50%	.64	.34
Mean	.65	.38
75%	.58	.27
90%	.57	.24

Table 5.12.e: Proportion of Total Soil Moisture Available on Ripening of Wheat

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.71	.43
25%	.66	.40
50%	.60	.29
Mean	.62	.31
75%	.57	.24
90%	.55	.22

The interval between jointing and the soft dough stage is critical for wheat in terms of the development of the number and size of grains. By the heading stage, on clay soil, there was a 25% chance that the soil would contain less than 70% of available moisture capacity (table 5.12.c). However, within this constraint, there was only a 10% probability that it would be less than 66%. This would not indicate a serious deficit. On sandy soil there was 90% probability that the soil moisture content at this stage would be greater than 46% of capacity.

By the end of the soft dough stage, on clay soil there was a 50% probability that 65% of total moisture capacity would be available, with only a 10% chance that it would be less than 57% (table 5.12.d). Wheat can survive short periods of drought with little adverse affect (Agric. Canada Research Report, 1962-64). On sandy soil there was a mean availability of 38% of capacity., with only a 10% probability that it would be less than 24%.

The water requirement decreases substantially by the ripening stage. The mean amount of soil moisture available in the clay soil was 62%, with only a 10% chance that it would be lower than 55% of total capacity. There was a 10% probability that there would be 70% of capacity (that is, that water would be easily available). On sandy soil, the budgetting procedure estimated a mean water availability of 31% of capacity. The amount of moisture in the soil is critical at the end of the growing season because the crops

must be dried prior to harvest. As consumptive use plummets and atmospheric demand for water decreases with cooler temperatures, drying is slow. Field crop recommendations for the Pasquia Project suggest wheat cropping is appropriate for the drier years. This is evident in the ability of the soil environment to provide adequate moisture to the growing crops, with very little chance of drought.

#### 5.4.2 Forage: Water Use

Table 5.13.a shows the soil moisture availability in the spring after the forage has grown to full cover. At this stage soil water is readily available, with greater than 70% of total capacity in the clay and greater than 59% in the sandy soil.

By the time of cutting, between July 1 and August 15, there is a difference in soil moisture availability between the clay and sandy soils. With moisture content in the clay soil estimated at 53% to 67% of total available, rate of extraction by the plant roots begins to decrease. In the sandy soil, there is a 90% chance that soil moisture content is greater than the 30% of total below which extraction is limited, although the absolute moisture content is lower in this soil. There is no second cutting of forage so following the harvest the forage becomes reestablished and then continues to grow throughout the remainder of the season. There is a significant probability of moisture deficit by the end of the season (table 5.13.c), due to the high

Table 5.13.a: Proportion of Total Soil Moisture Available When the Forage Crop is at Full Cover

	Station 1 Clay Soil	Station 2 Sandy Soil
* 10%	.97	.95
25%	.94	.92
50%	.88	.84
Mean	.87	.82
75%	.80	.76
90%	.72	.59

\* Percentages refer to the probability that the soil moisture content will be greater than the amount indicated.

Table 5.13.b: Proportion of Total Soil Moisture Available at the Time of Cutting

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.67	.48
25%	.63	.39
50%	.56	.37
Mean	.58	.38
75%	.55	.32
90%	.53	.30

Table 5.13.c: Proportion of Total Soil Moisture Available at the End of the Growing Season

	Station 1 Clay Soil	Station 2 Sandy Soil
10%	.69	.36
25%	.64	.29
50%	.58	.23
Mean	.57	.22
75%	.48	.12
90%	.41	.09

consumptive use of a continuous cover forage crop with a large leaf area index throughout the season. On the clay soil water availability is less than 70% of capacity at the end of the season, with a 10% probability that the soil moisture content will be less than 41% of capacity. In the clay soil this moisture would not be readily extracted. Similarly, in the sandy soil there was a 25% probability that less than 12% of total capacity would remain in the soil at the end of the season. However, there was a 25% probability that soil moisture content would be greater than the 30% of capacity below which moisture becomes a limiting factor.

It is important to note that the Versatile Soil Moisture Budget considered precipitation to be infiltrated into the ground on the day of the precipitation event. For a rainfall in excess of 25.4 mm, (1 inch), a logarithmic equation determines runoff as a proportion of antecedent moisture content in the top zone. However, in this area of negligent slope and poor natural drainage, it is expected that infiltration will continue over a period of a few days following precipitation, and that there will be little runoff. In the period of water budgetting approximately 20 large rainfall events occurred which were estimated to have resulted in substantial runoff of as much as 15 mm (appendix A.2.12). It is more likely that this moisture would have been infiltrated into the ground over a period of a few days.

The analysis shows that soil moisture deficit would not be a limiting factor in this area. Exceptions were noted in some years when early drought did affect the establishment of some newly planted alfalfa and grass as well as grains. This was the case in 1957 when grass and wheat were damaged by dry conditions shortly after seeding. Particularly in regard to Station 2 on salinized soil, damage to clover and grasses occurred when water moved upward from the water table, evaporating near the surface and depositing dissolved salts in the soil. Therefore, damage was indirectly related to drought conditions, although the specific cause was not lack of subsurface moisture, but salinity (Ellis, 1958).

A far more major problem is identified in the post ripening period for annual crops. After the middle of July, insolation and temperature decrease. Long term precipitation normals throughout the season indicate, however, that moisture continues to enter the soil profile at the end of the summer. While energy to do work decreases after the middle of July, and while consumptive use by wheat of soil moisture drops following the ripening of the grain, there is still abundant precipitation. The "effective" precipitation is much greater because of the reduced atmospheric and biological demand.

The reports of variety and fertilizer trials for the Pasquia Project continually stressed the need to seed crops as soon as possible in the spring to ensure successful growth before autumn. Treidl (1978) indicated that

temperature in the Prairies decreases from southwest to northeast while precipitation increases from southwest to northeast. The combination of lower temperatures, short effective growing season and relatively high precipitation creates a major constraint to agriculture in the North.

## Chapter Six

## CONCLUSIONS

6.1 INTRODUCTION

The objective of this study has been to evaluate the climatic environment for agriculture in a northern region. In general, the area can sustain profitable agriculture. However, the variability of the climate increases the risks to successful production. This study has analysed the climatic elements during the growing season, in terms of an annual crop, wheat, and a perennial forage crop, alfalfa.

6.2 SUMMARY OF THE RESULTS

The growing season in the Pasquia area is relatively short. The period between killing frosts of less than  $-2.2^{\circ}\text{C}$ . is only 136 days on average, and only 115 days between frosts of  $0^{\circ}\text{C}$ . The study shows that there is sufficient energy to mature wheat. However, due to the brevity of the frost-free season, timing of activities in the spring and fall is extremely critical. Seeding must take place as soon as possible following removal of water in the spring and when risk of frost is acceptable. In the fall, the crops must be harvested before the onset of adverse weather conditions associated with precipitation,

decreasing energy and low evaporative demand for soil moisture. For these reasons, a dependence on grain farming alone is not appropriate for this area.

There is also adequate energy and moisture for forage growth. However, only one cutting of forage is possible in most years because of the early frost and the reduction of energy required for reestablishment of the plants following cutting. Leguminous forage improves the soil by adding nitrogen. Ellis (1961.b) recommended forage for use in rotation with grains, as forage provides an enhancement to soil fertility. This is important as the cost of importing commercial fertilizers is high.

The results of the moisture budgetting procedure show that moisture deficiency is not a problem in most years. The reverse situation of surplus moisture is a problem for grain culture in the Pasquia Project.

### 6.3 YIELDS FROM VARIETY TRIALS

Notwithstanding the marginal nature of this environment with respect to profitable agriculture, it has been found that quite good yields are possible from the Pasquia Area. Each year the Province of Manitoba Department of Agriculture conducts variety trials in the crop reporting districts. Comparison of results averaged from other districts in Manitoba with those found in two stations in the Pasquia Project demonstrates this (table 6.1).

Table 6.1:

Wheat Yields at Stations 1 and 2  
 Compared with Average Manitoba Yields  
 (Bushels per Acre)\*\*\*

Year	Station 1	Station 2	Manitoba
1957	51.5	20.9	31.2
1958	50.5	26.1	36.5
1959	50.9	26.9	22.0
1960	47.6	9.9	31.7
1961	46.9	24.6	20.8
1962	32.6		30.3
1963	47.1		24.7
1964	20.5		30.0
1965**			
1966	56.4		34.3
1967	73.7		37.5
1968	57.0		42.0
1969	50.3		38.2

\*\* Year characterized by high precipitation and low mean temperature - no yield data available for this year.

\*\*\* Figures taken from annual reports of field crop variety trials

Reclamation projects have helped to alleviate some of the soil problems related to poor drainage and waterlogging. The excellent yields achieved by some operators in the Pasquia area show that this northern area can be very productive. However, due to the variability of the climate and overall short season, good management is necessary for success.

#### 6.4 SUGGESTIONS FOR FUTURE RESEARCH

As the requirement for agricultural land increases, the northern areas will continue to be of interest for development. In northern locations the high costs of transporting food and fuel suggest that it would be more economical for needs to be met locally than by importing produce from the south. The need to evaluate the capacity of the land to support agriculture is apparent.

Northern locations experience specific problems related to agriculture. In the Peace River Region, (Wallis et al., 1983) the growth of forage was modelled to deal with the limitations of temperature and moisture. In the Pasquia Region, there is sufficient moisture and, in addition, thermal deficiency results in low evaporative demand.

An immediate possibility for research developing out of this study would involve the use of climate based programs to evaluate the probabilities of field workdays in the spring and fall.

A need exists for a field study of meteorological and soil conditions throughout the growing season. This would provide measurements of actual soil moisture content at various levels in different soil types. Measurement of soil heat flux would provide an indication of the change from positive to negative energy balance as insolation decreases rapidly in July and August. Measurement of precipitation and evaporation would provide a good understanding of the actual moisture and energy regime in the northern location

at the end of the season.

Current research interests of governments are concerned with possible ramifications of global warming associated with increase of atmospheric carbon dioxide. The warming is postulated to result in longer growing seasons, warmer summer temperature and changes in atmospheric evaporative demand. In the event of such a warming trend taking place, it is possible that northern agricultural regions such as The Pas area would benefit. The Pas area presents an ideal situation for research of this type.

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## APPENDIX 1

Description of soil types utilized in this study: From Soils Report No. 11, Report of Detailed Soil Survey of Pasquia Map Area in Northern Manitoba. By W. A. Ehrlich, L. E. Pratt, F. P. Leclaire & J. A. Barr, 1960.

Appendix A.1.1 Station 1

Le Pas Clay, Le Pas drained phase, 14,932 acres in Pasquia Map Area, (7500 hectares), (River Lot 50, Carrot River Road, J. Jaeger Farm in Reports of Crop Adaptation Trials and Field Crop Recommendations).

"Soils of this phase occur generally as long strips bordering some of the more prominent levees, notably those of the Carrot River and Nels Creek. These soils have silty clay to clay textures and are moderately calcareous throughout the soil section. No salinity of consequence has been noted; the conductivities of the soils tested were less than 2.0 mmhos/cm.

Surface drainage is moderately good because of the gentle fall of the terrain toward the deeper recesses of the delta. Internal drainage, however, is restricted by the retentive nature of the fine textured sediments. The high water table, originally the main problem, is being lowered by the numerous surface drains constructed in the delta area.

Prior to cultivation and fires, these soils had a layer of peat usually less than 12 inches in thickness. Horizon development in general is negligible and the dark coloured surface layer in cultivated fields is due to mechanical mixing of the peat and muck with the underlying mineral sediments.

Appendix A.1.2 Station 2

Pasquia Drained, Saline Phase, 2,429 acres in the Pasquia Map Area (approximately 1200 hectares):

Pasquia Drained Phase: "The drained phase, in comparison with the modal phase, has better surface drainage, a thinner layer of clay on the surface of the soil and less banding of finer textured sediments within the profile. In a few places, the surface layer of clay is absent. A thin layer of muck or peat was present on the surface prior to burning and cultivation. These soils are moderately calcareous and the predominant textural fraction consists of fine sand. Iron mottling is pronounced throughout the soil profiles.."

Pasquia Drained, Saline Phase: "The saline phase is similar to the drained phase in the physical and chemical features except for a general higher degree of salinity. Salinity in this phase ranges from a low of less than 2 mmhos/cm. conductivity to a high of over 20 mmhos/cm. In a few small areas, the salinity is sufficiently high to inhibit all plant growth. The salts, which are primarily chlorides, can only be detected by soil tests or by the presence of indicator plants such as goosefoot, wild barley, salt grass, gum weed, sea blite and glasswort.

"Salinity in these sandy soils is variable from one season to another. This variation is due to rapid changes in the ground water level. When the water table is low, the salt concentration in the sandy surface layers is quickly lowered through the leaching effect of percolating rain water. If the water table is kept at a low level, in a few years time soil salinity would not be a serious problem in crop production."

APPENDIX A.2  
Yearly Data Derived from the Models

Appendix A.2.a

No. of Days with Minimum Temperature  
Greater than 0°C.

Year	Spring (Julian date)	Fall	Season No. of Days
1943	164	259	95
1944	137	266	129
1945	156	275	119
1946	143	245	102
1947	148	260	112
1948	149	285	136
1949	145	277	132
1950	158	259	101
1951	156	266	110
1952	150	266	116
1953	156	277	121
1954	151	274	123
1955	136	254	118
1956	152	248	96
1957	152	261	109
1958	159	266	107
1959	147	253	106
1960	138	266	128
1961	137	248	111
1962	134	251	117
1963	146	255	109
1964	155	258	103
1965	147	265	118
1966	137	272	135
1967	155	275	120
1968	141	277	136
1969	164	260	96
1970	146	257	111
1971	139	264	125
1972	167	265	98
1973	133	258	125
1974	145	252	107
1975	154	250	96
1976	138	245	107
1977	126	274	148
1978	152	270	118
1979	155	264	109
1980	153	260	107
1981	152	259	107
1982	159	257	98
1983	149	265	116

Appendix A.2.2

No. of Days with Minimum Temperature  
Greater than  $-2.2^{\circ}\text{C}$ .

Year	Spring (Julian date)	Fall	Season No. of Days
1943	138	285	147
1944	132	273	141
1945	148	275	127
1946	134	280	146
1947	148	265	117
1948	131	288	157
1949	144	281	137
1950	136	278	142
1951	136	268	132
1952	113	278	165
1953	139	278	139
1954	149	274	125
1955	131	254	123
1956	144	258	114
1957	152	261	109
1958	159	269	110
1959	141	258	117
1960	127	266	139
1961	137	266	129
1962	126	262	136
1963	146	301	155
1964	120	271	151
1965	139	267	128
1966	132	287	155
1967	140	293	153
1968	141	277	136
1969	144	266	122
1970	139	257	118
1971	138	264	126
1972	128	268	140
1973	133	261	128
1974	138	252	114
1975	113	286	173
1976	127	268	141
1977	126	284	158
1978	119	290	171
1979	134	265	131
1980	134	262	128
1981	137	270	133
1982	130	257	127
1983	144	272	128

Appendix A.2.3

Phenological data from Biometeorological Time Scale for  
Wheat, Using Climatic Estimator to Set Planting Date:

Year	P	E	J	H	S	R	PE	EJ	JH	HS	SR	PR
1955	156	164	181	201	225	237	8	17	20	24	12	81
1956	141	150	168	191	215	227	9	18	23	24	12	86
1957	132	149	172	196	219	234	17	23	24	23	15	102
1958	134	144	169	198	222	235	10	25	29	24	13	101
1959	137	150	170	196	218	233	13	20	26	22	15	96
1960	133	142	163	189	210	223	9	21	26	21	13	90
1961	136	144	164	187	212	225	8	20	23	25	13	89
1962	129	140	162	184	207	223	11	22	22	23	16	94
1963	138	151	170	190	213	224	13	19	20	23	11	86
1964	127	138	163	189	211	227	11	25	26	22	16	100
1965	132	144	166	191	216	228	12	22	25	25	12	96
1966	129	143	166	185	209	221	14	23	19	24	12	92
1967	133	144	167	194	218	231	11	23	27	24	13	98
1968	130	142	162	194	222	241	12	20	32	28	19	111
1969	126	141	168	199	222	233	15	27	31	23	11	107
1970	131	142	164	187	208	220	11	22	23	21	12	89
1971	131	141	162	188	216	229	10	21	26	28	13	98
1972	127	136	158	186	215	230	9	22	28	29	15	103
1973	127	138	160	187	211	222	11	22	27	24	11	95
1974	138	152	172	192	216	227	14	20	20	24	11	89
1975	132	147	168	188	210	224	15	21	20	22	14	92
1976	130	139	158	186	210	224	9	19	28	24	14	94
1977	127	135	156	182	207	227	8	21	26	25	20	100
1978	126	136	160	186	212	227	10	24	26	26	15	101
1979	142	149	171	190	213	231	7	22	19	23	18	89
1980	127	139	161	189	212	226	12	22	28	23	14	99
1981	130	140	165	189	213	224	10	25	24	24	11	94
1982	126	141	165	192	217	230	15	24	27	25	13	104
1983	169	175	193	212	237	246	6	18	19	25	9	77
Mean	134	145	166	191	215	229	11	22	25	24	14	95

Appendix A.2.4

Phenological data from Biometeorological Time Scale for  
Wheat, Using Date of 25% Chance of Frost as Planting Date:  
Day 142

Year	E	J	H	S	R	PE	EJ	JH	HS	SR	PR
1955	150	168	192	212	224	8	18	24	20	12	82
1956	152	169	193	217	230	10	17	24	24	13	88
1957	152	174	197	220	235	10	22	23	23	15	93
1958	151	175	200	225	240	9	24	25	25	15	98
1959	151	170	196	218	233	9	19	26	22	15	91
1960	150	170	192	214	226	8	20	22	22	12	84
1961	150	169	191	217	231	8	19	22	26	14	88
1962	152	169	191	216	230	10	17	22	25	14	88
1963	152	171	190	213	224	10	19	19	23	11	82
1964	153	175	194	219	236	11	22	19	25	17	94
1965	153	171	199	223	238	11	18	28	24	15	96
1966	151	171	190	215	228	9	20	19	25	13	86
1967	150	171	197	222	234	8	21	26	25	12	92
1968	149	168	198	230	247	7	19	30	32	17	105
1969	153	177	203	226	238	11	24	26	23	12	96
1970	153	171	193	216	226	11	18	22	23	10	84
1971	150	168	196	222	236	8	18	28	26	14	94
1972	150	169	195	228	239	8	19	26	33	11	97
1973	149	169	192	216	227	7	20	23	24	11	85
1974	152	172	192	216	227	10	20	20	24	11	85
1975	154	173	192	215	232	12	19	19	23	17	90
1976	148	165	190	215	229	6	17	25	25	14	87
1977	148	168	191	217	242	6	20	23	26	25	100
1978	149	172	195	221	238	7	23	23	26	17	96
1979	149	171	190	213	231	7	22	19	23	18	89
1980	148	170	194	220	233	6	22	24	26	13	91
1981	151	171	192	216	228	9	20	21	24	12	86
1982	153	174	198	224	243	11	21	24	26	19	101
1983	152	171	195	217	227	10	19	24	22	10	85
Mean	151	171	194	219	233	9	20	23	25	14	90

Appendix A.2.5

Phenological data from Biometeorological Time Scale for  
Wheat, Using Date of 10% Chance of Frost as Planting Date:  
Day 148

Year	E	J	H	S	R	PE	EJ	JH	HS	SR	PR
1955	154	172	195	216	228	6	18	23	21	12	80
1956	157	172	196	221	236	9	15	24	25	15	88
1957	158	178	200	225	243	10	20	22	25	18	95
1958	159	180	203	230	248	11	21	23	27	18	100
1959	156	175	198	220	235	8	19	23	22	15	87
1960	158	175	197	220	232	10	17	22	23	12	84
1961	155	174	194	219	233	7	19	20	25	14	85
1962	157	174	197	223	236	9	17	23	26	13	88
1963	156	174	193	216	227	8	18	19	23	11	79
1964	158	178	196	225	240	10	20	18	29	15	92
1965	156	174	201	225	243	8	18	27	24	18	95
1966	157	175	194	219	235	9	18	19	25	16	87
1967	157	177	200	225	239	9	20	23	25	14	91
1968	156	175	201	236	255	8	19	26	35	19	107
1969	158	181	205	228	239	10	23	24	23	11	91
1970	156	174	195	218	229	8	18	21	23	11	81
1971	155	173	201	228	240	7	18	28	27	12	92
1972	155	174	199	231	242	7	19	25	32	11	94
1973	156	175	199	222	233	8	19	24	23	11	85
1974	156	176	197	219	232	8	20	21	22	13	84
1975	158	175	194	218	235	10	17	19	24	17	87
1976	155	173	197	221	233	7	18	24	24	12	85
1977	155	174	198	230	254	7	19	24	32	24	106
1978	156	176	198	225	243	8	20	22	27	18	95
1979	159	177	193	218	236	11	18	16	25	18	88
1980	157	176	201	229	245	9	19	25	28	16	97
1981	156	176	195	219	231	8	20	19	24	12	83
1982	159	179	201	227	247	11	20	22	26	20	99
1983	157	175	198	219	230	9	18	23	21	11	82
Mean	157	175	198	223	238	9	19	22	25	15	90

Appendix A.2.6

Phenological data from Biometeorological Time Scale for Wheat, Using Actual Planting Dates for Field Trials At J. Jaeger Farm, Station 1, 1957-1964

Year	P	E	J	H	S	R	PE	EJ	JH	HS	SR	PR	Harvest
1957	145	154	175	198	222	238	9	21	23	24	16	93	
1958	143	152	176	201	227	242	9	24	25	26	15	94	
1959	135	148	168	194	215	229	13	20	26	21	14	94	
1960	151	160	177	199	222	234	9	17	22	23	12	83	245
1961	145	153	171	192	218	233	8	18	21	26	15	88	240
1962	151	158	175	198	224	237	7	17	23	26	13	86	251
1963	143	153	172	191	214	225	10	19	19	23	11	82	235
1964	148	158	178	196	225	240	10	20	18	29	15	92	271*
Mean	145	154	174	196	221	235	9	20	22	25	14	90	

\* Abnormal seasonal conditions: high precip values late summer  
low temperatures early fall

Appendix A.2.6

Soil Moisture Deficit on Dates of Reaching Successive Phenological Stages:

Wheat Grown on Clay Soil (Station1), Showing Comparison Between Water Use Estimated from Actual Dates and Estimated Dates for the Years (1957-64)

Year	Emergence	Jointing	Heading	Soft Dough	Ripe
1957	22.3	51.6	78.5	112.0	72.6
1958	19.3	45.1	87.6	95.1	106.3
1959	20.1	33.6	79.1	88.0	88.1
1960	8.1	37.1	81.4	107.1	120.5
1961	11.1	48.5	84.5	111.5	123.6
1962	20.7	23.8	80.6	97.7	98.1
1963	20.9	27.8	20.6	69.8	89.1
1964	21.8	49.2	73.4	56.0	69.2

Appendix A.2.7

Phenological Dates for Forage, using Degree Day Accumulation to Set Cutting Date

Year	Begin Growth	Full Cover	First Cutting	Full Cover	End
1955	138	142	190	201	254
1956	146	161	215	225	258
1957	125	169	215	225	261
1958	126	136	189	199	269
1959	143	159	209	219	258
1960	149	153	204	214	266
1961	126	153	196	206	266
1962	139	162	209	219	262
1963	144	156	211	221	301
1964	123	177	232	242	271
1965	136	155	206	216	267
1966	141	165	216	226	287
1967	122	153	202	212	293
1968	134	150	201	211	277
1969	125	180	223	233	266
1970	121	158	213	225	257
1971	133	154	202	212	264
1972	130	146	196	206	268
1973	137	152	206	221	261
1974	147	158	208	218	252
1975	127	162	214	224	286
1976	135	146	196	206	268
1977	128	132	178	188	284
1978	122	176	221	231	290
1979	143	147	196	214	265
1980	122	144	190	200	262
1981	133	157	205	215	270
1982	122	145	198	208	257
1983	132	165	215	225	272

### Appendix A.2.8

Soil Moisture Deficit (mm) on Dates of Reaching Successive Phenological Stages:

Wheat Grown on Clay Soil (Station1), Using Climatic Estimator to Set Dates (I)

Year	Emergence	Jointing	Heading	Soft Dough	Ripe
1955	15.8	43.6	50.9	102.9	104.2
1956	21.0	48.1	63.9	103.3	110.8
1957	17.6	51.1	75.4	111.3	90.8
1958	22.3	46.1	91.6	110.0	110.3
1959	19.9	37.6	75.0	78.1	90.4
1960	3.0	25.6	79.6	100.5	116.0
1961	22.9	50.3	84.5	110.9	121.8
1962	22.2	33.2	90.1	116.0	106.8
1963	17.8	21.3	15.4	67.8	87.8
1964	13.2	48.5	76.1	90.8	75.5
1965	18.2	30.8	76.9	92.3	97.8
1966	11.6	6.7	60.3	44.0	75.3
1967	19.5	50.5	76.1	87.1	111.3
1968	7.1	19.6	62.9	91.2	105.6
1969	17.8	42.3	94.2	110.2	105.2
1970	13.1	30.5	5.6	70.5	92.2
1971	22.5	44.0	76.0	110.1	115.1
1972	20.1	47.4	41.8	88.8	97.1
1973	19.6	17.7	58.5	100.4	104.5
1974	9.1	42.5	75.7	100.6	77.1
1975	0.9	31.8	24.6	86.2	75.7
1976	16.6	4.9	27.0	48.5	87.1
1977	25.2	43.3	63.3	77.0	50.3
1978	19.6	45.5	75.1	87.6	111.2
1979	18.4	44.0	85.1	105.9	107.9
1980	22.5	35.2	78.7	103.8	109.8
1981	24.1	36.3	79.9	79.9	97.0
1982	18.1	43.5	87.1	111.0	120.0
1983	17.9	11.3	32.5	72.8	89.5

### Appendix A.2.9

Soil Moisture Deficit (mm) on Dates of Reaching Successive Phenological Stages:

Wheat Grown on Sandy Soil (Station2), Using Climatic Estimator to Set Dates (I)

Year	Emergence	Jointing	Heading	Soft Dough	Ripe
1955	18.7	55.5	51.1	111.9	115.9
1956	25.6	58.7	93.3	167.1	180.7
1957	21.2	61.7	113.6	181.1	161.0
1958	26.7	59.7	134.5	179.7	184.3
1959	23.9	48.4	112.8	141.6	157.3
1960	3.0	27.8	112.4	168.0	188.3
1961	26.9	62.3	125.5	182.7	192.6
1962	26.4	42.2	116.9	184.1	175.0
1963	21.8	28.1	28.2	104.9	142.2
1964	13.2	58.8	113.2	155.4	140.3
1965	19.6	36.5	111.5	155.1	169.4
1966	14.5	12.0	77.9	83.7	136.7
1967	20.8	64.1	115.2	148.1	184.4
1968	9.7	28.9	104.7	158.2	178.2
1969	17.8	55.6	143.3	171.5	175.4
1970	17.5	42.2	15.1	105.7	145.7
1971	26.6	55.2	115.3	175.6	181.9
1972	25.3	60.2	77.9	162.6	171.3
1973	24.8	28.6	89.3	167.9	176.0
1974	10.5	50.2	109.1	163.6	146.6
1975	0.9	35.1	42.8	136.0	141.0
1976	17.0	7.1	34.8	79.7	143.3
1977	30.0	52.9	106.4	135.7	113.8
1978	24.3	56.5	112.7	154.4	185.2
1979	21.9	55.7	122.7	174.0	178.2
1980	26.7	48.5	124.9	174.7	180.9
1981	28.0	49.7	115.1	144.2	169.5
1982	21.9	57.4	129.2	180.5	190.9
1983	20.0	22.3	37.6	110.8	143.2

Appendix A.2.10

Soil Moisture Deficit on Dates of Reaching Successive Phenological Stages:

Forage Grown on Clay Soil (Station1), Using Climatic Estimator to Set Dates

Year	Start	Cutting	Reestablish	End
1955	18.7	81.7	110.0	158.7
1956	39.6	121.4	127.6	136.0
1957	57.4	165.1	175.6	146.4
1958	28.4	113.1	125.4	118.2
1959	37.4	110.0	103.8	100.2
1960	12.0	116.2	124.4	144.3
1961	7.5	110.7	117.9	153.5
1962	13.2	118.2	108.9	80.4
1963	31.7	94.2	116.1	97.9
1964	75.0	99.3	95.0	60.8
1965	8.4	84.7	110.9	48.1
1966	8.0	93.5	89.4	105.5
1967	52.8	116.3	113.3	102.1
1968	32.5	107.0	108.4	117.6
1969	76.6	123.1	117.8	133.0
1970	56.0	96.2	124.5	125.9
1971	48.7	114.4	126.2	133.3
1972	37.3	93.7	92.7	81.4
1973	33.3	116.4	122.1	107.2
1974	14.4	114.9	127.3	97.4
1975	24.3	113.3	101.2	114.0
1976	28.9	65.3	87.5	155.8
1977	19.5	113.8	99.8	84.2
1978	72.7	118.8	109.1	90.3
1979	17.2	113.2	129.4	82.9
1980	49.5	105.0	106.9	108.2
1981	54.8	98.8	117.2	114.5
1982	40.1	118.9	133.1	141.0
1983	12.7	95.4	104.5	94.6

Appendix A.2.11

Soil Moisture Deficit on Dates of Reaching Successive Phenological Stages:

Forage Grown on Clay Soil (Station1), Using Climatic Estimator to Set Dates

Year	Start	Cutting	Reestablish	End
1955	20.9	112.7	166.4	229.0
1956	49.3	169.5	196.6	214.1
1957	57.3	165.1	199.0	175.1
1958	33.7	146.7	192.2	188.4
1959	46.0	160.0	168.4	182.9
1960	12.7	153.7	190.3	211.7
1961	9.1	150.0	183.2	219.2
1962	17.7	160.4	171.3	156.2
1963	37.8	134.1	198.4	184.5
1964	92.8	150.9	153.6	125.3
1965	11.0	123.5	168.2	133.9
1966	13.0	135.8	168.6	195.3
1967	62.3	162.7	175.8	166.3
1968	36.5	154.1	170.5	199.9
1969	96.8	168.8	182.2	213.6
1970	69.5	146.9	210.8	207.7
1970	59.4	162.8	191.3	209.4
1972	47.3	145.2	170.5	160.5
1973	42.0	162.9	202.4	182.5
1974	14.5	159.4	196.8	177.3
1975	27.4	159.9	168.6	199.8
1976	33.8	86.2	126.4	230.6
1977	22.9	149.7	152.7	154.8
1978	97.3	177.9	185.0	173.8
1979	18.2	142.0	208.3	159.0
1980	58.0	147.3	170.9	178.3
1981	67.0	148.0	196.8	196.3
1982	48.4	161.2	203.0	213.7
1983	23.9	152.1	185.8	181.6

Appendix A.2.12

Exceptional Precipitation Events During the Growing Season  
Which Probably Make Soil Moisture Budget Inappropriate for  
This Site

Year	Julian Date	Mo.	Dy.	Antecedent Mois.Defic	Precip. mm.	Runoff mm.
1959	178	6	27	52.1	31.0	18.6
1960	147	5	26	1.0	30.5	23.4
1963	185	7	4	48.3	54.6	12.9
1964	128	5	7	4.9	27.2	21.6
1964	180	6	28	84.1	27.7	12.7
1964	213	7	31	87.8	42.4	20.3
1965	145	5	25	0.6	22.4	21.0
1966	188	7	7	31.7	33.5	19.1
1968	217	8	4	91.6	27.9	18.8
1970	179	6	28	53.5	51.6	14.0
1975	176	6	25	33.2	28.5	14.2
1976	153	6	1	42.0	25.6	12.5
1977	221	8	9	102.2	60.5	12.1
1979	192	7	11	89.3	25.9	15.4
1981	168	6	17	44.6	25.6	17.8
1981	182	7	1	69.2	26.7	15.2
1983	196	7	15	22.5	45.0	14.3

Appendix A.2.13

Proportion of Soil Moisture Available at End of Phenological Stages, Wheat grown on Clay Soil:

Year	PE	EJ	JH	HS	SR
1955	.94	.83	.80	.60	.60
1956	.92	.82	.75	.60	.57
1957	.93	.80	.71	.57	.65
1958	.91	.82	.65	.58	.58
1959	.92	.86	.71	.70	.65
1960	.99	.90	.69	.61	.55
1961	.91	.81	.68	.57	.53
1962	.91	.87	.69	.55	.59
1963	.93	.92	.94	.74	.66
1964	.95	.81	.71	.65	.71
1965	.93	.88	.70	.64	.62
1966	.96	.97	.77	.83	.71
1967	.92	.80	.71	.66	.57
1968	.97	.92	.76	.65	.59
1969	.93	.84	.64	.58	.60
1970	.95	.88	.98	.73	.64
1971	.91	.83	.71	.58	.56
1972	.92	.82	.84	.66	.63
1973	.92	.93	.78	.61	.60
1974	.96	.84	.71	.61	.70
1975	1.00	.88	.90	.67	.71
1976	.94	.98	.90	.81	.66
1977	.90	.83	.76	.70	.81
1978	.92	.82	.71	.66	.57
1979	.93	.83	.67	.59	.58
1980	.91	.86	.70	.60	.58
1981	.91	.86	.69	.69	.63
1982	.93	.83	.66	.57	.54
1983	.93	.96	.88	.72	.66

Appendix A.2.14

Proportion of Soil Moisture Available at end of Phenological Stages, Wheat grown on Sandy Soil:

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Year	PE	EJ	JH	HS	SR
1955	.92	.77	.79	.53	.52
1956	.89	.76	.61	.30	.25
1957	.91	.74	.53	.25	.33
1958	.89	.75	.44	.25	.23
1959	.90	.80	.53	.41	.34
1960	.99	.88	.53	.30	.22
1961	.89	.74	.48	.24	.20
1962	.89	.82	.51	.23	.27
1963	.91	.88	.88	.56	.41
1964	.95	.76	.53	.35	.42
1965	.92	.85	.54	.35	.29
1966	.94	.95	.68	.65	.43
1967	.91	.73	.52	.38	.23
1968	.96	.88	.56	.34	.26
1969	.93	.77	.40	.29	.27
1970	.93	.82	.94	.56	.39
1971	.89	.77	.52	.27	.24
1972	.89	.75	.68	.32	.29
1973	.90	.88	.63	.30	.27
1974	.96	.79	.55	.32	.39
1975	1.00	.85	.82	.43	.41
1976	.93	.97	.86	.67	.40
1977	.88	.78	.56	.43	.53
1978	.90	.76	.53	.36	.23
1979	.91	.77	.49	.28	.26
1980	.89	.80	.48	.27	.25
1981	.88	.79	.52	.40	.29
1982	.91	.76	.46	.25	.20
1983	.92	.91	.84	.54	.40

Appendix A.2.15

Proportion of Soil Moisture Available at End of Phenological Stages for Forage Grown on Clay Soil

Year	Full Cover	First Cut	Reest- ablish	End of Season
1955	.93	.69	.58	.39
1956	.85	.53	.51	.48
1957	.78	.36	.32	.44
1958	.89	.56	.52	.54
1959	.86	.58	.60	.61
1960	.95	.55	.52	.44
1961	.97	.57	.55	.41
1962	.95	.54	.58	.69
1963	.88	.64	.55	.62
1964	.71	.62	.63	.77
1965	.97	.67	.57	.82
1966	.97	.64	.66	.59
1967	.80	.55	.56	.61
1968	.88	.59	.58	.55
1969	.70	.53	.55	.49
1970	.78	.63	.52	.52
1971	.81	.56	.51	.49
1972	.86	.64	.64	.69
1973	.87	.55	.53	.59
1974	.94	.56	.51	.62
1975	.91	.56	.61	.56
1976	.89	.75	.66	.40
1977	.93	.56	.62	.68
1978	.72	.54	.58	.65
1979	.93	.56	.50	.68
1980	.81	.60	.59	.58
1981	.79	.62	.54	.56
1982	.84	.54	.49	.46
1983	.95	.63	.60	.64

Appendix A.2.16

Proportion of Soil Moisture Available at End of Phenological Stages for Forage Grown on Sandy Soil

Year	Full Cover	First Cutting	Rees- tablish	End of Season
1955	.91	.53	.31	.04
1956	.79	.29	.18	.11
1957	.76	.31	.17	.27
1958	.86	.39	.20	.22
1959	.81	.33	.30	.24
1960	.95	.36	.21	.12
1961	.96	.38	.24	.09
1962	.93	.33	.29	.35
1963	.84	.44	.17	.23
1964	.61	.37	.36	.48
1965	.95	.48	.30	.44
1966	.94	.43	.30	.19
1967	.74	.32	.27	.31
1968	.85	.36	.29	.17
1969	.60	.30	.24	.11
1970	.71	.39	.12	.13
1971	.75	.32	.20	.13
1972	.80	.40	.29	.33
1973	.82	.32	.16	.24
1974	.94	.34	.19	.26
1975	.88	.33	.30	.17
1976	.86	.64	.47	.04
1977	.90	.38	.36	.36
1978	.59	.26	.23	.28
1979	.92	.41	.13	.34
1980	.76	.39	.29	.26
1981	.72	.38	.18	.18
1982	.80	.33	.15	.11
1983	.90	.37	.22	.24

Figure 5.2: Climatological Data and Biometeorological Time Scale for Wheat

