An Agroclimatology of Southern Manitoba

by

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AN AGROCLIMATOLOGY OF SOUTHERN MANITOBA

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ABSTRACT

A quantitative assessment of the spatial distribution of Southern Manitoba's agroclimatic resource base was undertaken. The research objectives were twofold: i) to establish a data base, using readily available climatic data, sufficient to evaluate the climatic resources and/or potentials of this area with respect to the utilization of this knowledge in agricultural planning; and ii) to statistically analyse this data base so as to describe the climatic risks and/or advantages associated with various regions within the province.

Thermal and moisture conditions within the province were studied using specially developed computer programs. Past records of daily climatic data from meteorological stations within the study area were used to derive agroclimatic parameters which relate the effect of temperature and moisture to plant growth and development. The parameters derived focused on three essential climatic features: i) the occurrence of frosts in the spring and fall and the subsequent lengths of the frost free periods, ii) values of heat accumulated during the growing season; and iii) the analysis of soil moisture conditions under three different crops.

Probability analysis was carried out on each parameter at the 50%, 25% and 10% risk levels. The analysis undertaken showed the optimum climatically suited area for intense agricultural crop production is the Red River Valley. Thermal constraints in the area west of the escarp-

ment and in the south east section of the province prevent these areas from being suitable for crops requiring a long frost free period and high accumulated heat requirements. The entire study area is generally suited to cereal production, but grain corn is feasible in only a few selected regions. Moisture constraints to high productivity are evident in the south west region of the province in areas such as Souris, Pierson and Brandon.

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Chapter I

INTRODUCTION

1.1 OBJECTIVES OF THE STUDY

This thesis represents a quantitative assessment of the spatial distribution of Southern Manitoba's agroclimatic resource base. This research consists of analyses of past weather data, with emphasis on the study of climatic parameters directly affecting agriculture and/or agricultural production. The ultimate aim of this study is to provide a precise evaluation of the agroclimatic resources and potentials of this area, to be used in making recommendations for future agricultural strategies. As Stringer (1972) states,

> Climate may be regarded as a natural resource, and an important application of climatology must then be to determine whether or not this resource is being properly utilized. (Stringer, 1972:399).

The research objectives of the present study are essentially twofold in nature:

1. to develop an agroclimatic data base sufficient to describe the climatic resources and potentials of the study area with respect to its suitability for agricultural crop production, that is, the interpretation of raw climatic data to provide input into agricultural planning.
2. to establish the probability of occurrence of certain climatic events and/or derived agroclimatic parameters important with re-

spect to successful agriculture in Southern Manitoba, so as to provide a statistical perspective for assessment of the area. It must be stressed here that in a thesis of limited length, a complete coverage of all aspects of plant/climate relationships is impossible. Focus will thus be on the climatic elements which are of paramount importance with respect to successful agricultural operations in Southern Manitoba, that is, temperature and moisture considerations.

1.2 STUDY AREA AND DATA BASE

The study area for the present investigation consists of the southern portion of Manitoba as delineated by the fourteen provincial crop-reporting districts (Figure 1). Climatic records from meteorological observing stations within these districts will be utilized in this research, so as to provide a complete spatial assessment of the climatic resource base of this important agricultural-producing area (Figure 2). The temporal setting for this research encompasses climatic data from 1929 to 1978. The length of recording, however, will vary from station to station. A complete listing of all weather stations used in this analysis, their location and years of recording can be found in Appendix A.

Agriculture has traditionally been and continues to be one of the most significant primary resource industries in Manitoba. Over 14% of Manitoba's total land base is utilized in agricultural production. The cash values of Prairie farm products represents a substantial proportion of total income. In 1979, for example, the cash value of crops grown in Manitoba accounted for 56% of total farm income (with dollar value figures of $716.4 million) (Fraser, 1980:60).

Figure 1: Manitoba's Fourteen Crop-Reporting Districts.

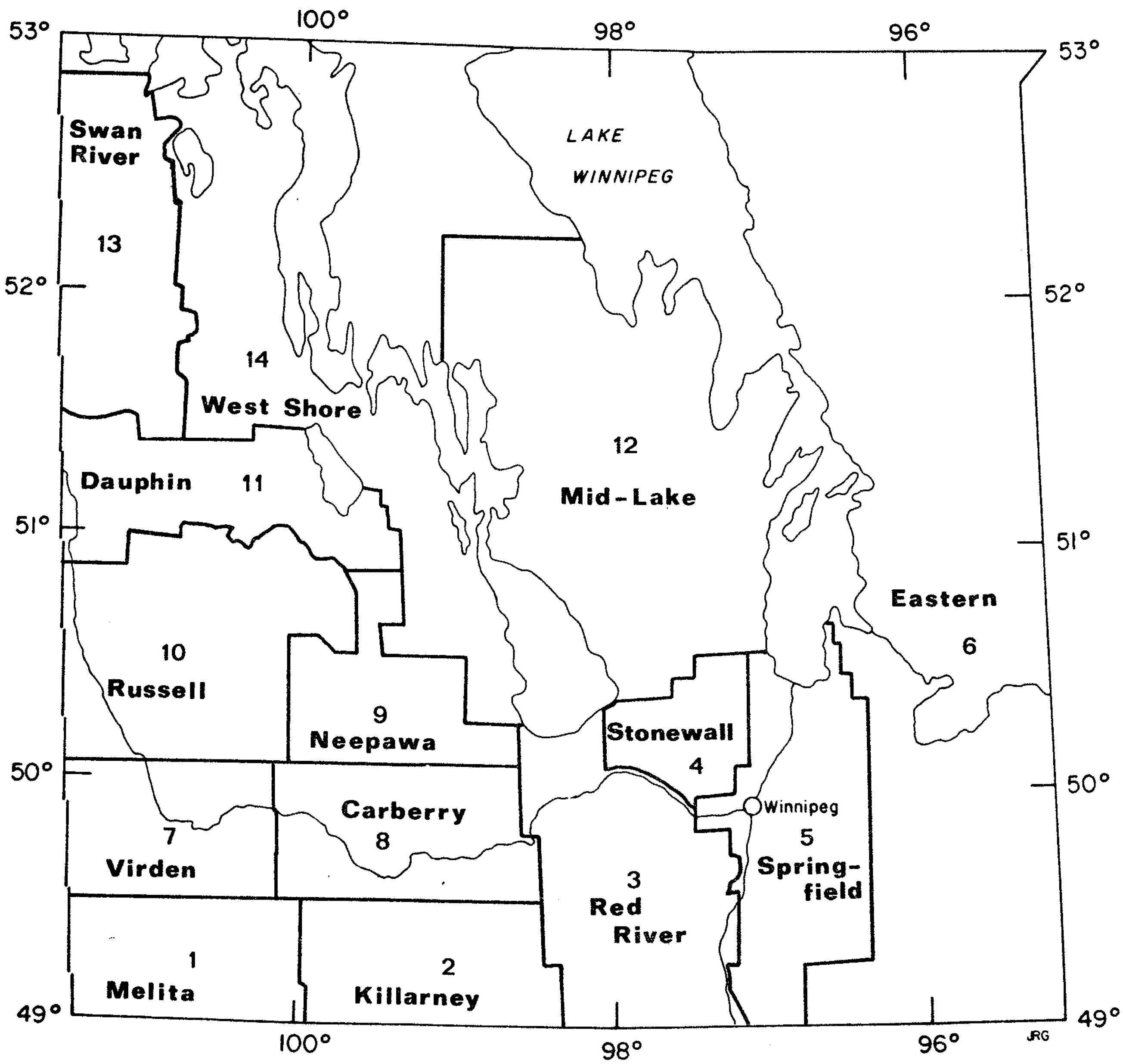
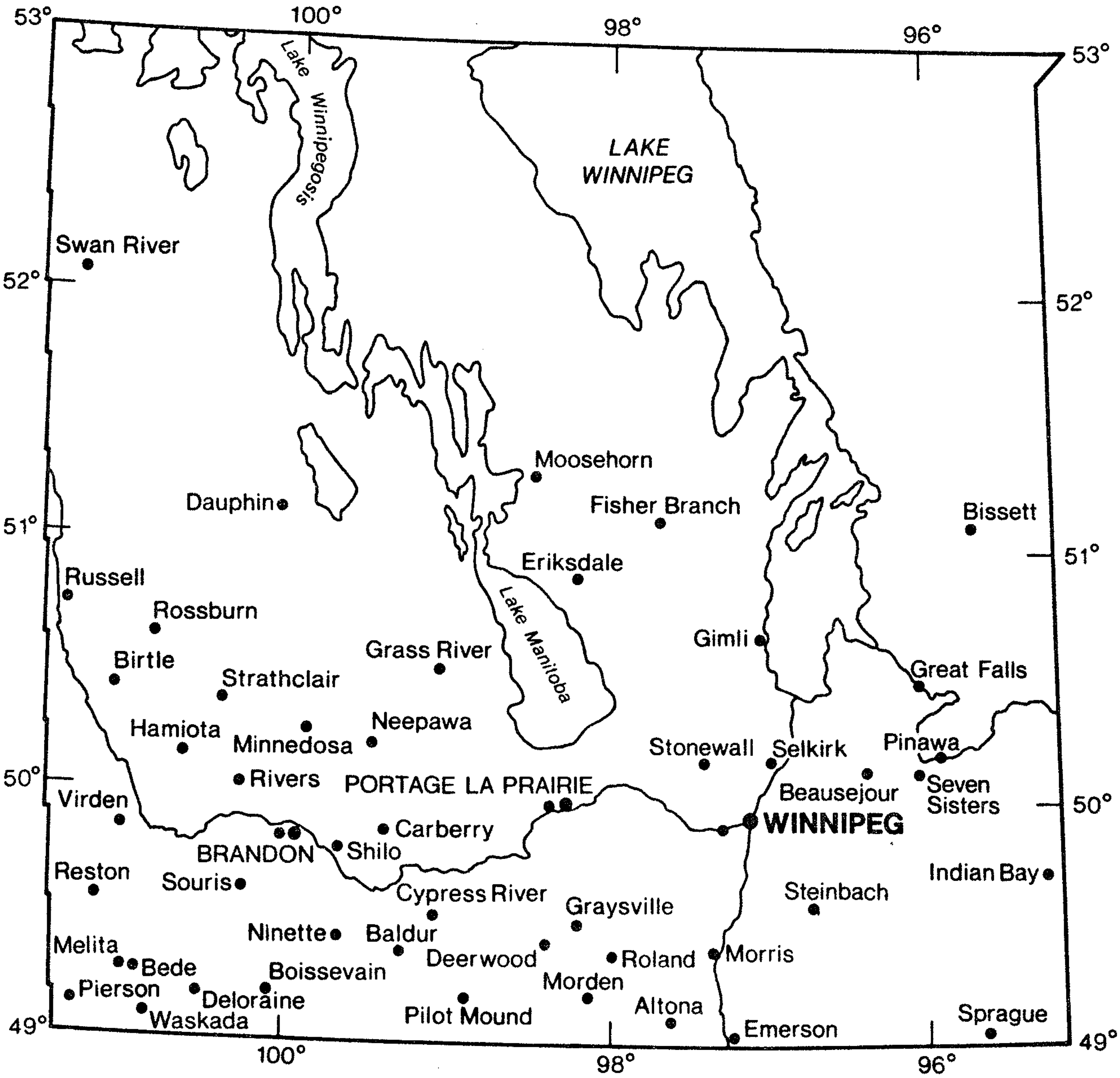


Figure 2: Meteorological Stations Utilized in this Research.



Weather and climate exert a major influence on crop production with respect to both quality and quantity. The effect of climate and climatic variability, that is, the susceptibility of regions to fluctuations, is especially marked in regions where agriculture, or any other economic operation is carried out near its critical threshold. An assessment of climatic resources is thus particularily important in an area such as Southern Manitoba. This important agricultural producing region is located close to the northern limit of successful crop cultivation, and is characterized, as are many regions of the Great Canadian Plains by both moisture and thermal limitations. As pointed out by the National Academy of Sciences (1976),

> The emphasis of agricultural research on environmental stress (chilling, frost, heat,...) points to the extent to which many crops are cultivated in marginal environments. (National Academy of Sciences, 1976:81-83).

The climatic evaluation carried out in this research can then be extended to assess optimum land use management and in accurate selection of types and varieties of crops which may be grown in specific areas.

All climatological analyses in this research were performed by specially developed computer programs written in Fortran(H) language for the IBM 360/370 system. All the programs require as input daily climatological observations of maximum and minimum temperature and precipitation amounts as recorded at Atmospheric Environment Services meteorological observing stations.

1.3 ORGANIZATION OF THE THESIS

The thesis has been organized so as to first provide a brief introduction of the research objectives of this study. After these introductory comments of Chapter 1, there follows a short review of previous agroclimatic studies undertaken. The literature review is broken down into essentially two categories: i) a review of various agroclimatic relationships developed; and ii) a review of regional agroclimatic studies.

The third section will justify the theoretical considerations employed in establishing a data base sufficient to fully describe the climatic resources and/or potentials of the study area with respect to its suitability for successful agricultural crop production. It begins with a discussion of the climatic data available and its temporal and spatial limitations with respect to its usage in this thesis. Following this is a discussion of the plant/climate considerations needed to derive a data base. The fourth chapter of the thesis deals with a detailed discussion of the agroclimatic data base developed. Each parameter derived will be highlighted and its significance discussed.

The fifth chapter will be the presentation of results obtained. The majority of these will be presented either: i)graphically, in the form of tables and graphs; and/or ii)cartographically, through the development of a computer mapping and plotting technique. The results obtained will be discussed with respect to their applicability to people involved in various fields of agroclimatology.

The final chapter will conclude with a brief summary of the pertinent sections of the thesis as well as of the major findings derived from the analytical techniques employed. A concluding section offers directions for future research based on the findings of this study as well as on the existing gaps known to exist within the field of agricultural climatology.

Chapter II

LITERATURE REVIEW

This chapter provides a short review of literature pertinent to this study in the field of agricultural climatology. Emphasis will be on the development of the agro-climatic parameters used in this study, as well as on the regional studies focusing spatially on the Prairie Provinces. The significance of the research will be emphasized so as to note its contribution to existing literature within this field.

2.1 AGROCLIMATOLOGY: AN OVERVIEW

"The weather and climate exert a major influence on many economic activities, but few activities appear to be more profoundly affected than agriculture" (Maunder, 1970:84). The effects of weather and the limitations imposed by climate, with respect to successful cultivation of crops, have been recognized by man since early times. With the ever-increasing importance of agricultural production in today's society, increasing emphasis both academically and financially, is being given to various agroclimatological studies. These investigations of the relationships between weather/climate and agriculture are of extreme importance since weather is an important variable in crop production in two basic ways: i) through obvious climatic hazards to crops such as frost, drought, insufficient heat and moisture for growth and development; and ii) through the misuse of land with respect to its climatic resources and potentials.

The science of applied agro-climatology can serve as the fundamental basis for future land-use planning, as well as for initiating future agricultural activities and/or strategies. Application of the findings of agro-climatic studies can contribute to various decision-making processes which involve the correct assessments of climatic factors. Examples include: i) choosing of types and varieties of agricultural crops, ii) establishing the potential of land for agricultural use; and iii) aiding in determining the most suitable methods of cultivation, scheduling of irrigation requirements, etc... The realization of the importance of accurate climatic assessments and their economic benefits can best be evidenced by the score of papers stressing the need for such detailed studies (Baier, 1975; McKay, 1976; McKay, 1980; Wallen, 1972).

A short literature review of agro-climatic studies will now be presented so as to provide a background perspective to the research work undertaken in this thesis.

Many books and scientific articles are available in the general field of agricultural climatology/ meteorology (American Meteorological Society, 1965; Chang, 1968, 1971; Smith, 1975; Wang, 1963; World Meteorological Organization, 1963, 1972). These studies synthesize the various relationships between meteorological elements and agricultural crop growth and development. To facilitate a complete understanding of the complex interrelations between climate and agriculture and to develop a knowledge of the special statistical/analytical tools necessary in climatological research, reference can also be made to basic texts in climatology and/or climatological statistics (Brooks and Carruthers, 1953; Conrad and Pollak, 1950; Mather, 1976; Panofsky and Brier, 1968; Thom, 1966; etc...).

More specifically, much of the work done in the field of agricultural climatology can be divided into two categories: i)the study and derivation of fundamental plant-climate relationships; and ii) the study of agricultural and climatic data for a number of places within a given area. A brief review of work in these two sub-fields will now be discussed, with emphasis on those relating to the Canadian Prairies, and Manitoba in particular.

2.2 AGROCLIMATIC RELATIONSHIPS

Recently, a considerable number of investigations dealing with the influence of selected climatic parameters on many aspects of crop agriculture, particularly with respect to plant growth, development and yield, have been undertaken. A brief discussion of the results of some of these undertakings will follow, but will be limited to those concerned with the climatic elements under investigation in this study, namely assessments of thermal and moisture considerations directly influencing successful plant crop growth and development.

2.2.1 Temperature Considerations

Temperature is one of the primary climatic factors controlling the growth and development of plants. This was recognized in the early 1700's and prompted the development of the heat unit concept. The premise of this concept being, that to reach maturity a plant must receive a certain accumulated temperature requirement. These growing degree days are calculated simply as the summed difference between the daily mean temperature and a base temperature necessary for plant growth. This has served as the basis for many agro-climatic studies and as a focal point for further research to develop a more precise method of assessing the effects of temperature on plant growth.

Due to several inherent inadequacies within this concept, Brown (1964) suggested as an alternative the use of corn heat units. Corn heat units are obtained by summing daily accumulations of units derived from a mathematical formula:

$$CHU = \{3.3[maxt(i)]-.084[maxt(i)-10)]^2 +1.8[mint(i)-4.4]\}/2$$

where i includes all the days between May 15 and the first -2.2C frost in autumn.

The corn heat unit concept assumes growth increases with increasing temperature but sets a lower critical and upper optimum temperature necessary for growth to proceed. While this concept is an improvement over the original heat unit concept, by recognizing the importance of both day and night temperatures and the detrimental effects of very high temperatures, it still fails to take into account the effects of other climatic variables on plant development. The heat unit concept, however, continues to be used in many modern agro-climatic studies, (Boughner, 1964; Chen, 1973; Edey, 1977), many of which justify usage of it for its simplicity as opposed to its accuracy.

Robertson (1968) derived a mathematical model for calculating the daily rate of crop development of a cereal crop (Marquis wheat). The resultant model was a biometeorological time scale for cereal crop development involving day and night temperature and photoperiod. In this model Robertson assumed the rate of development to be determined by a combination of a curvilinear function for photoperiod and one for each of day and night temperature. Integrating this equation over time led him to develop an equation for calculating the degree of maturity over various phenological stages. Five major phenological stages of development were recognized. For each stage upper and lower threshold values were established for photoperiod and day and night temperatures, and thus each day's contribution to crop maturity could be calculated and summed. A detailed explanation of Robertson's model will be given in a later section. Williams (1969) used derived temperature normals based on latitude, longitude and elevation together with the biometeorological model to determine areas on the Canadian Prairies where spring wheat would mature.

Williams (1974a, 1974b) following the example set by Robertson, related the daily rate of development of Olli barley to daily temperature and photoperiod. It should be noted that while barley is the quickest maturing cereal crop, wheat is a later- maturing crop, but has a higher economic return. Williams (1974c) again using derived normals of temperature and the biometeorological time scale mapped the physical frontier for growing barley to maturity in Canada. Thus, both of these models used in conjunction with climatic data can determine areas where specific crops have sufficient temperature and photoperiod to grow to maturity.

2.2.2 Moisture Considerations

Moisture, is the second major climatic factor that is of paramount importance with respect to successful agricultural operations. Much of the literature expresses precipitation as the sole moisture consideration in plant growth and development. But as in temperature studies, analyses based strictly on a single climatic element are too simple to fully explain the complex interrelations between plants and their moisture needs. Precipitation is the main source of moisture for plant growth, but it is the study of soil moisture which can best describe the climatic resources and/or potentials of an area. Soil moisture is a more reliable indicator since it represents a complex interaction between a variety of climatic elements, including precipitation, temperature, radiation, and photoperiod, as well a combination of various physical soil properties.

Several empirical soil moisture budgets have been proposed which calculate soil moisture amounts using readily available climatological data. Thornthwaite and Mather (1954) recognized evapotranspiration as a climatic factor as important as precipitation in plant growth. Evapotranspiration represents the combined water loss through evaporation from soil surfaces and transpiration from growing plants. This evaporative demand for water is a function of the energy available (solar radiation), the movement of moisture from the evaporating surface (wind), the dryness of the atmosphere which is affected by the humidity, the temperature of the air and the temperature of the evaporating surface. The difficulty of actually measuring potential evapotranpiration, necessary to calculate soil moisture amounts, led Thornthwaite to devise an empirical formula for calculating it from a knowledge of mean monthly temperatures and daylength. Penman (1956) related several climatic factors to estimating values of actual and potential evapotranspiration. The climatic elements used included measurements of short-wave radiation, hours of bright sunshine, air and surface temperatures, saturation vapor pressure of the surface and vapor pressure of the air. Baier and Robertson (1965) developed a technique for estimating daily latent evaporation from simple meteorological observations and astronomical data. Since most of the readily available climatic data consists of temperature and precipitation records only, the original equation containing some ten meteorological and astronomical parameters was simplified to include only three elements, namely maximum temperature, temperature range, and radiation amounts received at the top of the atmosphere. Latent evaporation can be converted to potential evapotranspiration by multiplication of a suitable factor. Baier (1971) compared values obtained from this formula with those estimates from models by Penman and Thornthwaite and found them to be superior to either of the other approaches. DeJong (1978) found that estimates of potential evapotranspiration at Pinawa by the Baier and Robertson equation were more in line with pan evaporation at Bissett and Indian Bay than were estimates by either the Thornthwaite or Penman equations.

Baier and Robertson (1966) subsequently devised a versatile soil moisture budget for estimating daily soil moisture in various zones within the soil profile using daily totals of evapotranspiration and precipitation. They suggest that the use of a soil budgeting method in conjunction with past climatic records "would be most valuable for the interpretation of plant growth habitudes, variations of crop yields and for an analysis of the agro-climatic conditions of an area." (Baier and Robertson, 1966:313).

2.3 REGIONAL AGROCLIMATIC STUDIES

Climatic studies of Canada and/or regions within Canada have been undertaken for some time. Climate was recognized as an integral part of the resource base of a region, but was seen as a constant, unchanging variable. Only recently have more studies emerged in which the study of climate, its distributions, descriptions and variations, has been the prime focus.

Significant strides in the field of mapping climatic resources for agriculture have been reached. Baier (1976) was one of the first to use not only simple measured climatic elements, but also various derived agroclimatic parameters to describe the climatic resource base of Canada. As previously stated, when one is attempting to assess the suitability of an area for agriculture crop production, parameters of direct influence on plants must be used. It is not sufficient to merely use standard temperature and precipitation data, except as a first, very crude indication. The particular significance of this research is the description of the agroclimatic resource base in a statistical perspective. In using climatic data as a delineating factor in agricultural land-use stategies it is precisely these climatic risks and advantages of specific areas which are of paramount importance.

Simpson-Lewis et al (1979) also undertook an extensive research investigation by attempting to allocate the land resource of Canada among a number of uses (agriculture, outdoor recreation, wildlife, forestry, urban growth and energy development). The baseline data consisted of a variety of physical, climatic, economic, social and aesthetic parameters.

With respect to smaller regional studies, reference can be made to those in Eastern Canada by Wilson (1971) and Chapman and Brown (1966). Within the Prairie Provinces, the dominant agricultural producing area in Canada, comprehensive agroclimatic studies are limited. McKay et al (1967) presented a general analysis of temperature and moisture conditions in Saskatchewan with respect to their importance for agriculture. Shaykewich (1974), in his study of Southern Manitoba, calculated mean values for several agroclimatic parameters and attempted a classification of agroclimatic regions within the province.

Many more climatic and/or agroclimatic studies have been carried out in Canada and particularily in the Prairie Provinces. However, much of the work done has concentrated generally on either a small specific area or on a single climatic parameter. The magnitude of the work undertaken precludes a review of it, instead reference can be made to one of the comprehensive bibliographies of climatic studies by Longley and Powell (1971), Thomas (1973,1978), and Thomas et al (1979). Pertinent investigations relative to the research undertaken in this study will be discussed in greater detail later in the thesis.

2.3.1 Agroclimatology

Baier et al (1976) demonstrated the successful use of standard climatological data, using biometeorological methods and soil moisture budgeting, in evaluating crop-weather relationships and in the analysis of climatic resources.

> Long-term research into the relationships between Canadian Prairie crop yields and development...and selected climatic and soil variables has been used successfully for estimating regional crop production, for determining climatic limitations of the area suitable for the cultivation of these crops, and

> for assessing the impact of postulated climatic changes on crop production. (Baier et al, 1976:108)

Maunder (1973) stated that in the past, agroclimatic studies were hampered by : i) lack of quality data and statistical methods necessary to analyse it; and ii) lack of knowledge of the responses of plants to weather influences. As evidenced by a brief review of existing literature, significant advances have been made recently in the field of agricultural climatology. The introduction of modern computers, improved statistical/mathematical techniques, as well as more reliable climatic and agricultural data have made feasible much of the intensive agroclimatological research being undertaken today.

2.4 SIGNIFICANCE OF THE RESEARCH

This research represents a precise evaluation of Southern Manitoba's agroclimatic resources by investigating those climatic conditions which directly affect the growth of crops. The agroclimatic resource base will be presented in a statistical perspective in an attempt to fully portray the climatic risks and advantages associated with various regions within the province. This study will hopefully be able to provide agricultural specialists, government decision-makers and individual citizens with a better foundation for future agricultural strategies based on the optimum utilization of the agroclimatic resources and potentials of this area.

The significance of this research is most evident when put into the context of recent actions and statements by various institutions and/or individuals in the fields of agriculture and climatology. McKay and Findlay (1978) state that,

> reporting the climatic state in a statistical perspective and evaluating its potential impact and the likelihood of its persistence or changes, enhances its utility in political, social and economic decisions (McKay and Findlay, 1978:411).

and even with our inability to forecast into the future, climatic probabilities can yield fairly accurate predictions, although ignoring the exact timing. The United States National Academy of Sciences (1976:9) identified "a number of realistic, attainable strategies such as using climatic information in selecting crop varieties, for planning irrigation systems, etc..." The World Meteorological Organization and the International Council of Scientific Unions in unison with other various international agencies are planning a World Climate Programme for 1980 - 2000. The three focal points for the research are: i) applied climatic studies, ii) investigating the impact of climate on human activities; and iii) studying climatic change and variablilty (Mason, 1978).

Some time in the future, Canada, and the Prairie Provinces in particular, will have a need to use as much land as possible for agricultural production. A sound knowledge of the climatic advantages and risks of an area can facilitate the obtaining of this objective through: i) efficient land-use management and planning; and ii) attaining maximum efficiency with respect to quality and quantity of agricultural production.

Although many argue that the highly variable nature of the atmosphere renders analysis of past climatic records questionable as guides for the future, it must be stressed that: i) climate does not change rapidly over short time periods (such as that used in this study); and ii) until climatic forecasting advances beyond its present state, the past is the best guide to what we can expect in the near future. Lamb (1965) best sums up the present state of the science, A table of statistics of the past can never be a substitute for a forecast. But forecasting of the climatic trends must wait until the proper scientific basis for it exists... In the meantime, practical decisions for the future involving climate have to be made by many practical men and institutions and climatic statistics of the past have to be used for this. (Lamb, 1965:25)

Chapter III

METHODOLOGY

This chapter contains a description of the theoretical considerations used in this thesis as aids in achieving the research objectives. Various theoretical and statistical methodologies were employed in the two stages within this investigation:

1. The first stage begins with the assembling of all existing climatological data so as to describe the behaviour of climatic elements having an effect on the successful growth of agricultural crops. Much of the climatic data to be analysed is in the form of derived agroclimatic parameters, that is, data which is not directly measured on a site, but can be derived, through mathematical formulas, from actual meteorological observations. It is these parameters which are necessary when one is attempting to describe the climatic resources of an area with respect to the application of this knowledge for usage in agricultural crop production.
2. The second stage in this research is the analysis of these data in various ways. In this section, the data base developed, that is, both natural and derived parameters, will be subjected to rigorous statistical probability analysis to present the agroclimatic environment of Southern Manitoba in a statistical perspective.

Lowry (1972) warns, however, that caution is needed when approaching these two objectives, since any analysis of climatic data is hampered by two problems: i) the accuracy and reliability of the data used; and ii) the validity of the methods and techniques utilized.

This chapter will focus primarily on the procedures and techniques used in the development of the agroclimatic data base.

3.1 DEVELOPMENT OF THE AGROCLIMATIC DATA BASE

3.1.1 Availability of Climatic Data

Before attempting to begin analysis in this research, a study of the availability and reliability of readily accessible climatic data was undertaken. Atmospheric Environment Services (AES) is the Federal Government agency responsible for the collection and distribution of meteorological data throughout Canada.

The meteorological observing network within Canada is arranged into a hierachy of recording station importance. The synoptic or first order stations record all or most of the surface meteorological elements by radio or telecommunications every one, three, or six hours. There are 290 of these stations operating in Canada, of which 20 are in Manitoba. These represent the stations maintained by professionally trained personnel. By far the most common type of observing stations are the climatological stations. These stations, primarily supervised by volunteer observers, are responsible for recording daily maximum and minimum temperatures and daily precipitation amounts. Within Canada a total of 2200 stations are currently within the observing network of which 140 are in Manitoba (Fraser, 1979). To complete the meteorological network, Canada maintains a few upper air stations which sound the atmosphere twice a day to supply additional information to AES.

Climatic data used in this study consists of daily maximum and minimum temperatures, as well as daily precipitation amounts recorded at both the first order synoptic and the climatological observing stations within Southern Manitoba.

3.1.2 Limitations of the Data

Since much of the climatic data used in this study consists of observations made by volunteer personnel, the data records and contents are subject to various discrepancies. The quality of this meteorological data can be affected by several factors:

1. changes in observing site and exposure of the recording instruments, and changes in observing personnel. This presents one of the largest problems encountered when attempting to analyse climatic data of sufficient length of recording. The volunteer climatological network in Manitoba is highly unstable, resulting from many changes in station location and observer, siting and exposure of instruments, and a greater lag time in the detection of faulty instruments and poor exposure (Catchpole and Ponce, 1976). Any of these changes could have detrimental effects on the quality of the meteorological data recorded.
2. the quality and durability of the instruments themselves can also lead to erroneous observations. Prior to recent times there was little standardization with respect to instrument type, site and/or exposure, thus again suggesting caution when dealing with rigorous statistical testing of the data.

3. the limited spatial and temporal coverage afforded the present meteorological observing network. There is no systematic organization of the recording network in Manitoba. Stations are distributed at random, with a heavy concentration in higher populated areas and correspondingly fewer in the sparsely populated northern rural fringe, thus limiting the spatial and geographical extensiveness. The volunteer nature of the network also limits the temporal coverage of many areas, as mentioned previously.

3.1.2.1 Selection of the Stations

The unstable nature of the climatic network causes much of the data to be unsuitable for statistical analysis, specifically with respect to length of station record, inhomogenity of station location, instrumentation and the common occurrence of missing data. Recognizing the deficiences within the available climatic data made it incumbent on the researcher to attempt to overcome these in an objective, systematic manner.

Selection criteria for stations to be included in the analysis were adopted in order to: i) obtain a representative, distributional sample of stations within Southern Manitoba; and ii) to ensure that stations used had a sufficient length of continuous, homogeneous recording to render them suitable for statistical analysis.

A complete listing of all observing stations in Manitoba can be found in the AES Climatological Station Data Catalogue. This catalogue contains the station name and number, the latitude, longitude, and elevation of each station, as well as acting as a general guide to periods of time with no change in observing personnel, program, location or name.

Of the total number of stations listed, many were discarded due to insufficient length of recording. Climatic fluctuations/random variations necessitate an adequate number of years of recording to obtain a stable, representative value of the climatic element under investigation. A brief review of the existing literature presents a conflicting picture with respect to the number of years of data necessary to describe the climate and its variability within a region (Jagannathan et al, 1967). It has been an assumed standard to use 30 years as the length of record necessary for any type of statistical analysis. Other researchers consider values of 10 years adequate (Lamb, 1965; WMO, 1960, 1963), while yet others suggest 15 years as a minimum (Jagannathan et al, 1967: Rosini, 1963). Sharon (1968) maintains that the length of record needed is dependent on the climatic element under investigation and the variability associated with it.

In selecting the minimum number of years of record to be used in the analysis, it must be remembered that the longer the required record, the fewer will be the number of stations which can be used. Consideration must also be given to the restriction imposed by using data which is of too great a length. Secular variations in climatological series may cause climatic statistics obtained from too long a period to be unrepresentative of the contemporary climatic conditions of the region. In this study, a selection criteria of 15 years of record was adopted as the minimum number of years of recording required for a station to be included in the analysis. Simultaneously, data from stations with records longer than 50 years were truncated so that no analysis was carried out on climatic records prior to 1929. Stations selected into the analysis had to satisfy the condition of having relatively continous data. Stations with frequent gaps in their record were eliminated.

Following the selection of the stations suitable for analysis, the next step in establishing the data base was the problem of estimating missing values existing within the climatic records. The occurrence of missing data is quite frequent and is critical when using complex agroclimatic parameters which calculate plant growth and development on a daily basis.

3.1.2.2 Estimation of Missing Data

The problem of estimating missing daily temperature data was accomplished through the technique of linear regression analysis with surrounding stations. In determining a linear regression to estimate the missing data, a series of parameters were established which had to be met by stations to be used in the estimation process. The surrounding station having the highest correlation coefficient with the station having missing data was then used to complete the data records.

It should be noted that, the above method was only applied to the temperature data in this thesis. No estimation of the missing daily precipitation data was attempted, since no valid method of doing so is known to the author. Summer precipitation in Southern Manitoba consists mainly of localized random showers and according to Fraser (1980) close to 50% of the total growing season rainfall orginates from random air mass showers. Thus daily rainfall at a near-by station may not be representative of the station with missing data. As Paulhus and Kohler (1952) state, no effort should be made to interpolate daily amounts when they are caused by sporadic rainfall.

3.1.2.3 Limitations to the Study

The availability of accurate, continuous, spatially distributed records used in this study, somewhat limit the possibilities of more in-depth research in the field of agricultural climatology. The results obtained in this study are only as reliable as the available climatological and agricultural data permits. The serious problems of inhomogenities existing within the data are acknowledged, but to undertake a rigorous study of this would involve a tremendous amount of time and money which cannot be warranted in a thesis of limited extent (MacGregor, 1977). In this thesis, only a superficial investigation of the data was undertaken. Thus, in any discussion of the results, caution will be exercised and only those findings that can be substantiated by statistical testing will be presented as significant. The large number of stations utilized in this study will also facilitate detection of false results caused by inaccurate data.

Another limitation is imposed through the adoption of a minimum requirement of 15 years of record. In using data covering, in some cases, only 15 years the analyst runs the risk of dealing with periods of time too short in their temporal distribution to be representative of the area due to the existence of climatic variations and fluctuations, as well as modifying influences of the micro-environment.

3.2 DERIVATION OF THE AGROCLIMATIC DATA BASE

While all elements of climate are interrelated in their influence on plant growth and development, the most important climatic determinants are temperature, moisture and light. This thesis deals only with those agroclimatic parameters concerned with thermal and moisture considerations important to agriculture on the Canadian Plains. As stated previously, simple measures of daily, monthly, seasonal or annual values of these elements are not sufficient to explain the growth and development of plant crops. The agroclimatic parameters, used and derived in this investigation, range from simple parameters such as dates of occurrence of frosts to use of a biometeorological time scale involving a variety of meteorological and astronomical elements.

3.2.1 Thermal Considerations

Temperature is one of the main climatic factors of extreme importance to plant growth and development and can effectively determine what crops can be grown successfully at specific locations. Thermal considerations are given paramount importance in this research due to the relatively northerly location of the study area.

As stated by Simpson-Lewis et al (1979),

> Canadian agriculture is especially vulnerable...The climate for agriculture is generally less favorable as compared to other major food producing areas of the world. When combined with an overall inability to predict seasonal or annual conditions, it leaves much of Canadian agriculture susceptible to economic losses from climatic factors. The more northerly farm areas are particularly vulnerable. (Simpson-Lewis et al, 1979:34).

Plant growth can occur in a wide range of temperatures varying from 0 C to 60 C. However, every plant has a specific upper and lower temperature threshold, above or below which plant growth and development is hampered or stopped completely. Within this interval lies an optimum temperature range, within which plant growth occurs at its maximum. These three cardinal temperatures vary through-out the various stages of plant development.

Even with temperatures adequate for plant growth, a number of limiting temperature considerations seriously affect crop growth. Thermal considerations are essential in three aspects of plant growth: i) temperatures at the beginning of plant growth, ii) temperatures over the progress of the growing season; and iii) the length of the growing season. These three aspects can be converted into agroclimatic parameters which are of more importance to plant growth than mean values of daily or monthly temperature.

The dates of occurrence of the last spring frosts of 0 C and -2.2 C are valuable indicators of temperature near the beginning of plant growth. A temperature of -2.2 C or lower is sometimes referred to as a ´killing frost´. The occurrence of spring frosts can determine the date of planting. Knowledge of the average date of the occurrence of the last frost in spring can facilitate the scheduling of seeding to correspond to times when the chance of frost damaging young plants is minimal or at the level of risk at which the farmer is willing to take.

Accumulated values of temperature above the growth threshold can be used as indicators of thermal conditions during the progress of the growing season. The use of derived parameters such as growing degree-days, corn heat units and biophotothermal units can facilitate characterization of the temperature regime encountered by plants during the growing season. Mapping of critical values of these temperature accumulations necessary for plant growth can aid in the evaluation and delineation of areas suitable for cultivation of specific crops.

The length of the growing season is probably the most crucial determinant in delimiting areas suitable for the successful production of various crops, since this period represents the time available for crop growth. The derived parameters of the date of occurrence of the first fall frost and thus the subsequent actual length of the frost-free period provide effective measures for determining the approximate length of time available for plants to grow and mature.

3.2.2 Moisture Considerations

The second major limiting climatic factor of consequence in Southern Manitoba is precipitation and/or soil moisture amounts. Growing season precipitation, along with stored soil moisture in the spring represents an estimation of the total amount of water available for plant growth.

The two factors of importance with respect to moisture considerations are: i) the variability of precipitation; and ii) the accumulation of precipitation over the growing season. A simplistic approach to the study of the agroclimatic potential of an area with respect to moisture considerations can be accomplished by calculating the total amount of precipitation received during the growing season. A simple total amount, however, can misrepresent the moisture situation, since it gives no indication as to the timing of the rainfall. Variations in the timing of the occurrence of precipitation can have considerable implications. Availability of water at certain, often short, critical periods in a crop's growing season, can greatly influence plant growth, development and ultimately yield.

An analysis of precipitation alone cannot fully describe the relation between plants and their water requirements. Soil moisture is the source of water of prime concern for crops and is a more suitable variable when investigating the influence of climate on plant growth and development. Soil moisture data reflects the influence of various climatic elements, namely precipitation, temperature, radiation and evapotranspiration, on the availability of water in the soil layers. Unfortunately, observed soil moisture data are scarce, and subject to a high degree of uncertainty due to measuring techniques, erroneous readings and random fluctuations of soil moisture over short distances (Baier, 1976). This study will thus utilize the empirical method of calculating potential evapotranspiration by Baier and Robertson (1965) to calculate soil moisture amounts as a function of potential and actual evapotranspiration and precipitation amounts. Soil moisture budgeting was carried out for three different crops in this study: i) wheat, ii) corn (grain and silage corn); and iii) alfalfa, at various stages in their development.

3.2.3 Estimation of Planting Dates using Climatological Data

As previously stated, extensive agroclimatic analyses are hampered by both lack of quality and quantity of agricultural and climatological data. In addition to the derivation of the agroclimatic data base from existing climatic records, lack of agricultural data in the form of dates of planting, necessitated the derivation of this factor.

Many of the agroclimatic parameters derived and used in this thesis require knowledge of the date of planting. To facilitate an accurate representation of crop growth and development during a specific year, knowledge of dates of seeding is essential. The phasing of stages of plant development, especially of annual crops, depends on the date of sowing. Each different sowing time causes the crop to react to the various elements comprising its environment in a distinct way and with varying results.

Previous studies have tended to use an average date to indicate the beginning of the growing season, usually chosen as May 1 or May 15. A more precise method of determining the actual meteorological conditions encountered by crops during a year is by using observed or actual planting dates as markers of the beginning of the plants growth season.

Planting dates are available from Statistics Canada: Crop Reporting Files (Field Crop Reporting Catalogue #22-002) for the years 1948 - 1978. Planting dates are assigned to each of the 14 crop-reporting districts based on surveys of percentage of seeding completed at selected areas within the crop district. Planting dates are determined when seeding within the area is 50% or more completed. These field crop reports are published weekly beginning in May and continue through till harvesting operations are generally completed in late September. Since Statistics Canada records planting dates according to weeks, an empirical formula was used to convert week of planting to actual day numbers. When seeding was recorded as being 50%, or more completed during a specific week, planting dates were then calculated by the following formula:

$$\text{Planting date} = (\text{Week number} - 1) \times 7 + 3$$

Week number was calculated from May 1 (Dyck, 1978).

In all, 31 years of seeding dates are available. In the analysis undertaken in this thesis it was necessary to have approximately 50 years of such data to obtain a reliable statistical distribution. To this end, a Fortran computer program was written to estimate planting dates using only climatological data. Selirio (1969) and Selirio and Brown (1972) conducted similar estimation studies to determine the probability of having suitable conditions for early cultivation and seeding operations, since it is widely accepted that early seeding of annual grains tends to promote higher yields. Using a soil moisture budgeting technique, they established several climatic criteria to determine when the soil was assumed to be tractable (i.e.: suitable for seeding), namely: i) soil moisture was at or below 90% of field capacity, ii) daily precipitation (snowfall) less than 2.5 cm., (a value of .25 cm. in water equivalent terms); and iii) maximum air temperature was above 0 C.

Baier (1973) used the versatile soil moisture budget to estimate field workdays during various times within the calendar year, as well as during various stages of crop development. A field workday was defined as a day with no snow cover and various levels of estimated soil moisture conditions in the upper three soil zones. An average date of planting was used to mark the beginning of plant growth, but Baier stressed the need for future research to develop a planting date estimator for various crops and soils. Hassan and Broughton (1975) presented a review of other studies which use soil moisture levels as a criteria for soil tractability (field workdays).

Soil moisture budgeting techniques were used in this research in an attempt to estimate planting dates from climatological data. Soil moisture budgeting began on April 15 with the soil moisture level assumed to be at field capacity. Soil moisture budgeting was performed as follows: soil moisture (day i) = soil moisture (day i-1) + precipitation (day i) - actual evapotranspiration (day i). Actual evapotranspiration was calculated as a proportion of the potential evapotranspiration as defined by Baier and Robertson (1965). To determine daily amounts of actual evapotranspiration (AE), consumptive use factors (CU) were established following the example set by Selirio (1969). The consumptive use factor, the ratio of AE/PE, is a function of available soil moisture and is equal to 1 (unity) when the soil moisture is between 95 - 100% of field capacity and is calculated by the following expression when the soil moisture is below 95%:

$$CU = (0.01) \times (127.42) \exp(\theta/100)$$

where θ is the percentage of soil moisture. AE was then determined by AE = PE x CU.

Criteria used in this study to estimate planting dates were as follows: i) soil moisture was at 90% or less of field capacity, ii) maximum temperature was above 0 C, iii) precipitation was less than 2.54 mm.; and iv) planting was assumed not to start until after 5 consecutive days with the above climatic conditions. Regression analysis was then run on the observed and estimated planting dates to establish regression lines to facilitate the estimation of planting dates for the years prior to 1948. Correlation values from this procedure ranged from r=.4 to r=.6. Although these values were lower than those obtained by Selirio (1969) they were deemed acceptable since circumstances surrounding the two studies are quite different. In Selirio's study actual planting dates were used, as opposed to dates estimated by Statistics Canada in the present study. Also, the previous study was concerned with only one basic soil type while the present study involves three different soil types.

Chapter IV

ANALYSIS OF THE AGROCLIMATIC DATABASE

This chapter discusses the derived agroclimatic data base developed and introduces the probability analysis undertaken whose results are presented in chapter 5. This chapter is organized so as to first provide some introductory comments on the importance of probability theory within agricultural climatology. Following this, determination of the probabilities associated with each of the derived agroclimatic parameters will be discussed separately in the following order: i) frosts and frost-free periods, ii) growing degree-days and corn heat unit accumulations, iii) the biometeorological time scale for a cereal crop; and iv) soil moisture analysis for three different crops.

4.1 PROBABILITY THEORY IN AGROCLIMATIC RESEARCH

The main focus of the analytical stage within this thesis deals with the probability analysis of the agroclimatic parameters derived. The concept of probability is fundamental to the study of many climatological problems. As stated by Stringer (1972),

> In view of the complexity of the atmosphere... one can never be certain of any explanation or prediction in climatology. Data in climatology are almost always used to make some sort of decision or statement, and in any problems of decision-making under uncertainty, the mathematics of probability provides the logical guide. (Stringer, 1972:107).

Sutcliffe (1968) stresses the fact that in agroclimatology, both the meteorological and agronomic factors are extremely variable, both temporally and spatially. He then goes on to state that trends on any time scale cannot be extrapolated into the future, but that the climate can be predicted in terms of means or frequencies or probabilities for time periods ahead.

Probability can thus be defined as the relative frequency with which an event occurs over the long run, that is, a measure of the assessment of the likelihood that an event will occur. It is precisely the establishment of these probabilities or risks associated with the occurrence of climatic events affecting crop production which provide a sound climatic basis for the assessment of future agricultural strategies. Determination of empirical probabilities based on past meteorological observations can directly aid people involved in the decision-making aspects in agriculture. Mean-value maps of important agroclimatic parameters can only provide a first look at the climatic capabilities of given regions. More important are maps of those parameters showing the probability of occurrence of various climatic conditions, that is, the climatic variability associated with specific areas. Knowledge of these risks are essential, since it is the extremes which generally play the key role limiting factors in agricultural production and ultimately financial/economic considerations.

Thus, probability analysis was undertaken in this study to provide estimates of degrees of risk associated with particular climatic events in order to facilitate improved agricultural strategies based on a sound knowledge of the climate.

4.2 PROBABILITY THEORY

Calculating values of the derived agroclimatic parameters using past climatic records results in a series of values known as a climatological series. The agroclimatic parameters utilized in this study are continuous random variables since precipitation, temperature or any element measured on a continuous scale is a continuous random variable (Thom, 1966). Collectively the values derived from these variables form a statistical series.

Before attempting any type of probability analysis on a climatological series, one must determine the frequency distribution of the data in question. Every climatological statistic is a random variable which forms a population for which there is a frequency distribution. The distribution of any continuous random variable is described by a frequency curve. The area under this curve between two limits on the horizontal scale represents the probability that the variable will assume a value lying within this interval. These distribution curves for continuous random variables are specified by mathematical formulas. Relevant probability tables have been established for commonly used frequency curves. Thus, once the distribution of the data is know, the probability of occurrence of specific climatic conditions can be readily determined using the relevant probability tables.

In this research where some of the agroclimatic parameters under investigation have not been fit to a known frequency distribution, the first stage in the analysis is the fitting of the data to a frequency distribution. Results of this analysis can be found in Appendix B. The second stage is the application of the data, with its known frequency distribution, and the corresponding probability tables to determine the probability of the parameter taking on specific ranges of values.

Each of the derived agroclimatic parameters established and calculated will be discussed in turn. Their importance with respect to agriculture, as well as their unique statistical properties will be discussed in order to highlight the significance of the results of the probability analysis undertaken.

4.3 FROST

Frost is a climatic condition on a land surface which occurs when the temperature drops below 0 C. The level of 0 C has generally been used in many frost studies since this represents the temperature at which water will freeze. The freezing of water within plant tissues can seriously affect plant growth, development and yield. The extent of damage imposed on crops by freezing temperatures depends upon several factors: i) the degree of frost intensity, ii) duration of the freezing temperature, iii) stage of development of the plant; and iv) the plant species under consideration. Carder (1965) and Hayter (1978) maintain that a temperature of 0 C does not usually result in cereal crops being killed or severely damaged. They prefer to use -2.2 C as the critical temperature at which frost frequently results in extensive damage to plants.

In an area such as Southern Manitoba where crop production is practiced close to its northern limit, frosts are a serious economic consideration in agricultural production. As Hayter (1978) states,

> Frost is both a constant limitation to the range of agricultural practices and a killing hazard which can occur sporadically during the growing season. (Hayter, 1978:95).

Frosts and their occurrence are especially critical at specific times through-out the year. The dates of occurrence of the last spring frost can determine the date of planting, while the occurrence of frost in the fall determines the last date on which plant growth can proceed. The frost-free period, that is, the period of time between the date of occurrence of the last spring and the first fall frost, represents the total time available for plant growth and development. Calculated mean and probability values of these various parameters, along with a knowledge of the approximate number of days required for a given crop to mature (Table 1) can aid in delineating areas suitable for specific types and varieties.

TABLE 1

Number of Days Required to Mature Various Crops

Crop		Days to Mature
Barley		60 - 80
Buckwheat		80 - 90
Canary grass seed		95 - 105
Grain corn		110 - 120
Field beans		105 - 115
Field peas		90 - 100
Flax		85 - 100
Mustard		83 - 102
Oats		85 - 88
Rapeseed	late	92 - 102
	early	73 - 83
Sunflowers		120 - 130
Sugar beets		120 - 140
Wheat		90 - 100
	bread	90 - 100
	durum	100 - 107

(Principles and Practices of Commercial Farming, 1971:120-142).

The limitations imposed on the successful cultivation of agricultural crops by the occurrence of frost have been recognized for a considerable period of time. The occurrence of frosts in the spring and fall and the resulting frost-free periods have been studied for most areas in Canada. (Baier, 1976; Hayter, 1978; Longley, 1967; McKay et al, 1967; Rheumer, 1953; Shaykewich, 1974). Few however, have attempted to describe the occurrence of frosts in a statistical perspective. Mean values of the dates of occurrence of frosts and average lengths of frost-free periods can only yield a very crude estimate of the suitability of an area for specific crop production. More important is knowledge of the climatic risks and/or advantages of an area, that is, the probabilities associated with the occurrence of frosts after or before specific dates in the spring and fall and the probability of receiving a shorter frost-free period than indicated. Since the occurrence of frost has serious economic implications with respect to the successful cultivation of crops, people involved in agriculture should have full knowledge of the climatic risks of regions to allow them to plan their agricultural strategy based on a level of risk which they are willing to accept. As Smith (1975) states,

> The easiest and cheapest way to prevent frost is to attempt to avoid it, either by selecting areas where frost is least likely or by arranging the growth of the plant by planting it when the chance of frost is at a minimum. (Smith, 1975:8).

The analysis of the occurrence of frost was accomplished by calculating the dates of occurrence of the last spring and first fall frosts and the subsequent frost-free periods defined as normal parameters at 0 C and as killing-frost parameters at -2.2 C. Spring frosts were defined as days between January 1 and June 30 during which the temperature fell below the base temperature. Fall frosts were defined as those days between July 1 and December 31 during which the temperature fell below the base temperatures set in this study.

As previously stated, before attempting any sort of probability analysis, the frequency distribution of the data under investigation must be determined. Thom and Shaw (1958) determined that the dates of occurrence of the last spring and first fall frost were normally distributed and could be fit to a normal frequency distribution. They also concluded that the difference between the dates of spring and fall frosts, that is, the frost-free period, would also be normally distributed. Rosenberg and Myers (1962) extended this research and showed that frost series based on both advective and radiative spring and fall frosts were random and normally distributed. These two studies thus provide the basis for the use of the mean and the standard deviation values in the probability analysis, assuming a normal distribution.

At this point, it must again be stressed that the concept of the frost-free period can be misleading. The occurrence of micro-climatic variations of air temperature over short distances can cause complications, since the temperature values used in the study are measured in a standard instrument shelter, not within the growing crop itself. Thus values of the length of the frost-free period and the dates of occurrence of frosts in spring and fall can only be used as rough approximations to the total length of time favorable for plant growth.

4.4 HEAT UNIT CONCEPTS

Growing degree-days and corn heat units are agroclimatic parameters of the accumulated expressions of the accumulated temperatures encountered by plants throughout their growth season. These parameters are mathematically derived from empirical formulas using daily maximum and minimum temperature records. Simplistic as both these parameters are, their areas of application still in use today include: i) their use in predicting stages of crop development, ii) as forecasts of harvest dates, crop yields, and crop quality; and iii) as delineating factors for selecting crop varieties for an area either for introducing new crops into an area or for introducing different varieties into regions

4.4.1 Growing Degree-days

The growing degree-day heat unit concept is one of the oldest derived agroclimatic parameters which attempted to use climatic data as a basis for application in agricultural planning. This growing degree-day concept is based on the assumption that a plant requires a definite amount of heat in order to reach its various stages of development. It also assumes that there exists a certain base temperature, for each plant, below which plant growth ceases and above which growth increases linearly with increasing temperature. Thus the amount of effective growth heat received during the day is calculated as the difference between the mean daily temperature and the base temperature for the crop being studied. These growing degree-days are accumulated over a specific time period, usually the growing season as defined from May 1 to September 30. The empirical formula used to derive growing degree-days is as follows:

Total # growing degree-days= sum{[maxt(i)+mint(i)]/2 - base temperature}
where i represents all the days between May 1 and September 30.

The base temperature of 5.5 C is the accepted normal for most cereal crops and was used in this study after Boughner (1964), McKay et al (1967) and Shaykewich (1974).

The weaknesses of this simple approach to describing the heat requirements of various crops lie in its inherent assumptions with regard to the relationships between thermal considerations and effective plant growth and development: i) this concept assumes that there exists only one base temperature throughout the entire life of the plant. It has been shown many times that as plants grow and develop, their heat requirements change and thus the base temperature for most plants change from one developmental stage to the next, ii) it assumes that the rate of plant growth increases linearly with increasing temperature. It recognizes the lower critical temperature, but does not take into account the detrimental effects of extremely high temperatures. Thus, it fails to recognize the three cardinal temperatures, that is, the upper and lower thresholds and the optimum temperature, important in a plant's rate of growth and development, iii) it also assumes that day and night temperatures are of equal importance with respect to plant growth. It does not recognize the concept of thermoperiodism, which stresses the importance of considering day and night temperatures separately; and iv) this concept also fails in that it does not take into account other climatic or astronomical variables which affect growth and development, (e.g.: photoperiod). Even with these proven inadequacies, the use of growing degree-day calculations continues to be an important part of many agroclimatic studies. Growing degree-days are calculated in this study to facilitate comparison of results obtained here with similar studies previously carried out in Manitoba and other parts of Canada.

4.4.2 Corn Heat Units

Corn is increasingly becoming an important crop in Manitoba, both for its high economic return as grain corn and as high energy silage for livestock production. As with all other crops high production of both silage and grain corn requires sound management. Essential to high productivity in Southern Manitoba is the selection of corn hybrids climatically suited to particular climatic regions, based on both thermal and moisture assessments. Temperature is probably the most critical factor limiting corn growing in Manitoba, since corn requires higher temperatures to mature than smaller cereal crops. In attempting to classify areas suitable for corn production it was shown that the simple growing degree-day calculation was not sufficient to delineate areas adequately. Brown (1964) introduced the corn heat unit concept as a mathematical formula to calculate an accumulated heat expression to help classify areas that have the climatic potential to grow corn successfully to maturity.

The underlying concept of the corn heat unit calculation is essentially the same as for the growing degree-day determination, that is, the rate of plant growth is assumed to increase with increasing temperature. The corn heat unit attempts to overcome some of the disadvantages of the simple degree-day system by incorporating two restrictions: i) it assumes no growth takes place at day temperatures below 10 C and at night temperatures below 4.4 C; and ii) it assumes that the rate of plant growth increases with increasing temperature up to 30 C and subsequently decreases at temperatures above this. Corn heat units are accumulated over the period from May 15 to the first date of occurrence of a fall frost of -2.2 C or lower (Shaykewich, 1974). Daily corn heat units are mathematically calculated using the following empirical formula:

$$CHU = \{3.3[maxt(i)]-.084[maxt(i)-10)]^{2}+1.8[mint(i)-4.4]\}/2$$

where i includes all the days between May 15 and the first -2.2C frost in autumn. This quadratic equation considers daytime and nightime temperatures separately. The daytime portion uses 10 C as the base temperature necessary for growth and 30 C as the optimum temperature. The nightime contribution to growth uses 4.4 C as the base temperature. Ideal thermal conditions for growth and development of corn range from day temperatures of 24 - 29 C and cool night time temperatures ranging down to 14 C. (Manitoba Corn Committee, 1978:5). Silage corn requires an accumulation of 2000-2100 corn heat units to successfully produce high quality silage. Many of the grain corn hybrids grown in Manitoba require 2200-2300 corn heat units (e.g.: Morden 88 & Stewart's 2300). Others require approximately 2600 corn heat units to successfully mature (e.g.:UH106). In addition, corn requires a higher heat requirement in the spring to germinate than smaller cereal crops and thus can generally escape damage from late spring frosts. However it is extremely susceptible to early fall frosts. Thus careful scheduling of the growth of corn is essential to insure successful production.

4.4.3 Bio Photo Thermal Units (A Biometeorological Time Scale)

Recently, significant advances in the derivation of agroclimatic expressions of heat accumulations and their relation to plant growth and development have been made. Robertson (1968) introduced the concept of a biometeorological time scale for crop development using daily temperature and photoperiod. Associated with each of these variables are threshold and optimum values which vary for each developmental stage in a plant's life. The superiority of this technique as compared to previous concepts, is that: i) it recognizes the fact that the response of crop development to temperature is not linear; it recognizes the three cardinal temperatures, that is, the upper and lower critical threshold values, as well as an optimum value with respect to plant response to both temperature and photoperiod, ii) it considers plant response to day and night time temperatures separately, iii) it recognizes that the climatic requirements of plants vary throughout the different stages of plant development and integrates the influence of the three climatic factors over short phenological periods which possess relatively uniform physiological processes; and iv) it uses daily temperature and photoperiod values, so that actual meteorological conditions experienced by plants are used in the model and not average monthly values (Robertson, 1968).

The mathematical expression ultimately derived was:

$$dM/dT = [\{a1(L-a0)+a2(L-a0)^2\}\{b1(T1-b0)+b2(T1-b0)^2 + b3(T2-b0)+b4(T2-b0)^2\}]$$

L - daily photoperiod

T1 - daily maximum temperature

T2 - daily minimum temperature

a0,a1,a2,b0,b1,b2,b3,b4 - coefficients

dM/dT - daily rate of development

The biometeorological time scale developed is a continuous scale since it is calculated on a daily basis from weather data. Each day's contribution to final maturity is determined and summed from the period when the crop is planted till the day of final maturity. As the plant develops, the thermal and photoperiod requirements change thus the coefficients within the equation change as the plant matures. The model recognizes five developmental stages for the period of growth from planting to maturity: planting (P) to crop emergence (E) to jointing (J) to heading (H) to soft dough stage (S) to ripe (R).

Table 2,

TABLE 2

Biometeorological Development stages

Biological Time	Biometeorological Time
Planting	0
Emergence	1
Jointing	2
Heading	3
Soft dough	4
Ripe	5

(Robertson, 1968:20).

All coefficients in the model were determined by an iterative regression technique which provided the best relationship for the rate of development of the crop as influenced by maximum and minimum temperature and photoperiod. These coefficients were then used to derive characteristic response curves for each of the environmental factors, that is, to determine the three cardinal values for each stage of development of the crop.

For the first stage (P - E) there was no response to photoperiod since the crop had not yet emerged, thus daylength cannot affect plant development. The response to both maximum and minimum temperatures was curvilinear with a lower threshold of 44.4 F and an upper limit of 95 F. In the E - J stage, there was a strong linear response to photoperiod above a threshold value of 8.4 hours. There was also a weak curvilinear response to minimum temperature, with a lower threshold of 23.6 F, an optimum of 65 F and an upper threshold of 92 F. In the next stage of development, J - H, there was a weaker curvilinear response to photoperiod with a threshold of 10.9 hours and an optimum of 19 hours. It was also determined that in Canada as far as the rate of development, wheat can benefit from high temperatures as there was no indication of a decreasing response as temperatures increased as high as 90 - 100 F. This was true for all succeeding stages of development also. The H - S stage showed a continuing decrease in response to daylength, with a threshold of 10.9 hours and an optimum of 20.0 hours. The minimum temperature threshold was 42.2 F. In the final stage of development S - R there was a negative response to photoperiod. According to Robertson this negative response of rate of development to daylength could reflect a slowing of the active growth resulting in an increasing ripening rate. The minimum temperature was lower than the previous stage at 37.67 F. The coefficients established for each of the various stages of development are as shown in Table 3

TABLE 3

Coefficients used in each Phenological Stage

	P - E	E - J	J - H	H - S	S - R
a0	0.0E0	8.413E0	10.93E0	10.94E0	24.38E0
a1	0.0E0	1.005E0	9.256E-1	1.389E0	-1.140E0
a2	0.0E0	0.0E0	-6.025E-1	-8.191E-2	0.0E0
b0	44.37E0	23.64E0	42.65E0	42.18E0	37.67E0
b1	1.086E-2	-3.512E-3	2.958E-4	2.458E-4	6.733E-5
b2	-2.23E-4	5.026E-5	0.0E0	0.0E0	0.0E0
b3	9.732E-3	3.666E-4	3.943E-4	3.109E-5	3.442E-4
b4	-2.267E-4	-4.282E-6	0.0E0	0.0E0	0.0E0

(Robertson, 1968:211).

4.5 SOIL MOISTURE CONSIDERATIONS

"While temperature limits the broad distribution of crops, it is precipitation and in particular the soil moisture balance that subjects agriculture to more localized controls." (Simpson-Lewis et al, 1979:11). Almost every process occurring in plants is affected by water availability, but the interrelations are extremely complex. Climate influences water requirements of plants mainly through the amount of and distribution of precipitation and through the amount of potential evapotranspiration that can take place at a given location.

In much of the Canadian Prairies precipitation is greatest in summer and least in winter thus nearly paralleling the seasonal moisture needs of agricultural crops. Unfortunately, the variability associated with this seasonal precipitation is extremely high for much of Southern Manitoba. This natural variability associated with the spatial and temporal distribution of precipitation has far-reaching consequences on agricultural production.

Rainfall alone is not a sufficient condition to judge the water balance available for useful consumption by crops. Another component of climate equally as important as precipitation with respect to plant growth is potential evapotranspiration or the evaporative demand of the atmosphere. This loss of water through evapotranspiration is also a fundamental climatic factor necessary for a thorough analysis of moisture conditions encountered by growing plants. Evapotranspiration represents the combined water loss through evaporation from soil surfaces and transpiration from actively growing plants. A distinction must be made between actual and potential evapotranspiration. Potential evapotranspiration (PE) is a process completely a function of climate and can be defined as

> the amount of water which will be lost from an extensive water surface or one completely covered with vegetation where there is abundant moisture in the soil at all times (Thornthwaite and Mather, 1954:4).

Actual evapotranspiration (AE) is the actual amount of water lost to the atmosphere and is a function of several factors: i) climatic factors such as net radiation, wind velocity, humidity, temperature, (i.e.:potential evapotranspiration), ii) soil type and the actual amount of moisture in the ground, iii) type of vegetation, its stage of development and its depth of rooting; and iv) land management and cultivation practices.

As mentioned previously, several empirical approaches have been used to determine potential evapotranspiration values (Thornthwaite, 1948; Penman, 1956; Baier and Robertson, 1965). Potential evapotranspiration in this study was calculated using the empirical expression derived by Baier and Robertson (1956) due to its use of readily available climatic data and its relative accuracy in comparsion with any of the other approaches. The original equation established to estimate values of potential evapotranspiration contained some ten climatic/astronomical variables. Although more physically sound than the simplified version used in this research it was deemed impossible to use in a study the magnitude of the one undertaken here. Use of the original equation would not have permitted the extended spatial and temporal setting afforded this study. The formula to calculate potential evapotranspiration used in this study is as follows:

$$PE(i) = 25.4 * .0034 \{.928 * MAXT(i) + .933 * (MAXT(i) - MINT(i)) + .0486 * Q(i,ilat) - 87.03\}.$$

i = day number from January 1st.

MAXT(i) = maximum temperature (F) for day number(i)

MINT(i) = minimum temperature (F) for day number(i)

Q(i,ilat) = radiation received at the top of the atmosphere in ly.

ilat = latitude class.

PE(i) = potential evapotranspiration (mm)

These values of potential evapotranspiration represent the maximum water loss from a vegetated surface, supplied at all times with an adequate moisture supply. When moisture is limited the actual amount of water lost to the atmosphere is less than the potential amount. Values of actual evapotranspiration represent the actual loss of water. The amount of water use varies with the stage of development of the crop. Early in the season, at the start of the soil moisture budgeting, the loss is by evaporation from a bare soil. As crop cover increases transpiration becomes the dominant factor. Actual evapotranspiration amounts are determined mathematically by multiplying the potential evapotranspiration amount occurring on that day by a consumptive use factor (CU). This CU factor is the ratio of AE:PE as determined by plant type, its stage of development and the amount of ground cover or total leaf area.

Consumptive use coefficients (CU) reflect the amount of water extracted by the plant during the growing season as a function of potential evapotranspiration. Water use by plants is dependent on the type of crop and its stage of development. The effects of plant type on water requirements are: i) the length of growing season for the crop; and ii) the degree to which the plant foliage covers the surface of the soil. The consumptive use coefficients change as the growing season progresses according to various phenological stages of development. As plants progress towards maturity there exists critical times when water use by plants is at its maximum. It is during these periods that water stress can cause its most serious economic considerations by reducing grain yields and/or quality. These CU factors are best described according to a crop development calendar as opposed to a calendar year, since crop growth stages do not occur on the same date each year. Thus to accurately portray the changing water consumption patterns by crops as they mature, soil moisture budgeting was carried out under three different crop growth models to simulate the time of occurrence of the various phenological stages of the crops under analysis. The various CU factors specific to each crop under investigation will be discussed in turn.

While precipitation represents the moisture necessary for plant growth and evapotranspiration represents the water lost from plants, consideration must be given to the supply of moisture that is readily available to plants. The amount of water held in the soil and available for plant use represents the actual moisture conditions encountered by growing plants.

4.6 SOIL MOISTURE

The soil occupied by plant roots is the most important source of water for the crop. Soils have the ability to store precipitation which can be used by plants for growth and development. Of the total amount of water present in the soil at a given time, only a portion of it is readily available for plant use. The upper limit of soil water available to plants is known as field capacity, while the lower limit of available soil water is referred to as the permanent wilting percentage. The amount of water held between these two limits is known as the plant available water. Soils vary in their plant available water holding capacities. The amount of water retained by the soil and available for plant use is primarily determined by soil type. Soil texture, structure and amount of organic matter are the principal factors which determine the plant available water holding capacity of the soil.

Soil texture is the primary controlling factor and can be defined as the size of the soil particles and indicates the degree of coarseness of the mineral material. Coarser soils, such as fine gravels and sands, are conducive to percolation of water down to very low soil depths. Their pore size distribution is such that they cannot retain as much water in the upper layers necessary for plant growth, as can the finer textured clay and loam soils. Soils with high percentages of sand have an available water storage capacity much less than that of loam or clay soils. Thus in order to maintain adequate soil moisture levels necessary for plant growth, sandy soils require rain or irrigation water more frequently than clay or loam soils to maintain the same level.

Since soil textures within the southern portion of Manitoba range from very coarse sands to fine clays, there exists a high degree of variation within the water holding capacities of the agricultural soils of the province. To accurately portray moisture conditions encountered by various crops, account of varying soil textures must be taken into consideration. To calculate daily plant growth and daily soil moisture levels, the various water holding capacities of the different soils encountered were considered. Each weather station used in the development of the agroclimatic database was classified into one of four soil textural classes, as determined from Soil Survey Maps. Stations were assigned into a soil textural class by placing them into the class to which most of the soils surrounding the weather station belonged to. The textural classes used and their assigned water holding capacities are as given in Table 4

TABLE 4

Available Water Holding Capacity (AWC) of Soils

Textural Class	A.W.C. (mm)
Coarse textured (S,LS)	70 mm
Moderately coarse (LVFS,SL)	80 mm
Medium texture (VFSL,L,SiL,Si)	100 mm
Moderately fine (CL,SCL,SiCL)	110 mm
Fine textured (SC,SiC,C)	100 mm

(Shaykewich, 1980).

These available water holding capacity values assigned to each soil texture are derived for a 90 cm (3 ft.) depth of soil and are modified by using a value of 1/2 of the available water as causing no stress for plants. The water holding capacities assigned to the soils within the area of each weather station can be found in Appendix A.

4.6.1 Soil Moisture Budgeting

The study of soil moisture can characterize plant growth in relation to climate better than any single climatic parameter. Because records of measured soil moisture contents suitable for statistical analysis are limited attempts have been made to estimate soil moisture from climatic data. Meteorological soil moisture budgeting techniques, in which potential evapotranspiration is modified according to crop type, soil type and the plant available water capacity, can be used to estimate actual soil moisture amounts from simple climatic data. A daily soil moisture budgeting technique was used in this study to determine actual soil moisture conditions encountered by growing plants. In a meteorological soil budgeting approach, the actual moisture amount in the soil is regarded as the balance between that incoming as a result of precipitation and that which is lost through evapotranspiration.

Soil moisture budgeting commenced on May 1, of each year under analysis, with the level of soil moisture assumed to be at field capacity for the specific soil type (Principles and Practises of Commercial Farming, 1977:57). The calculation is begun on May 1 assuming there are 100 mm of readily available water in the soil on that date. Most soils have an available water capacity of about 200 mm in a soil depth of 90 cm. It is considered that about half of this, 100 mm, is easily available, that is, decreasing soil moisture within this range has no detrimental effect on plant growth. Once the first 100 mm is used, the rate of plant growth decreases. The crop is then considered to be in a stress situation, and soil moisture amounts take on negative values, that is, a soil moisture deficit occurs. For each day till the plant reached maturity, the soil moisture amount was calculated as the amount of water in the soil on the previous day plus any precipitation occurring on that day minus the amount of water lost through evapotranspiration.

Soil moisture(i) = soil moisture(i-1) + precipitation(i) - actual evapotranspiration(i)

If on any day precipitation exceeds AE, the water balance of the soil can increase up to field capacity. Any excess water was considered as lost by runoff or deep percolation and was not included in the daily calculation. This soil moisture analysis was carried out under three different crops each of which will be discussed separately in turn.

4.6.1.1 Soil Moisture Analysis under a Wheat Crop

Since observed phenological data are scarce, and the consumptive water use by plants varies with the different stages of development, the determination of actual soil moisture amounts under an actively growing wheat crop was accomplished by incorporating a meterological soil moisture budgeting procedure within Robertson's (1968) biometerological time scale. Soil moisture amounts were calculated for each of the five phenological stages of plant development recognized by Robertson, namely PE, EJ, JH, HS, and SR. The various consumptive use factors for each development stage studied in the analysis are as in Table 5

TABLE 5

Consumptive Use Factors according to Stage of Development

Stage	Consumptive Use
Pre-planting	.3
Emergence	.3
Jointing	.8
Heading	1.0
Soft dough	.8
Ripe	.5
After maturity	.3

Consumptive use coefficients were assumed to increase or decrease linearly from one stage of maturity to the next. Thus if the biometerological time scale ranges from a value of 1 at emergence to a value of 5 at maturity, consumptive use factors were determined as follows in Table 6

TABLE 6

Calculation of consumptive Use Factors

Stage	Consumptive Use Factors
0<Bmts<1	CU=.3
1<Bmts<2	CU=.3+.5x(Bmts-1)
2<Bmts<3	CU=.8+.2x(Bmts-2)
3<Bmts<4	CU=1.0+{(-.2)x(Bmts-3)}
4<Bmts<5	Cu=.8+{(-.3)x(Bmts-4)}
Bmts=5	CU=.5
Bmts>5	CU=.3

The actual amount of water used by the plant is a proportion of the amount of potential evapotranspiration as determined by the consumptive water use by plants, that is, AE = PE x CU. These consumptive use values indicate that water use by a wheat crop is greatest at the heading to soft dough stages in the plant's growth cycle.

Although water stress is detrimental to plants at all stages of development, it is most critical at specific times within the crop's growth. Moisture stress affects that part of the plant which is growing most rapidly at the time that the stress occurs. Thus the effect on the quality and quantity (yield) of the crop depends on the time when the moisture deficit occurs. Lehane and Staple (1962) found that water stress occurring at the time of heading in wheat caused the greatest decrease in yield. Baier and Robertson (1968) found that a good moisture supply during the period J - H favored high yields, and that soil moisture during this period was the most highly correlated with yields. Mack and Ferguson (1968) concluded that 69 - 76% of the variability in yield was due to moisture stress occurring during the period from 5th leaf to soft dough and that only 3 - 4% of the variability in yield was due to moisture stress following the soft dough stage.

In this research soil moisture amounts were calculated yearly for each stage of development of wheat. However, only moisture amounts occurring at the stages, J - H and H - S were studied in detail and in a probabilistic perspective. This approach can be supported by the above mentioned studies which concluded that moisture deficiency at specific stages within the growth of cereals are most critical with respect to final yield.

4.6.1.2 Soil Moisture Analysis under a Corn Crop

As when attempting to study soil moisture under a cereal crop, analyses of moisture conditions under a corn crop are limited by the lack of observed phenological data. To facilitate examination of the moisture stress experienced by actively growing corn crops, a meterological soil moisture budgeting procedure was accomplished by incorporating this calculation in a corn development model. The growth model employed in this study used accumulated values of corn heat units as indicators of the various phenological stages in corn development. Soil moisture amounts were calculated at several stages in the crop's development, as follows: at 1000 CHU, 1200 CHU (this represents the silking stage), 1500 CHU, 1800 CHU, 2100 CHU and 2300 CHU (this represents final maturity for grain corn).

As with wheat, not all stages were studied with the same degree of statistical intensity. The specific sensitivity of corn to moisture stress had to be studied to determine the critical periods in the crop's growth when stress was most detrimental. Davis and Pallesen (1950) concluded that soil moisture status prior to silking was the most critical factor for optimum yield. Robins and Domingo (1953) reported that soil moisture depletion to the wilting point for 1-2 days during tasselling reduced corn yield by 22% and that stress over a longer period of time could reduce yields by as much as 50%. Howe and Rhoades (1955) determined that water stress prior to and during anthesis decreased corn grain yield, as did a dry period from silking to full maturity. Denmead and Shaw (1960) observed that moisture stress to the wilting point prior to silking reduced corn yield by 25% and that stress at the silking stage reduced yield by 50%. Based on the above findings, it was decided to analyse the soil moisture stress encountered by grain corn during the silking stage. The various consumptive use factors for the developmental stages studied are as follows in Table 7

TABLE 7

Consumptive Use Determination

Stage	Consumptive Use
0<CHU<1200	CU=.3+(.7xCHU)/1200
1200<CHU<2000	CU=1.0
2000<CHU<2300	CU=1.0-.001x(CHU-2000)

4.6.1.3 Soil Moisture Analysis under a Forage Crop

Along with silage corn, alfalfa is another of the important forage crops grown in Manitoba. As with corn, the two climatic parameters directly related to the successful growth of alfalfa are temperature and moisture. To analyse soil moisture conditions under a forage crop it was necessary to derive a forage growth model to determine the progression towards maturity. It was found in work referred to by Selirio and Brown (1979) that a suitable measure of heat accumulation necessary to mature alfalfa is the accumulation of 550 degree days above 5C (this is approximately equivalent to 990 degree days above 41F).

In the present study active growth was assumed to begin some time after April 15 when the mean daily temperature exceeded 5C for five consecutive days (Selirio and Brown, 1979). Daily soil moisture, as in the previous investigations, was determined using a daily soil moisture budgeting technique. This procedure started on April 15 assuming the soil to be at field capacity and a CU factor of .3. The CU factor remained constant till commencement of active growth of the forage crop, when the CU was assumed to be equal to 1.0 (i.e.:AE=PE) (Krogman and Hobbs, 1965). Evapotranspiration increases with increasing leaf area, that is, with increasing percentage of ground cover. The ground cover of alfalfa varies little throughout the year and thus it was assumed that when active growth began in the spring it was with complete ground cover. Thus, water use by alfalfa is essentially equal to PE regardless of season (i.e.:AE=PE), (Krogman and Hobbs, 1965). It should be noted that water use by perennials is much greater than for annuals. In Southern Manitoba it is climatically feasible to produce two crops of alfalfa within a single growing season. Degree days above 5C and soil moisture amounts were accumulated from the date of commencement of the first growth till the crop was assumed to be mature at 550 degree days. A regrowth period of 10 days was allowed between the date of maturity, the subsequent cutting and the recommencement of growth for the second cut. Daily soil moisture budgeting continued through this period with a CU factor increasing from .5 on the first day after cutting to a value of 1.0 on the day active growth recommenced. Krogman and Hobbs (1965) obtained varying number of days for this regrowth period for the various cuttings so an average value of 10 days was used in this study. The variation in the number of days was assumed to be the result of differences in seasonal temperature and daylength and varying yearly meteorological conditions. This analysis was carried out assuming one could successfully grow at least two crops of alfalfa. It is unlikely that in Manitoba three crops of alfalfa can safely be grown to maturity as indicated possible for other parts of Canada, namely in Alberta (Krogman and Hobbs, 1965) and Southern Ontario (Selirio and Brown, 1979). The harvesting of a third crop of alfalfa would leave the crop vulnerable to winterkill over the harsh winters experienced in Manitoba. Soil moisture amounts at the end of each cutting were the parameters that were selected to assess the moisture conditions encountered by a forage crop under Manitoba climatic conditions.

Chapter V

RESULTS OF THE PROBABILITY ANALYSIS AND DISCUSSION

This section represents the results of the second major objective of this research, that is, the probability analysis of the derived agroclimatic data base. As well as the main findings, this chapter will include a brief discussion of the interpretation of these results with respect to their usage in agricultural planning.

The statistical nature of this section of the thesis results in a large amount of quantitative numeric results. Presentation of these results are best accomplished through the use of figures which can show the magnitude of the values that each of the agroclimatic parameters can assume, that is, a quantitative assessment of Southern Manitoba's climatic resource base for agricultural production. A complete listing of all maps derived in this analysis and not included in the body of the thesis can be found in Appendix C. To spatially display this area's agroclimatic resource base a computer mapping technique (SYMAP) was utilized.

SYMAP (Syngraphic Mapping System) was initially developed for use in analyzing spatial data. This research utilized the contour SYMAP to spatially display the results obtained. A contour map consists of contour lines which connect all locations on the map having the same data value. The contour lines shown on the map are for specified values and these values are assumed to vary smoothly over the interval between any two adjacent contour lines forming a continuous surface. Data is displayed by interpolating a continuous surface in areas where there are no data points. These values are then based on the distance to and the value of the neighbouring data points. For this study the locations of the meteorological stations represented the data points and the values were those numbers associated with each of the agroclimatic parameters studied. For the base map used, a point distribution coefficient was calculated to measure the reliability of the interpolation based on the spatial distribution of the data points. This coefficient is used to determine whether the distribution of the points are well dispersed or too clustered for 'meaningful cartographic data portrayal' (Dougenik and Sheehan, 1975). The coefficient is determined using the nearest neighbour method and is calculated as the ratio between the mean distance between the points of the actual distribution and the expected random distibution. This coefficient ranges from a value of 0 to 2.15, where the higher the value the more representative the distribution is of the population. The coefficient of distribution can be seen in Table 8

TABLE 8

Point Distribution Coefficients

Distribution Type	Coefficient
Clustered to random	0.00 - 0.90
Random	0.90 - 1.25
Random to uniform	1.26 - 2.15

(Dougenik and Sheehan, 1975:27).

The point distribution coefficient obtained from the distribution of points utilized in this study was 1.28. Thus overall interpolation of the surface can be assumed to be reliable except in some parts of the map.

5.1 FROST ANALYSIS

Frost and its occurrence at various times within a year can have serious economic implications with respect to agricultural production. The occurrence of frost is of particular importance during two periods of time, in the spring (as defined from January 1 - June 30) and in the fall (as defined from July 1 - December 31). The date of occurrence of the last frost in spring can facilitate the scheduling of seeding to correspond to times when the risk of frost damaging young plants is minimal. The date of occurrence of frost in the fall indicates the final date on which plant growth can occur. The period between these two dates, that is, the frost-free period, represents the total time available for plant growth and development.

The frost parameters studied are of two types; i) those concerned with the occurrence of a 0C frost; and ii) those concerned with the occurrence of a frost of -2.2C (as well as the subsequent frost-free periods resulting from the above temperatures, respectively). Average values were determined for all parameters, as well as the 25% and 10% risk values associated with each of them. In analysing the occurrence of spring frosts the probabilities calculated represent the % chance of the last spring frost occurring after a specified date. In the analysis of fall frosts the probabilites calculated represent the % chance of the first fall frost occurring before the specified date. An average value for the resulting frost-free period represents the minimum length of the period that one can expect in one-half of the total years under consideration. The probabilites calculated represent the % chance of receiving a shorter frost-free period than that indicated.

When analysing the occurrence of frost it must be kept in mind that these occurrences are affected by a variety of phenomena, both natural and manmade:

1. presence of large bodies of water - the presence of lakes or large rivers have a local effect in modifying their immediate vicinity. Water has the natural property of heating more slowly than land and cooling less quickly. In spring the presence of large bodies of water tends to retard the advance of spring heating thus resulting in later occurrences of spring frosts. In fall the change in temperature of water as compared to land is slowed resulting in forestalling the occurrence of fall frosts, thereby extending the frost-free period. Water also has the additional ability to absorb and store radiant energy during the day and release it at night so as to reduce the risk of frost in the surrounding area.
2. topography (local relief) - the topography in the immediate vicinty of the recording station can affect the dates of occurrence of frosts. As an example, a station located at the bottom of a valley is highly subject to frosts since cold air formed on the slopes will flow downwards and gather in pockets, known as frost hollows.
3. altitude - areas at higher elevations tend to be subject to damaging frosts both in the spring and fall. Air is cooled as it

rises, thus areas at higher elevations tend to receive shorter frost-free periods by having later spring frosts and earlier fall frosts.

4. moisture of the soil - as in open water bodies, water in the soil has the ability to store heat during the day and release it at night, thus lessening the risk of frost on moist soils.
5. human habitation - changing natural surfaces to materials such as concrete and asphalt can affect climatic events such as the occurrence of frosts. These materials tend to absorb more heat in the day, than natural surfaces of soil or vegetation, and release it at night thus delaying the occurrence of frost (usually in the fall) of a severity great enough to cause damage to plants. The rapid removal of snow and precipitation in the spring tends to cause the last spring frost to occur earlier, since more radiation is used in heating the air as opposed to evaporating the moisture in whatever form.

Bearing in mind the impact of these controls, each of the analyses undertaken on each frost parameter will be discussed separately, their physical interpretation as well as their spatial distribution.

5.1.1 Last Spring Frosts

The first parameter studied involves the date of occurrence of the last spring frost of 0C. Across the total study area the average date of occurrence of the last frost is May 26. Average values range from an early date of May 15 at Portage la Prairie to the latest date of June 6 at Moosehorn. It must be remembered that the earliest date in this case represents the most desirable condition. The dates of occurrence of these frosts are relatively constant throughout the province with a standard deviation of only 2 days. The standard deviation associated with the occurrence of the last spring frost at a particular station is also relatively constant throughout at 12 days.

As a generalized overview, frosts occur later as one progresses northward. An exception is the southeast section of the province which is extremely subject to late spring frosts. The south central region, that is, the area west from Steinbach past Portage la Prairie is the most favored area with the advantage of having last spring frosts before the rest of the province. The average date of occurrence within in this area falls in the 5 day interval between May 20 - May 25 (Figure 3). Small anamolies are evident within the province which do not fit into the general pattern. For example, Brandon is subject to late spring frosts. This might possibly be explained by the location of the recording instrument in a low-lying area of the province.

The same general pattern of dates of occurrence is reflected in the 25% and 10% risk maps. The area around the Manitoba escarpment stands out as the area subject to a high degree of variation in the dates of occurrence. In 5 out of 10 years this area can expect to have the last frost occurring between May 25 - May 30, but in 1 out of 4 years it can be expected to occur after June 4, while in 1 out of 10 years the frost can be expected after June 9. The 10% risk map indicates that even the most favored areas within the province can in 1 out of 10 years expect to have frost occurring sometime after the beginning of June (Figure 4).

Figure 3: Average Date of Occurrence of the Last Spring Frost (0 C).

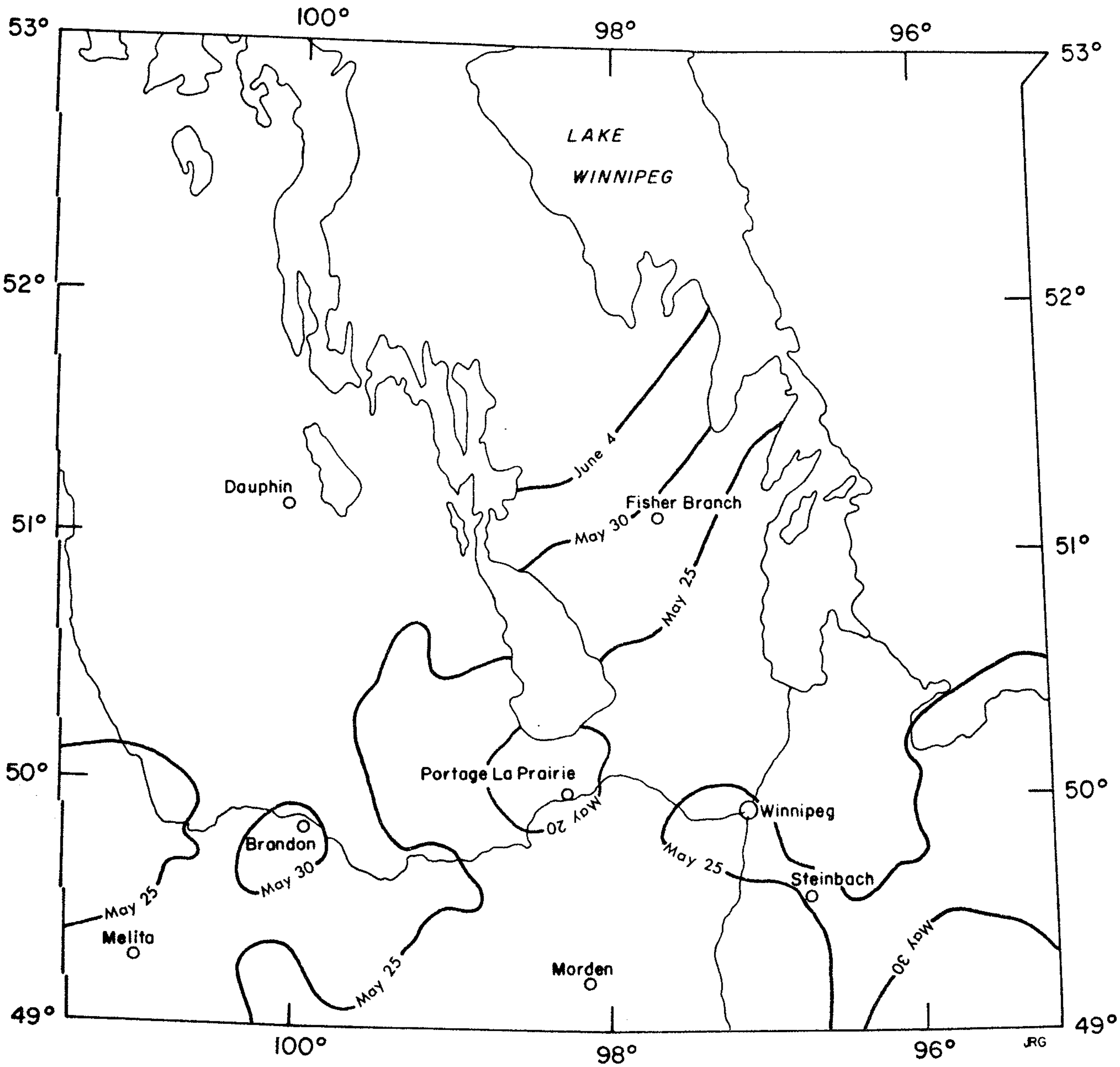
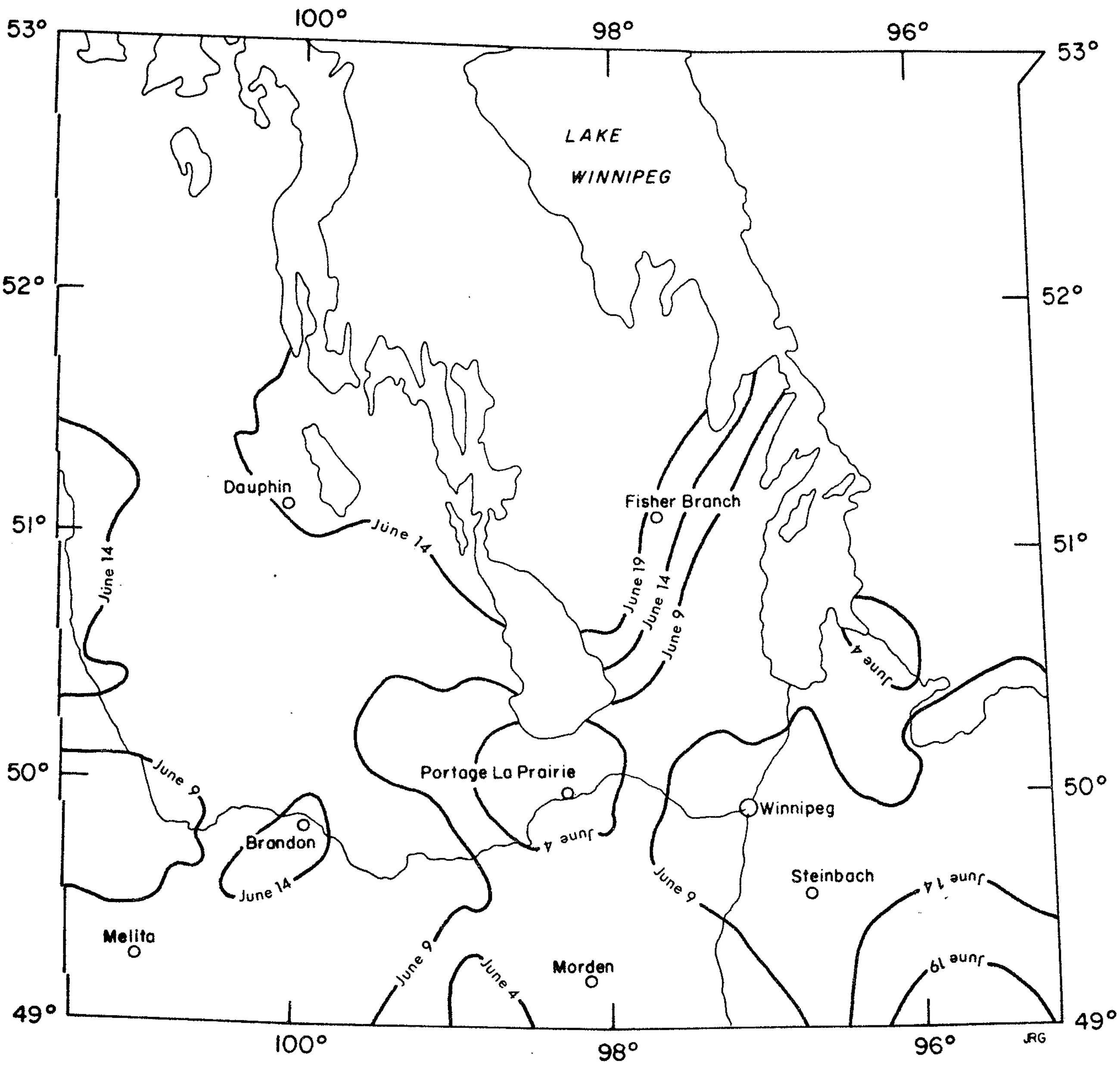
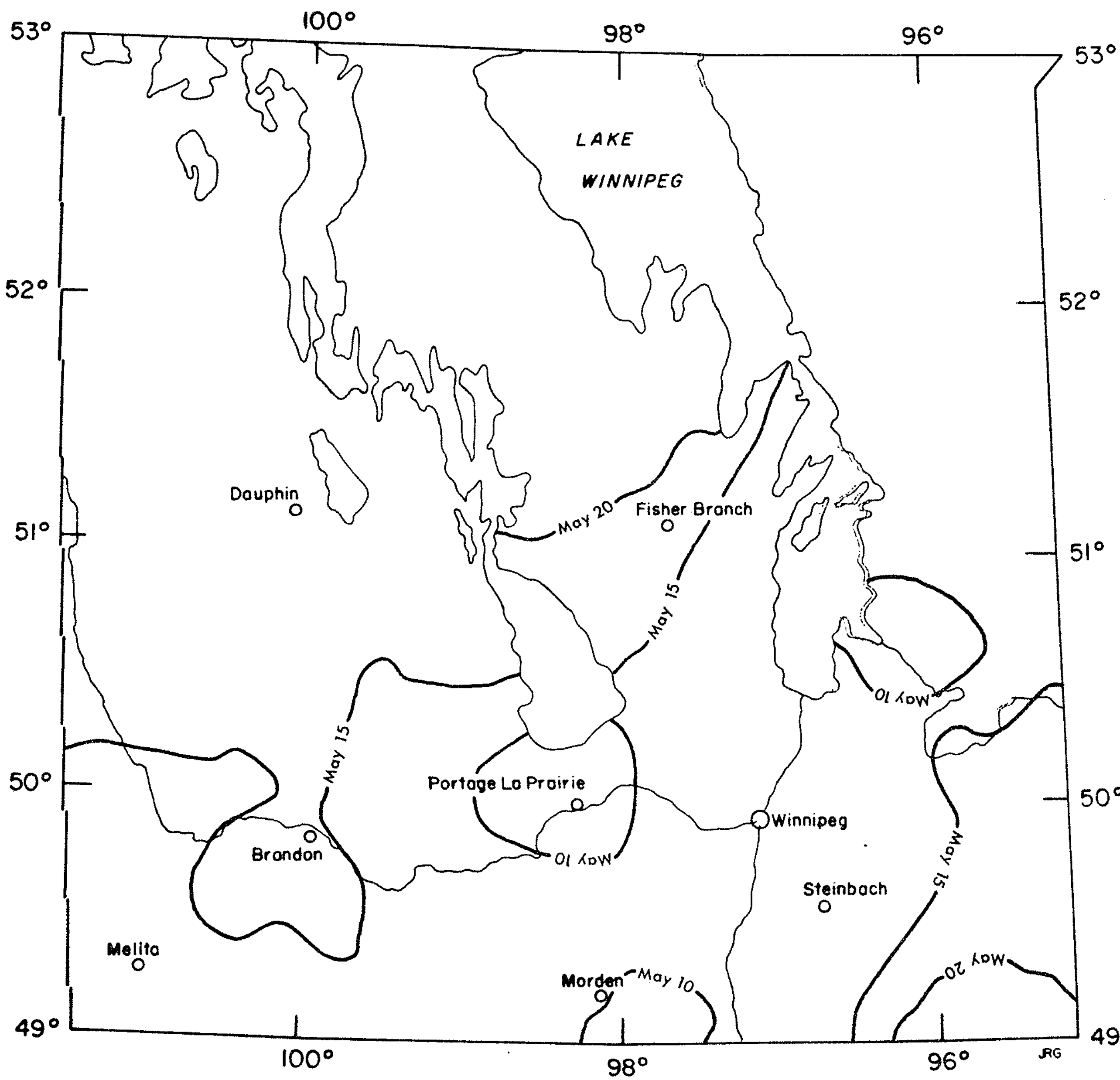


Figure 4: Dates after which the Risk of Occurrence of the Last Spring Frost of 0 C has been reduced to 10%.



The average date of occurrence of the last spring frost of -2.2C through out the study area is May 14, and as was the case in the occurrence of a OC frost, the variability throughout the province is relatively small at 4 days (Figure 5). Much the same general pattern is reflected in the maps of the -2.2C frosts as in the maps for the OC frosts. The area west of the Escarpment and the south-east tip of the province remain the areas most susceptible. Portage la Prairie and the Red River Valley enjoy early spring frosts as compared to the rest of the province.

Figure 5: Average Date of Occurrence of the Last Spring Frost (-2.2 C).

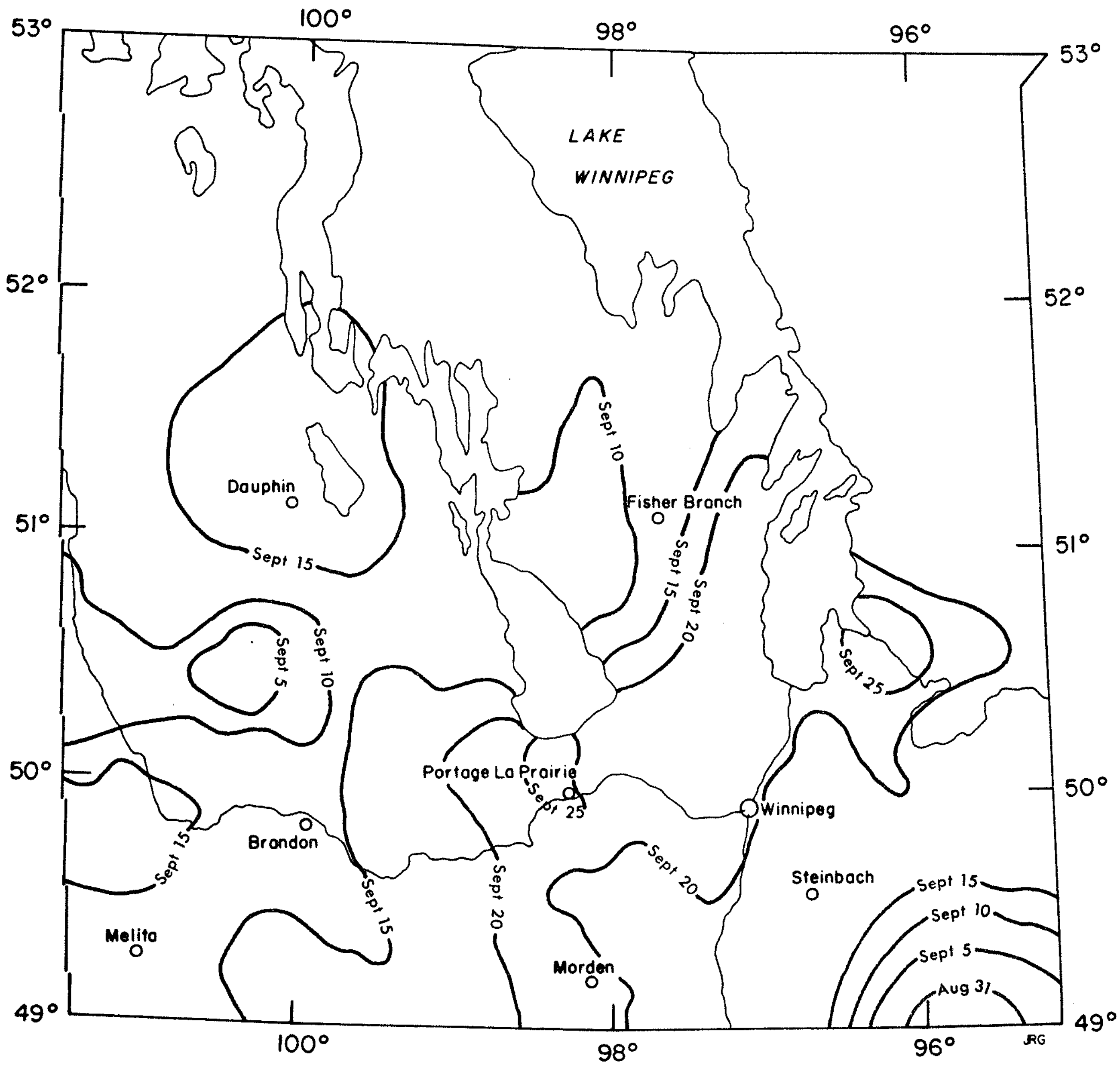


5.1.2 First Fall Frosts

The date of occurrence of the first frost in fall indicates the end of the period of time favorable for crop growth. In the case of this parameter the latest dates are the most favorable. As when considering the dates of occurrence of the last spring frost, the occurrence of the first fall frost is relatively constant through out the southern portion of Manitoba. The average date of occurrence is September 16 and ranges from the earliest date of August 31 to the latest date of September 30. The maps (Figure 6) indicate that on the average those areas susceptible to late spring frosts also risk having early fall frosts. The south central area of the province is favored not only by early spring frosts but also with fall frosts occurring later in the year, thus extending the growing season.

The average date of occurrence of the first fall frost of -2.2C is September 27, ranging from areas subject to early frosts occurring on September 10 to those regions where the first fall does not occur till October 10. The same general pattern is reflected in all maps denoting the occurrence of frosts. The 25% and 10% maps are spatially similar except for the gradient of change evident in certain areas of the province. Areas around the Manitoba escarpment and in the south east section have higher variabilities in their dates of occurrence of the 0C frosts than for the -2.2C frosts. Thus, the probability of receiving a fall frost earlier than indicated on the maps is higher for these particular areas.

Figure 6: Average Date of Occurrence of the First Fall Frost (0 C).



5.1.2.1 Frost Free Periods

The length of the frost free period is a result of the timing of the last frost in spring and the first frost in autumn. The resultant period is a reflection of the combined spatial patterns of the maps depicting the dates of occurrence of the spring and fall frosts. Those areas with early spring frost and late fall frosts have a longer frost free period than other areas.

The average length of the frost free period above OC is 113 days, ranging from a period as short as 88 days at Sprague to a length of 130 days at Portage la Prairie (Figure 7).

The frost free period above -2.2C is considerably longer than that observed for the season above OC. The provincial average length of this period is 137 days ranging from a short season of 115 days to favorably longer periods such as 154 days (Figure 8).

The probability analysis of the frost free period above OC and -2.2C shows the extreme variablity associated with these two climatic parameters. This is especially pronounced in the 25% and 10% risk maps which indicate the chance of receiving a shorter frost free period at a particular probability level. South Eastern Manitoba and the area west of the Escarpment have shorter frost free periods than most other regions in the study area. Particularily noteworthy is the fact that the 10% risk map shows that in 1 out of 10 years only a very narrow strip of Southern Manitoba has a frost free period above OC of 100 days or longer (Figure 9). The 100 day contour line represents the average number of days needed to successfully mature wheat and other cereals.

Figure 7: Average Length of the Frost-Free Period above 0 C.

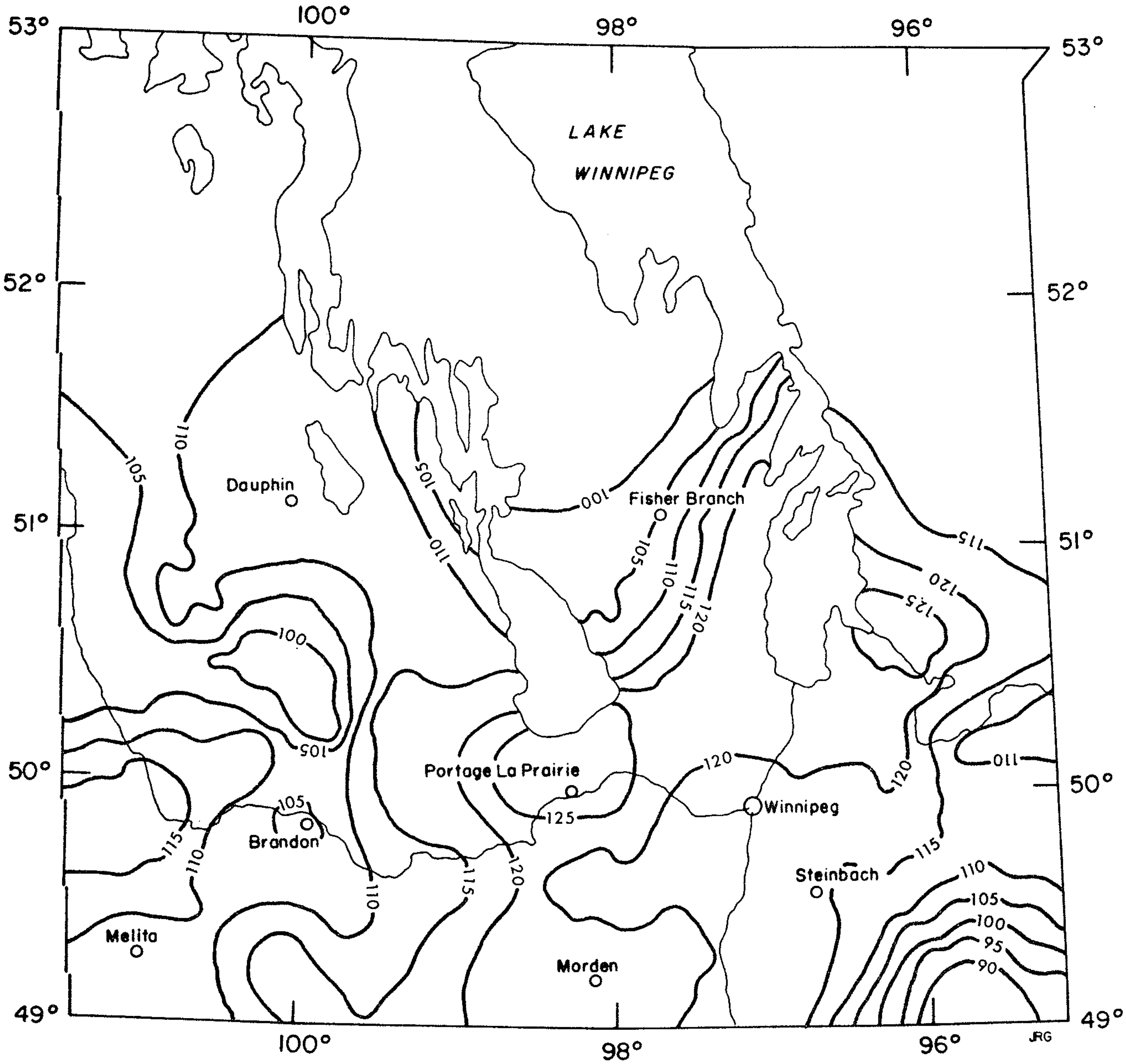


Figure 8: Average Length of the Frost-Free Period above -2.2 C.

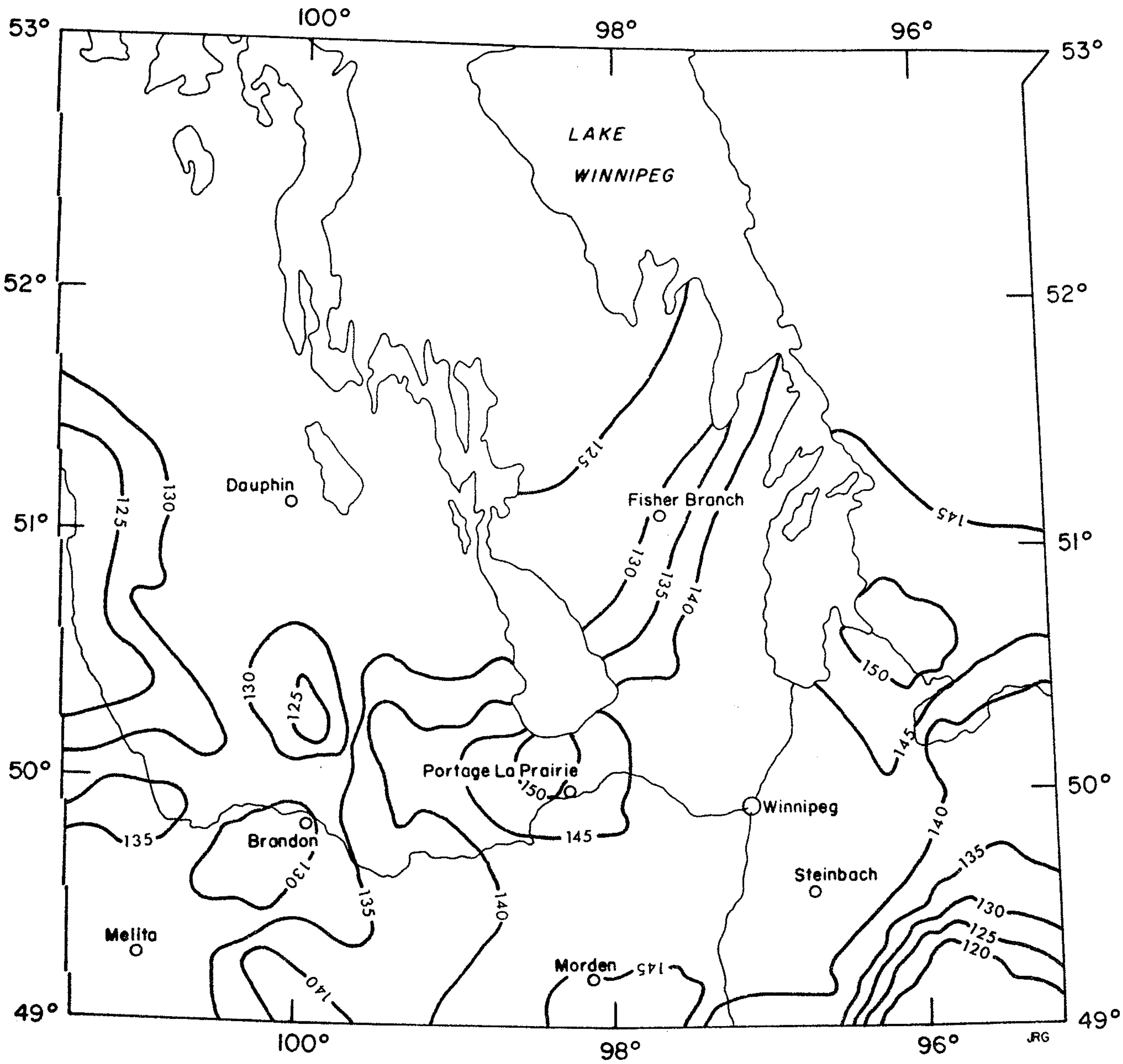
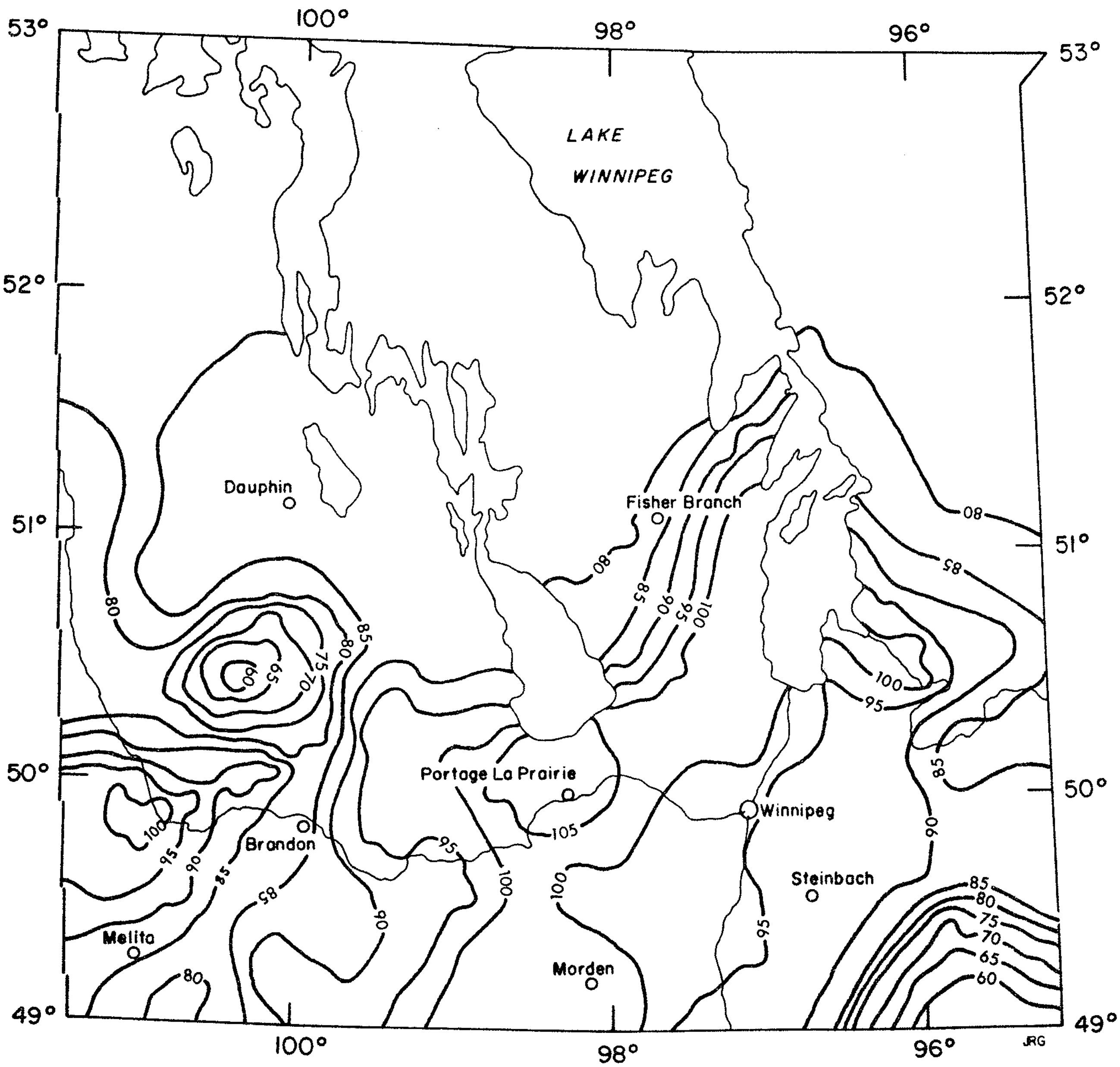


Figure 9: Length of the Frost-Free Period above 0 C at a 10% risk.



5.2 HEAT ACCUMULATIONS

Expressions of the accumulated temperatures received during the growing season are more valuable as indicators of the suitability of specific areas for plant growth than mere examination of the frost free periods. Many locations with sufficient lengths of frost free periods are unable to successfully mature crops due to the low intensity of heat received during the growth period. Growing degree days and corn heat units are the two most widely used expressions to determine those areas which have adequate accumulated temperatures during the growing season for successful crop production. Growing degree days are generally used to assess the suitability of an area for cereal crop production while corn heat units are used to determine those regions climatically suitable for commercial corn production. The differing base temperatures used in the formulas indicate the higher heat requirement of corn over smaller cereals. A value of 2300 corn heat units represents the accepted standard number of accumulated heat units required to successfully mature grain corn and 2100 units are necessary to grow silage corn. A minimum value of approximately 1200 degree days above 5 C is needed to successfully mature cereal grains such as spring wheat, durum, barley and oats.

The maps of corn heat units and growing degree days are similar in their spatial distribution. The map of corn heat units shows that on the average, silage corn can be grown almost anywhere in the southern half of the province except in the area around the escarpment (Figure 10). The high variability associated with this parameter indicates that in 1 out of 10 years even the most favorable areas for grain and/or silage corn run the risk of receiving less than 2300 corn heat units. The provincial average accumulation of corn heat units is approximately 2350, but the average standard deviation at any station is in the order of 200 heat units (Figure 11).

The map of accumulated growing degree days (Figure 12) shows that most places within the province are climatically suited for cereal production. Most areas in the southern half of the province show accumulated degree day values above 1200, ranging from a low of 1393 at Russell in northwestern Manitoba to a high of 1749 at Morden in the south central region. It must be kept in mind that this parameter was accumulated over the entire period May 1 to September 30 whereas killing frosts may occur sporadically before this ending date and prevent the crop from maturing successfully.

Figure 10: Average Accumulated Number of Corn Heat Units.

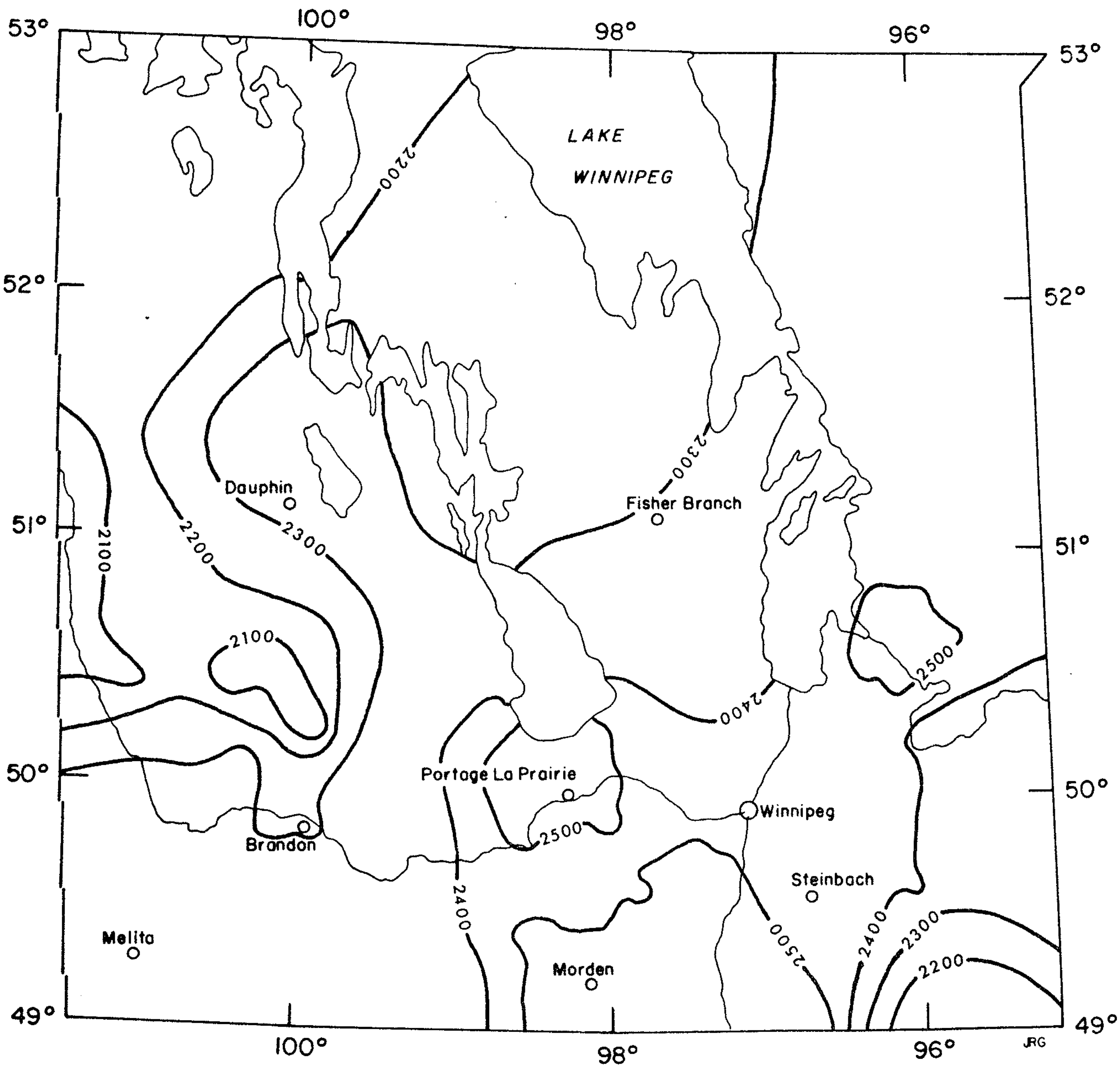


Figure 11: Minimum Accumulation of Corn Heat Units at a 10% Risk.

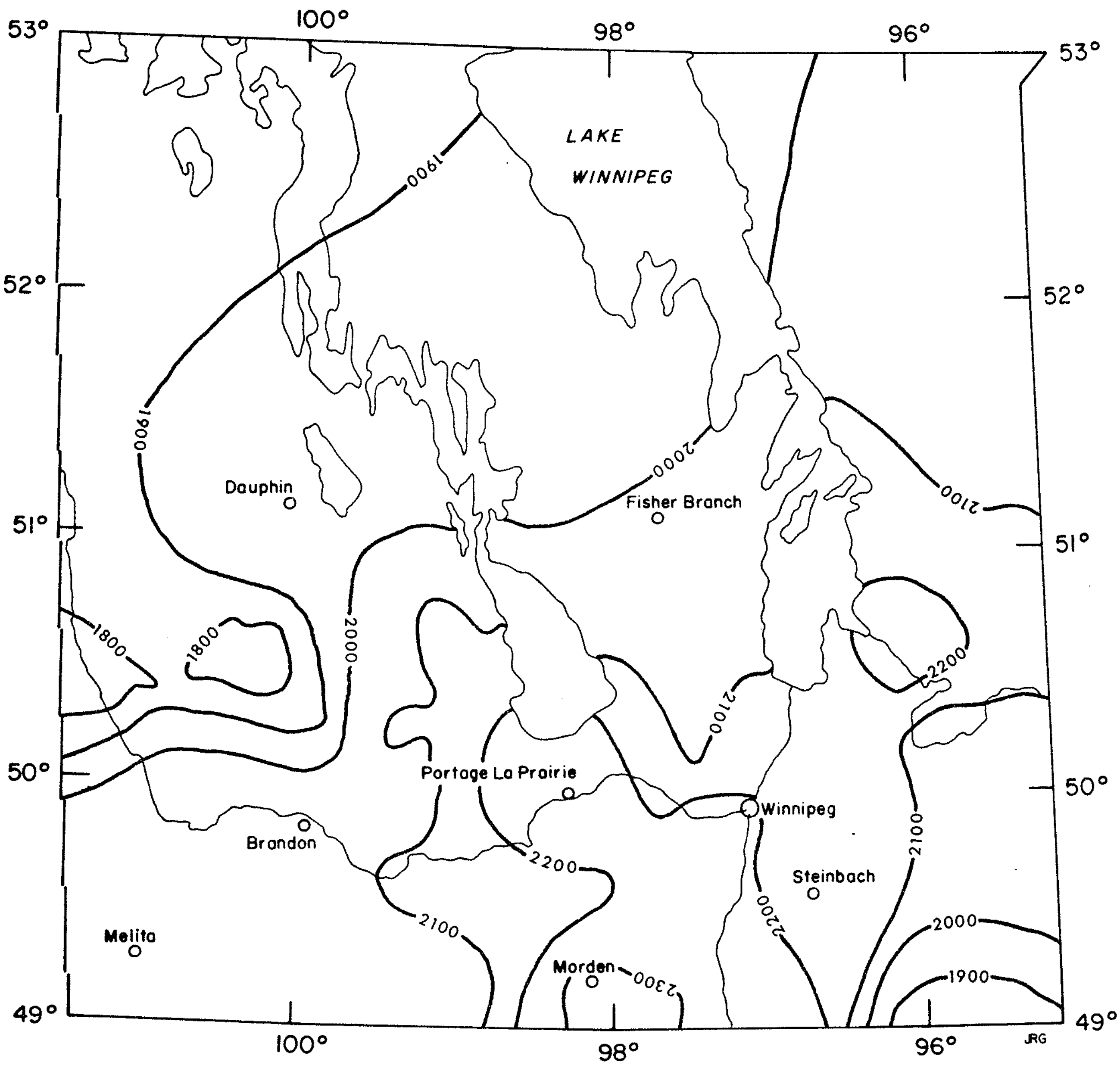
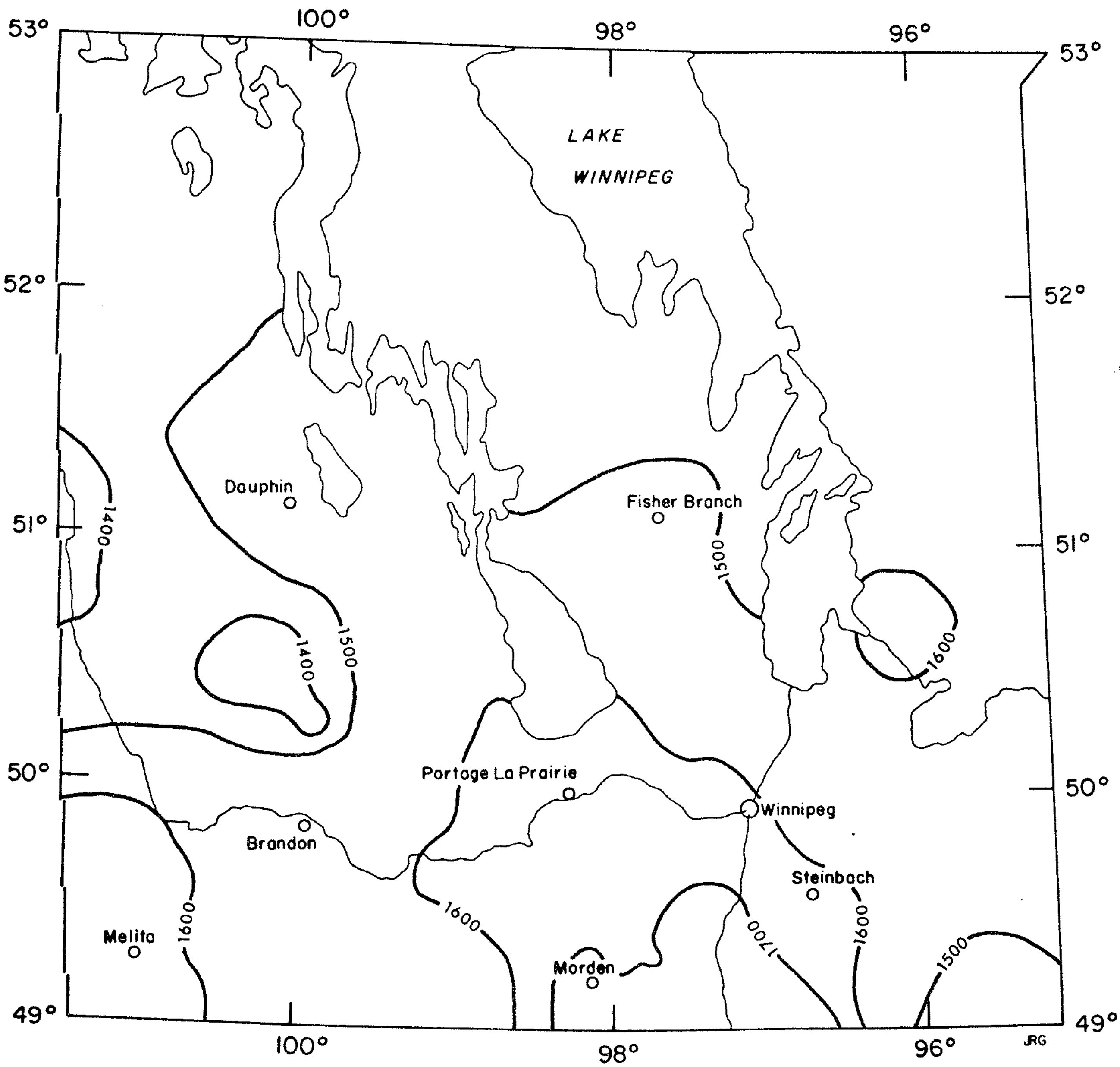


Figure 12: Average Accumulated Number of Growing Degree Days.



5.3 MOISTURE ANALYSIS

Examination of thermal conditions alone, within the province is insufficient to fully describe the suitability of an area for agricultural production. Consideration must also be given to the analysis of moisture conditions. As previously mentioned, soil moisture consumption represents a complex interaction between a variety of climatic and physical factors such as temperature, precipitation, humidity, wind, vapor pressure, the plant available water holding capacity of the soil, the specific type of crop and its stage of development. Soil moisture stress can greatly affect the yield and quality of the grains and/or crops grown. As previously established, there exists critical periods during the growth of each of the three crops under analysis in which moisture stress has its greatest influence.

As evidenced by examining the average values of soil moisture amounts at the specific stages of development for the different crops, there exists substantial variations in the amount of soil moisture throughout the agricultural area of Southern Manitoba. This is due to the spatial variability of precipitation as well as the distribution of different soil types/textures. In all cases areas in the south west corner of the province show high soil moisture deficits. The driest areas are those immediately surrounding Souris, Brandon and Carberry.

In the case of wheat, the average readily available soil moisture amounts at the heading stage for the province, excluding the dry southwest corner is between 25 - 50 mm. The south west area averages 0 - 25 mm of soil moisture. This indicates that on the average most of the province does not suffer too greatly from moisture stress at this stage of wheat development. The exceptions being those areas in the southwest corner of the province in the region surrounding Carberry, Cypress River, Ninette, Souris and Brandon (Figure 13). The spatial pattern is essentially the same for all three levels of probability. The only difference is the magnitude of the deficits that can be expected to occur.

At the soft dough stage, the deficits are larger than at the previous stage, since soil moisture deficits are accumulated through out the growth of the plant (Figure 14). The area suffering from damaging moisture stress evident in the previous stage of development has expanded. Soil moisture deficits are in the order of 25 to 50 mm. Again the only difference between the various maps are the magnitudes of the values. Since these two stages of development are the most critical with respect to final yield, careful assessments are needed of the moisture constraints on commercial crop production. To maintain adequate moisture for successful crop growth, additional water is needed to insure high yields. Assessment of irrigation systems are needed since naturally occurring precipiation is not sufficient to offset the heavy water consumption by actively growing plants

Soil moisture amounts at the silking stage of an actively growing corn crop reflect the same spatial pattern as those under a wheat crop. The magnitude of the deficits are similar to those experienced at the heading stage of wheat. The provincial average is 25.0 mm with the south west section averaging a larger amount than the rest of the province at 10.0 mm (Figure 15). As is the case with wheat, at the onset of the most sensitive stage to moisture stress in corn development, soil

Figure 13: Average Soil Moisture Amounts at Heading in Wheat.

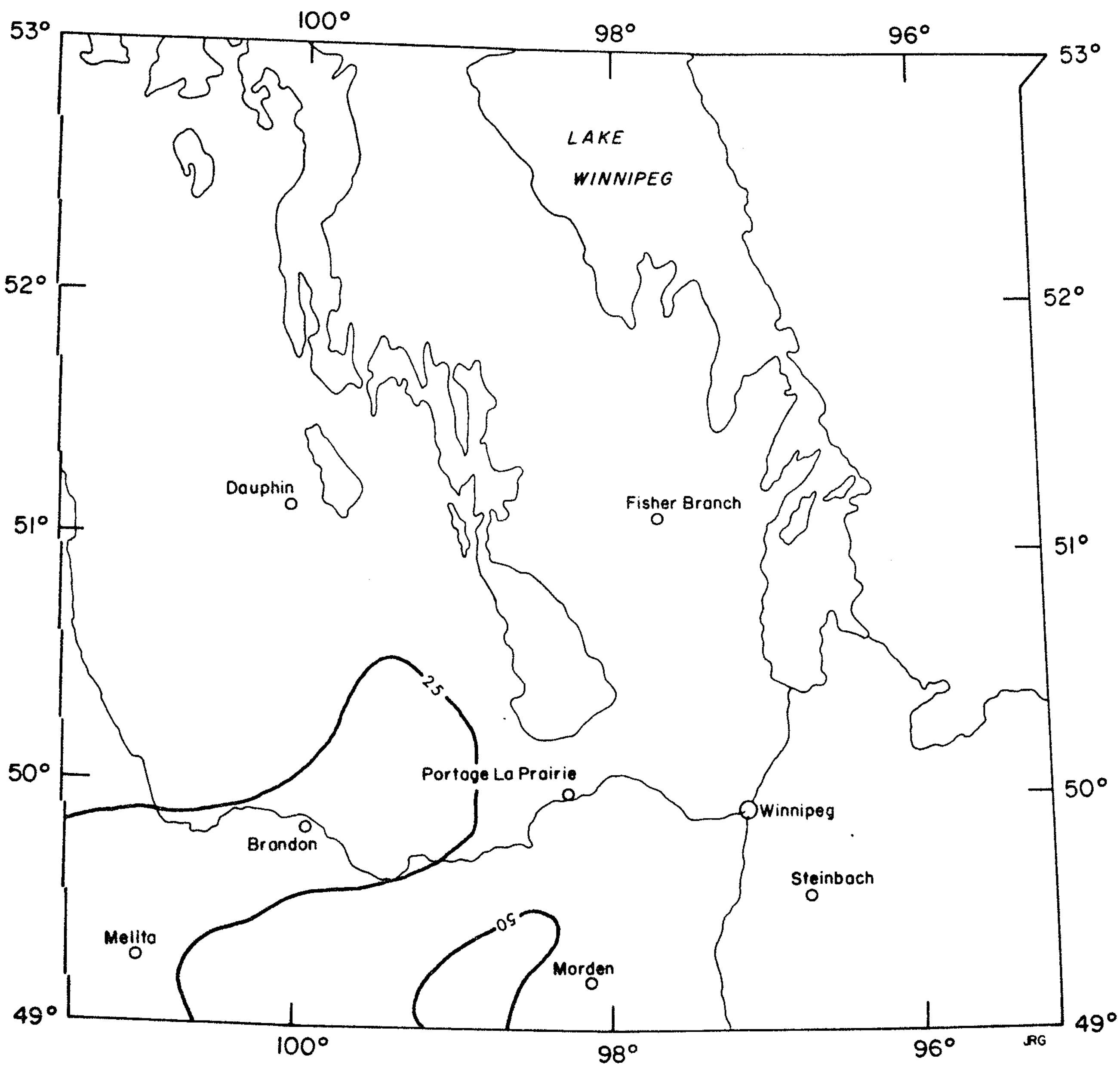
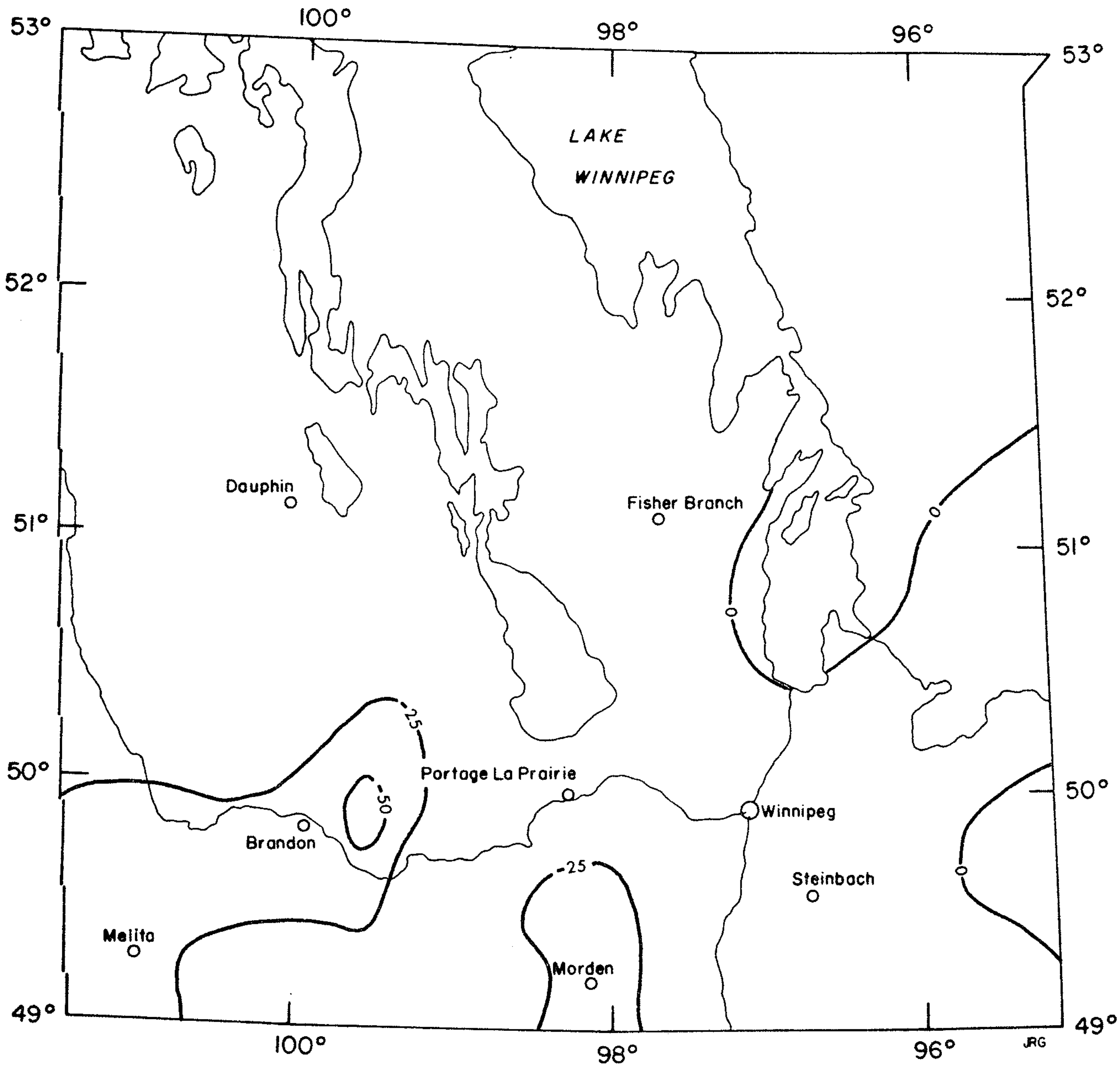


Figure 14: Average Soil Moisture Amounts at the Soft Dough Stage in Wheat.



moisture levels provincially are only adequate to maintain average yields. The southwest section is again limited with respect to its moisture suitability for commercial corn production. Corn not only has a higher heat requirement than cereals but also a higher moisture requirement, thus successful corn production is limited in its spatial distribution through the province.

Soil moisture analyses under a forage crop are again spatially similar. However the magnitudinal differences are substantial since a forage crop has essentially complete ground cover during the entire growing season and therefore consumes more water than the annual grains such as wheat and corn (Figure 16 and Figure 17).

Forage crops are the heaviest users of moisture through out the entire growing season. Since water consumption occurs at the potential rate through the entire growing season, adequate moisture through out this entire period is essential for successful growth. In many areas the harvesting of two crops of alfalfa would appear to be useless unless additional moisture can be supplied to the crop.

In analysing soil moisture conditions under the three different crops it was shown that the south west portion of the province is the area most subject to severe moisture deficits at the critical stages of plant development. The low water holding capacity of the soils in combination with the high variability of summer precipitation renders this area a high risk region with respect to damaging water stress on crop growth and yield.

Figure 15: Average Soil Moisture Amounts at Silking in Corn.

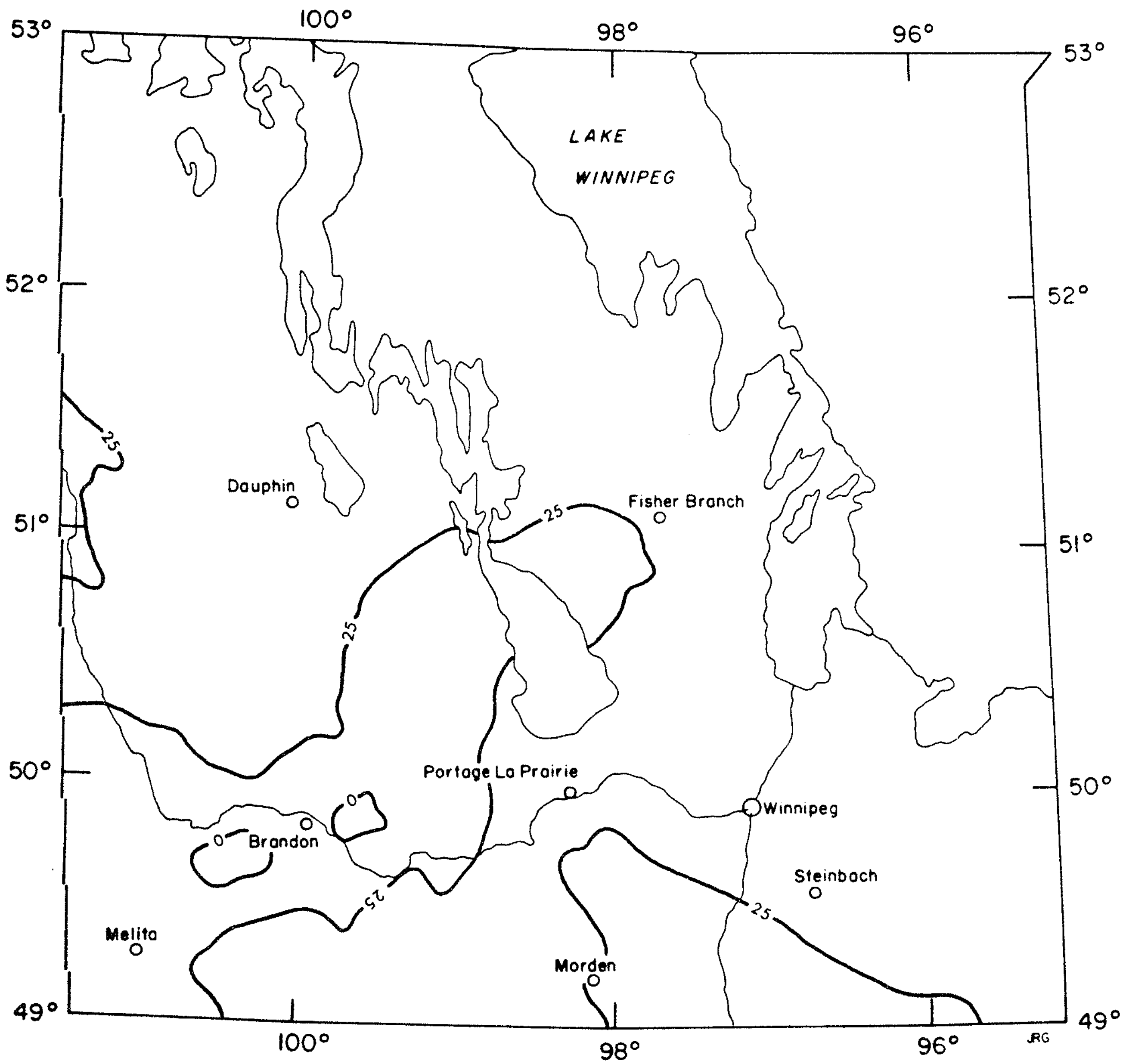


Figure 16: Average Soil Moisture Amounts after the First Crop of Alfalfa.

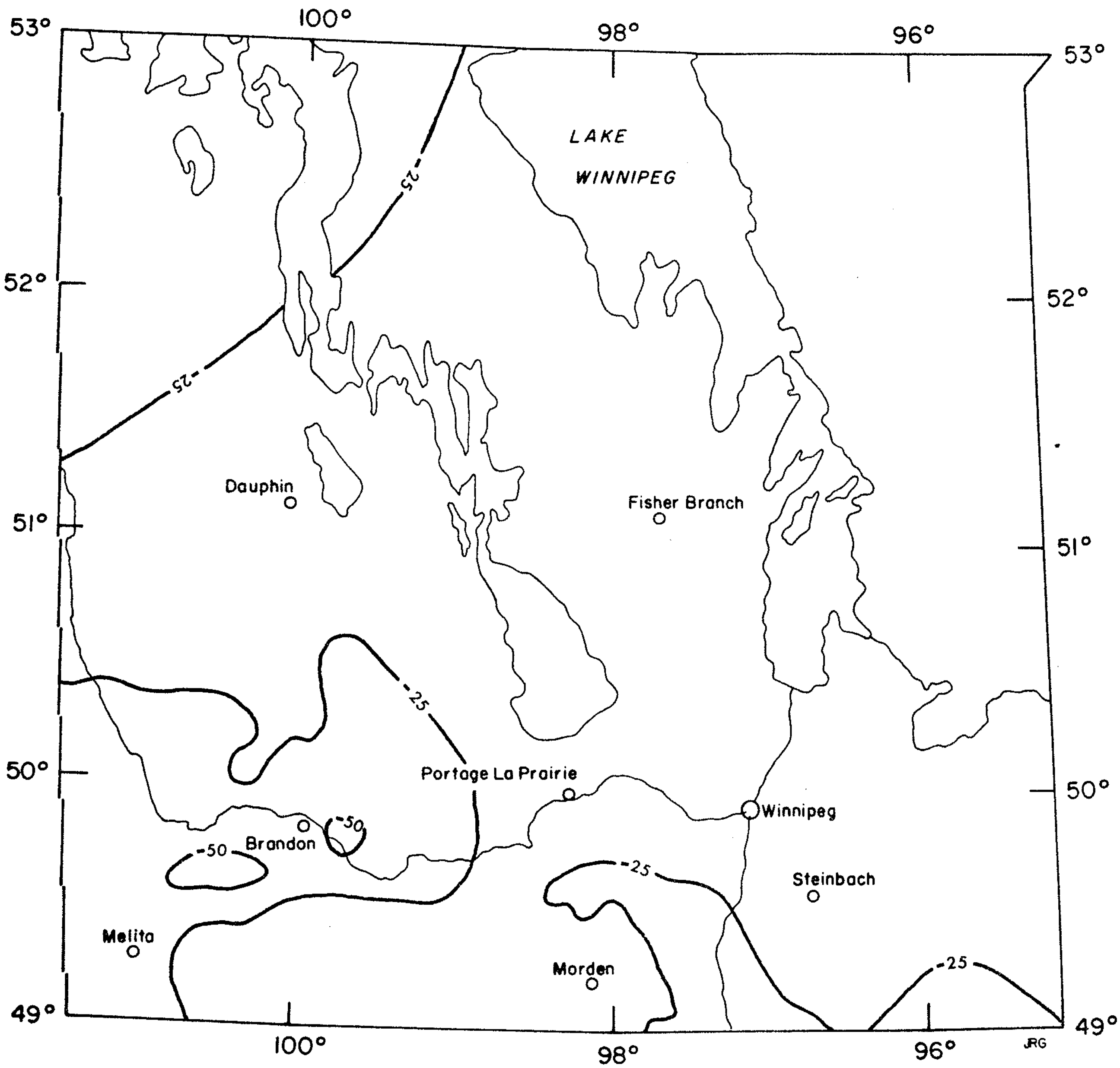
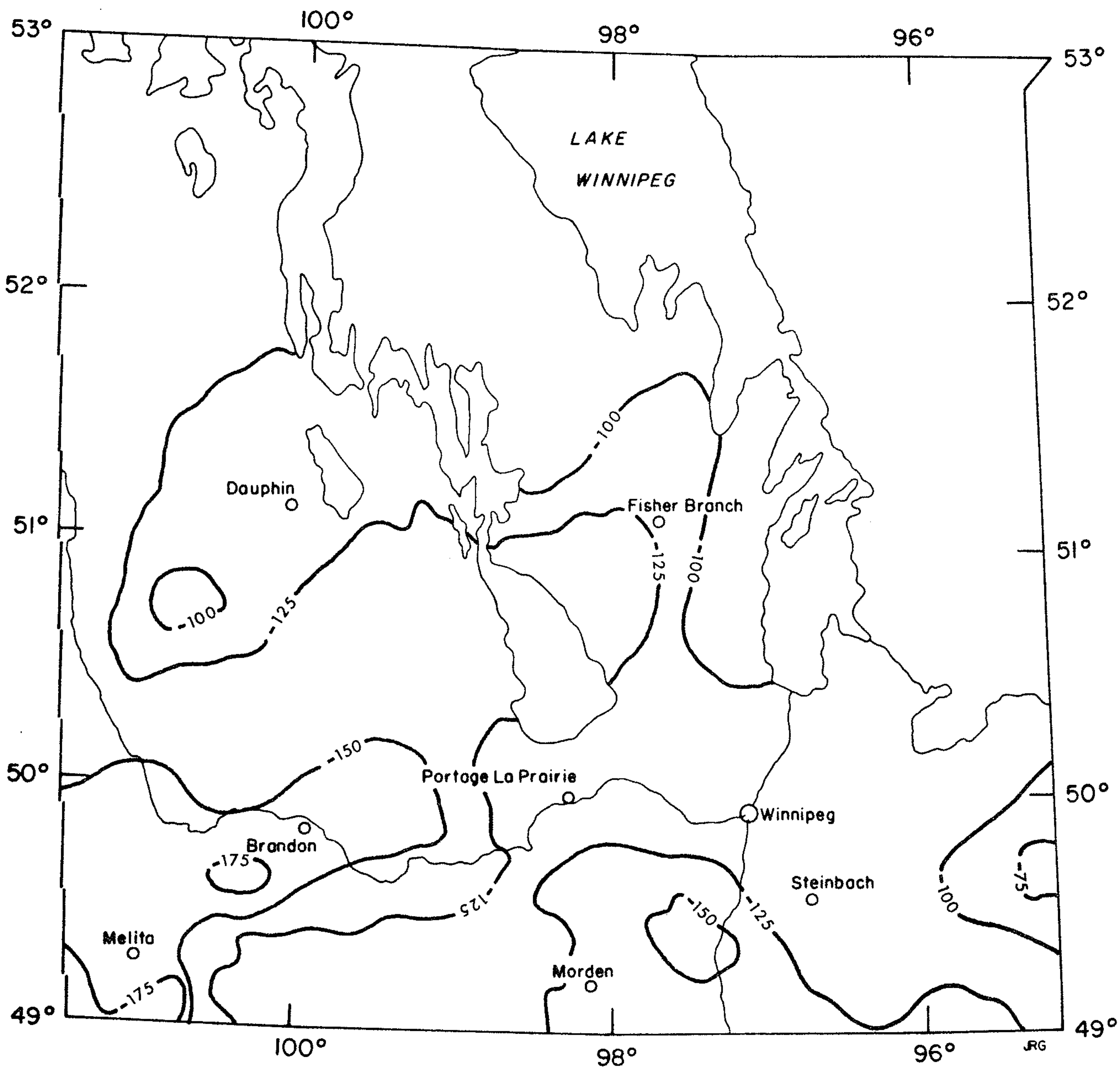


Figure 17: Average Soil Moisture Amounts after the Second Crop of Alfalfa.



Chapter VI

SUMMARY AND CONCLUSIONS

This chapter represents the last major section within this thesis. It includes a brief summary of the research undertaken, its major findings and suggestions for future research needed within the field of agricultural climatology.

6.1 SUMMARY

As a preliminary step in quantitatively determining the climatic resources and/or potentials of Southern Manitoba with respect to agricultural production two research objectives were formulated. The first was the derivation of a data base sufficient to describe the climate of the study area with respect to it´s suitability for agricultural crop production. This involved the transformation of raw climatic data into meaningful agroclimatic parameters so as to provide input into agricultural planning. The second objective was the analysis of this data base so as to provide a statistical perspective as to the climatic risks and/or advantages of specific regions within the province with respect to specific crop production. The increasing importance of agricultural production in today´s society and the highly unstable nature of the climate of this area renders a study of this nature of considerable practical significance.

The climatic data base utilized in this study included records of daily maximum and minimum temperatures and daily precipitation amounts recorded at meteorological stations located within the fourteen crop reporting districts. The agroclimatic data base derived focused solely on thermal and moisture considerations. The parameters focused on three essential climatic features: i) the occurrence of frosts in the spring and fall, and the subsequent frost free periods, ii) values of heat accumulated during the growing season; and iii) the analysis of soil moisture conditions under three different crops.

The derived agroclimatic data base was then subjected to probability analysis in order to provide some measure of the risks and advantages associated with certain areas. For all parameters derived mean values were calculated as well as the 25% and 10% risks values associated with each. These probability values indicate the probability of occurrence of the parameter in question in 1 out of 2 years, 1 out of 4 years and 1 out of 10 years, respectively. In the case of the 25% and the 10% risks these indicate the extreme negative conditions that can be expected to occur with the above mentioned frequencies.

Based on the analyses carried out in this research, the Red River Valley is the area most climatically suitable for a wide variety of crops, with respect to both temperature and moisture conditons. This region has the last spring frost occurring earlier in the year and the fall frost occurring later, resulting in the longest frost free period. Accumulated heat as expressed by the calculation of corn heat units and growing degree days indicates that as well as having a sufficiently long period of time favorable for successful crop growth, this area receives sufficient heat for successful plant growth. It was also shown that this area has a readily available soil moisture amount sufficient for good crop growth and yield, but not too large so as to cause damage to the growth and yield through water stress. The area around Russell and Birtle in the northwest region of the study area have a much lower potential for crop production. It is hampered by a relatively shorter frost free period as well as by high soil moisture deficits at critical stages in the development of various crops. The south western area of the province in general has sufficient growing season length and heat to mature a wide variety of crops but is hampered by the occurrence of high soil moisture deficits. The south eastern section on the other hand has sufficient moisture but lacks an adequate frost free period as well as intensity of heat during the growing season.

The above indicates the general suitability of the various regions of Manitoba to agriculture. To fully assess the climatic suitability of a specific area for crop production, the area must be evaluated based on the specific thermal and moisture requirements of the crop in question.

6.2 DIRECTIONS FOR FUTURE RESEARCH

The broad field of agricultural climatology/meteorology requires continual, ongoing research. Almost every field in agroclimatology offers many directions for future work. Systematic analyses into the relationships between crop growth and yield and selected climatic variables are needed as more and better climatic and agronomic data become available. Regional climatic studies are constantly needed, since the fluctuating nature of the atmosphere necessitates current re-evaluations of the climatic resources of an area. The research undertaken in this thesis represents the first step towards a complete assessment of the climatic suitability of Southern Manitoba for agricultural crop production. The results provide the climatic basis for the assessment which must be extended to study the effect of the magnitudinal values of these agroclimatic parameters on crop growth, development and yield.

The research undertaken in this study could be extended to assess the affect on yield caused by the various agroclimatic parameters studied. This is especially needed in the study of the influence of moisture stress on crop yields and development. Another area suggested by this research is the use of climatic data to determine the climatic limitations of areas suitable for crop cultivation. Emphasis on increasing crop production is pushing agriculture on to lands which are considered marginal with respect to their climatic suitability for grain production. Agroclimatic studies of these areas are necessary to determine the crop types and varieties which are economically feasible with respect to their production in these areas.

As stated by Smith (1975),

> It is sufficient to say at present that agroclimatology or the application of meteorological knowledge to questions of future strategic action present the greatest challenge to the applied scientist. (Smith, 1975:13).

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Appendix A

METEOROLOGICAL STATIONS UTILIZED.

Table 1: Meteorological Stations: Latitude, Longitude, Elevation and Years of Recording.

STATION NAME	NUMBER	YEARS	LAT.	LONG.	ELEV.(ft)
Altona	5020040	1949-1978	49,06	97,33	813
Baldur	5010140	1963-1978	49,19	99,20	1400
Beausejour	5030155	1960-1978	50,04	96,13	900
Bede	5010180	1957-1977	49,22	100,56	1450
Birtle	5010240	1934-1978	50,26	101,01	1707
Bissett	5030280	1934-1951	50,58	95,38	846
	5030282	1969-1978	51,02	95,40	846
Boissevain	5020320	1929-1978	49,13	100,05	1725
Brandon A	5010480	1955-1978	49,55	99,57	1337
Brandon CDA	5010485	1929-1972	49,52	99,58	1200
Camp Shilo	5010540	1955-1966			
	5012672	1967-1970	49,49	99,39	1253
Carberry	5010548	1963-1978	49,52	99,21	1263
Cypress River	5010640	1929-1978	49,33	99,05	1230
Dauphin	5040675	1929-1941	51,06	100,03	999
	5040680	1942-1978	51,09	100,02	957
Deerwood	5020720	1952-1972	49,24	98,19	1110
Deloraine	5010760	1966-1978			
	5010761	1955-1972	49,10	100,24	1750
Dugald	5020810	1963-1978	49,53	96,39	800
Emerson	5020880	1929-1978	49,00	97,12	792
Gimli A	5031038	1972-1976	50,37	96,59	730
	5031040	1944-1971	50,38	97,03	725
Grass River	5041140	1959-1978	50,31	98,58	885
Graysville	5021160	1929-1978	49,31	98,11	930
Great Falls	5031200	1929-1972	50,28	96,00	816
Hamiota	5011240	1931-1978	50,11	100,37	1700
Indian Bay	5031320	1929-1972	49,37	95,12	1072
Melita	5011720	1937-1959	49,20	101,00	1450
Minnedosa	5011760	1929-1978	50,16	99,50	1700
Moosehorn	5041800	1931-1965	51,18	98,37	820
Morden	5021848	1929-1978	49,11	98,05	992
Morris	5021920	1929-1978	49,21	97,22	778

Table 1 continued:

Neepawa	5042000	1946-1961			
	5042003	1963-1968			
	5042005	1970-1978	50,14	99,28	1273
Ninette	5022040	1929-1972	49,24	99,38	1367
Pierson	5012080	1933-1978	49,11	101,15	1538
Pilot Mound	5022120	1943-1956	49,12	98,53	1557
	5022125	1958-1978	49,12	98,54	1557
Pinawa	5032160	1929-1950	50,13	95,55	850
	5032162	1964-1978	50,11	96,03	875
P. la Prairie	5012280	1946-1970	49,58	98,18	857
P. la Prairie(2)	5012320	1953-1978	49,54	98,16	867
Reston	5012400	1953-1972	49,33	101,06	1521
Rivers A	5012440	1939-1970	50,01	100,19	1553
Roland	5022480	1952-1978	49,25	98,00	875
Rossburn	5012500	1957-1978	50,40	100,48	1936
Russell	5012520	1929-1978	50,47	101,17	1850
Selkirk	5022630	1964-1978	50,09	96,53	739
Seven Sisters	5032640	1951-1969	50,07	96,01	875
Souris	5012720	1929-1969	49,37	100,16	1400
Sprague	5022760	1929-1978	49,02	95,38	1072
Steinbach	5022780	1956-1977	49,32	96,41	880
Stonewall	5022788	1960-1978	50,07	97,20	825
Strathclair	5012796	1963-1978	50,24	100,24	1905
Swan River	5042800	1929-1978	52,07	101,16	1115
Virden	5012960	1929-1978	49,51	100,56	1451
Waskada	5013120	1929-1978	49,02	100,45	1540
Winnipeg	5023160	1938-1960			
	5023222	1961-1978	49,54	97,14	786

Table 2: Meteorological Stations: Crop District Assignment and Available-Water Holding Capacity of the Soils.

STATION NAME	STATION NUMBER	CROP REPORTING DISTRICT	AVAILABLE WATER HOLDING CAPACITY OF SOIL (MM)
Altona	5020040	5	100
Baldur	5010140	2	110
Beausejour	5030155	5	100
Bede	5010180	1	80
Birtle	5010240	10	100
Bissett	5030280	6	100
	5030282	6	100
Boissevain	5020320	1	110
Brandon A	5010480	8	100
Brandon CDA	5010485	8	100
Camp Shilo	5010540	8	80
	5012672	8	80
Carberry	5010548	8	80
Cypress River	5010640	8	100
Dauphin	5040675	11	110
	5040680	11	110
Deerwood	5020720	2	110
Deloraine	5010760	1	110
	5010761	1	110
Dugald	5020810	5	100
Emerson	5020880	5	100
Gimli A	5031038	12	100
	5031040	12	100
Grass River	5041140	9	110
Graysville	5021160	3	100
Great Falls	5031200	6	100
Hamiota	5011240	10	110
Indian Bay	5031320	6	100
Melita	5011720	1	100
Minnedosa	5011760	9	110
Moosehorn	5041800	12	100
Morden	5021848	3	100
Morris	5021920	5	100

Table 2 continued:

Neepawa	5042000	9	80
	5042003	9	80
	5042005	9	80
Ninette	5022040	2	100
Pierson	5012080	1	100
Pilot Mound	5022120	2	110
	5022125	2	110
Pinawa	5032160	6	100
	5032162	6	100
P. la Prairie	5012280	3	100
P. la Prairie (2)	5012320	3	100
Reston	5012400	7	100
Rivers A	5012440	10	100
Roland	5022480	3	100
Rossburn	5012500	10	110
Russell	5012520	10	110
Selkirk	5022630	5	100
Seven Sisters	5032640	6	100
Souris	5012720	7	80
Sprague	5022760	6	100
Steinbach	5022780	5	100
Stonewall	5022788	5	100
Strathclair	5012796	10	110
Swan River	5042800	13	100
Virden	5012960	7	100
Waskada	5013120	1	100
Winnipeg	5023160	5	100
	5023222	5	100

Appendix B

PROBABILITY ANALYSIS.

As stated in the thesis, before probability analysis can be applied to the agroclimatic parameters, one must determine whether the data follows a normal distribution. The object of this is to determine whether the normal distribution curve can be fit to the data so as to give the probability of occurrence of the parameters in a continuous distribution. The use of the normal curve represents a condition in which all occurrences are known. The area under the curve is 1, that is, it contains 100% of all cases. Under this curve, 68.27% of all cases can be expected to occur within one standard deviation of the mean, 95.45% within two standard deviations and 99.73% of all cases can be expected to occur wihtin three standard deviations of the mean.

A simplistic approach to test for normality of the data is to draw the frequency distributions of the parameters. If the resulting histogram resembles the normal bell-shaped curve, normality of the data can be assumed. This was done for a number of stations representing the different water-holding capacities of the various soils within the province. These subjective results tended to support the hypothesis that the data are normally distributed.

To objectively test the hypothesis of normality, the distribution of the data was tested against the theoretical normal distribution using the chi-square test (X**2) for normality. The e values were determined as a percentage of the observations expected in each interval. If there were n observations, then the theoretical number of observations expected to occur within one standard on each side of the mean would be (n*.6827)/2. These e values were calculated for the following intervals: (-i,-3s), (-3s,-2s), (-2s,-s), (-s,x), (x,s), (s,2s), (2s,3s), (3s,+i).

i=infinity, s=standard deviation, x=mean.

The calcualted X**2 value is then computed and tested against the X**2 value in a chi-square table at the .05 significance level. The chi-square test for normality was employed to test for normality for three stations used in this research. The stations used were Morden (5021848), Souris (5012720), and Sprague (5022760). The results obtained are illustrated in Table 3. These results tend to confirm the initial research hypothesis that the agroclimatic parameters derived follow a normal distribution function.

Table 3: Results of the Chi-Square Test for Normality

Morden (5021848) n = 50

e	.0675	1.07	6.795	17.0675	17.0675	6.795	1.07	.0675	X^2
f(1)*	0	2	8	15	15	9	1	0	2.3781
f(2)	0	1	7	18	17	6	1	0	.2947
f(3)	0	1	6	16	21	6	0	0	2.3685
f(4)	0	1	8	15	18	7	1	0	.6655
f(5)	0	2	5	15	21	7	0	0	3.6503
f(6)	0	1	8	15	20	5	1	0	1.5865
f(7)	0	1	6	16	21	5	1	0	1.714

Souris (5012720) n = 40

e	.054	.856	5.436	13.654	13.654	5.436	.856	.054	X^2
f(1)*	0	2	4	12	18	4	0	0	4.8352
f(2)	0	1	7	12	13	7	0	0	2.1197
f(3)	0	0	8	10	15	5	1	0	3.4044
f(4)	0	0	6	14	13	5	1	0	1.1260
f(5)	0	1	4	15	13	7	0	0	1.9815
f(6)	0	0	6	14	13	9	1	0	3.4240
f(7)	0	0	8	15	13	6	1	0	2.4200

Sprague (5022760) n = 5

e	.0675	1.07	6.795	17.0675	17.0675	6.795	1.07	.0675	X^2
f(1)*	0	0	7	19	16	5	3	0	5.4522
f(2)	0	0	8	19	12	10	0	0	5.7238
f(3)	0	0	10	14	19	3	3	0	9.0875
f(4)	0	1	6	17	15	10	0	0	3.0651
f(5)	0	0	7	20	12	8	2	0	4.2417
f(6)	0	0	10	15	16	9	0	0	4.8195
f(7)	0	0	10	15	17	6	2	0	3.8688

Table 3 continued:

e - expected frequency of occurrence

f(1)* - observed frequency of occurrence at the heading stage.
f(2) - observed frequency at the soft dough stage.
f(3) - observed frequency after the first crop of alfalfa.
f(4) - observed frequency after the second crop of alfalfa.
f(5) - observed frequency at silking stage.
f(6) - observed frequency of growing degree days.
f(7) - observed frequency of corn heat units.

Appendix C

RESULTS OF THE ANALYSIS OF THE AGROCLIMATIC PARAMETERS.

Table 4: Last Spring Frost (0 C)

Station	Mean	Std.	25%	10%
Altona	139	13	148	156
Baldur	145	13	154	162
Beausejour	140	12	148	156
Bede	143	12	151	159
Birtle	148	13	157	165
Bissett	144	11	152	159
Boissevain	143	13	152	160
Brandon A.	150	14	160	168
Brandon CDA.	152	11	159	166
Camp Shilo	147	11	155	162
Carberry	144	13	153	161
Cypress River	146	12	154	162
Dauphin	149	12	157	165
Deerwood	143	10	150	156
Deloraine	148	10	155	161
Emerson	143	12	151	159
Eriksdale	148	17	160	171
Gimli	143	10	150	156
Grass River	145	12	153	161
Graysville	144	11	151	158
Great Falls	141	10	148	154
Hamiota	146	13	155	163
Indian Bay	148	12	156	164
Melita	152	12	160	168
Minnedosa	155	10	162	168
Moosehorn	157	12	165	173
Morden	142	11	149	156
Morris	143	12	151	159
Neepawa	141	12	149	157
Ninette	150	11	157	164
Pierson	145	13	154	162
Pilot Mound	140	11	148	154
Pinawa	150	11	158	164
Portage la Prairie (1)	138	9	144	150
Portage la Prairie (2)	139	11	147	153
Reston	143	12	151	159
Rivers A.	145	10	152	158
Roland	141	12	149	157
Rossburn	145	12	153	161
Russell	150	12	158	166
Selkirk	143	13	152	160
Seven-Sisters	143	12	151	159
Souris	150	12	158	166
Sprague	155	12	163	171
Steinbach	145	14	155	164
Stonewall	144	12	152	160
Strathclair	145	13	154	162
Swan River	148	11	155	162
Virden	142	11	149	156
Waskada	148	13	157	165
Winnipeg A.	146	13	155	163

Table 5: Last Spring Frost (-2.2C)

Station	Mean	Std.	25%	10%
Altona	127	12	135	143
Baldur	131	11	139	146
Beausejour	131	12	139	147
Bede	128	12	136	144
Birtle	139	14	149	157
Bissett	131	11	139	146
Boissevain	130	11	137	144
Brandon A.	133	13	142	150
Brandon CDA.	140	11	147	154
Camp Shilo	134	11	142	149
Carberry	131	10	138	144
Cypress River	133	13	142	150
Dauphin	138	12	146	154
Deerwood	135	10	142	148
Deloraine	136	11	144	151
Emerson	132	12	140	148
Eriksdale	137	12	145	153
Gimli	131	11	139	145
Grass River	136	13	145	153
Graysville	131	9	137	143
Great Falls	128	12	136	144
Hamiota	136	13	145	153
Indian Bay	137	10	144	150
Melita	138	11	146	153
Minnedosa	140	11	147	154
Moosehorn	143	10	150	156
Morden	130	11	137	144
Morris	133	11	140	147
Neepawa	130	11	138	144
Ninette	137	11	144	151
Pierson	130	13	139	147
Pilot Mound	131	11	139	145
Pinawa	137	10	144	150
Portage la Prairie (1)	128	9	134	140
Portage la Prairie (2)	129	11	137	143
Reston	134	13	143	151
Rivers A.	133	9	139	145
Roland	130	9	136	142
Rossburn	132	12	140	148
Russell	139	14	149	157
Selkirk	130	12	138	146
Seven-Sisters	131	9	137	143
Souris	139	12	147	155
Sprague	142	12	150	158
Steinbach	133	11	141	148
Stonewall	132	10	137	145
Strathclair	136	13	145	153
Swan River	135	13	144	152
Virden	130	10	137	143
Waskada	134	10	141	147
Winnipeg A.	132	11	139	146

Table 6: First Fall Frost (0 C)

Station	Mean	Std.	25%	10%
Altona	262	9	256	250
Baldur	259	10	252	246
Beausejour	266	9	260	254
Bede	257	12	249	241
Birtle	247	19	234	222
Bissett	258	19	245	233
Boissevain	262	12	254	246
Brandon A.	254	9	248	242
Brandon CDA.	255	12	247	239
Camp Shilo	259	11	251	244
Carberry	261	11	253	246
Cypress River	260	9	254	248
Dauphin	260	12	252	244
Deerwood	268	11	260	253
Deloraine	257	22	242	228
Emerson	260	11	253	246
Eriksdale	252	10	245	239
Gimli	266	9	260	254
Grass River	256	10	249	243
Graysville	260	9	254	248
Great Falls	270	11	263	256
Hamiota	254	14	244	236
Indian Bay	259	11	252	245
Melita	255	7	250	246
Minnedosa	250	14	240	232
Moosehorn	253	12	245	237
Morden	265	8	260	255
Morris	263	9	257	251
Neepawa	264	8	259	254
Ninette	256	11	249	242
Pierson	255	12	247	239
Pilot Mound	260	10	253	247
Pinawa	258	18	246	234
Portage la Prairie (1)	269	14	259	251
Portage la Prairie (2)	267	10	260	254
Reston	259	10	252	246
Rivers A.	259	10	252	246
Roland	261	9	255	249
Rossburn	258	10	251	245
Russell	253	14	243	235
Selkirk	266	7	261	257
Seven-Sisters	263	11	255	248
Souris	256	10	249	243
Sprague	242	20	228	216
Steinbach	260	8	255	249
Stonewall	265	8	259	254
Strathclair	243	31	222	201
Swan River	255	16	244	234
Virden	260	9	254	248
Waskada	251	15	241	231
Winnipeg A.	264	9	258	252

Table 7: First Fall Frost (-2.2C)

Station	Mean	Std.	25%	10%
Altona	277	13	268	260
Baldur	272	12	264	256
Beausejour	279	15	269	259
Bede	266	10	259	253
Birtle	261	15	251	241
Bissett	276	10	269	263
Boissevain	273	12	265	257
Brandon A.	265	10	258	252
Brandon CDA.	263	8	258	253
Camp Shilo	270	15	260	250
Carberry	271	13	262	254
Cypress River	268	10	261	255
Dauphin	271	11	264	257
Deerwood	275	14	265	256
Deloraine	270	14	260	251
Emerson	271	11	264	257
Eriksdale	266	11	258	251
Gimli	276	11	268	262
Grass River	269	11	261	254
Graysville	270	10	263	257
Great Falls	282	11	275	268
Hamiota	265	11	258	251
Indian Bay	272	10	265	259
Melita	263	9	257	251
Minnedosa	262	8	257	252
Moosehorn	267	13	258	250
Morden	277	13	268	260
Morris	272	11	265	258
Neepawa	274	13	263	257
Ninette	269	12	261	253
Pierson	263	13	254	246
Pilot Mound	270	11	262	256
Pinawa	273	10	266	260
Portage la Prairie (1)	282	11	274	268
Portage la Prairie (2)	277	13	268	260
Reston	265	9	259	253
Rivers A.	270	11	262	256
Roland	273	13	264	256
Rossburn	266	14	256	247
Russell	262	11	255	248
Selkirk	279	12	271	263
Seven-Sisters	280	13	271	263
Souris	265	11	258	251
Sprague	258	11	251	244
Steinbach	274	14	264	255
Stonewall	271	12	263	255
Strathclair	266	12	258	250
Swan River	266	12	258	250
Virden	268	12	260	252
Waskada	265	12	257	249
Winnipeg A.	273	12	265	257

Table 8: Frost-Free Period (0 C)

Station	Mean	Std.	25%	10%
Altona	123	18	111	99
Baldur	114	17	102	91
Beausejour	126	15	116	106
Bede	114	16	103	93
Birtle	99	21	85	72
Bissett	114	26	96	80
Boissevain	119	19	106	94
Brandon A.	105	18	93	81
Brandon CDA.	103	18	91	80
Camp Shilo	112	13	103	95
Carberry	117	15	107	97
Cypress River	114	16	103	93
Dauphin	112	19	99	87
Deerwood	125	15	115	105
Deloraine	109	25	92	76
Emerson	116	20	102	90
Eriksdale	104	18	92	80
Gimli	123	14	113	105
Grass River	111	17	99	88
Graysville	116	15	106	97
Great Falls	128	15	118	108
Hamiota	108	20	94	82
Indian Bay	111	17	99	89
Melita	103	15	93	83
Minnedosa	95	18	83	72
Moosehorn	96	16	85	75
Morden	123	14	113	105
Morris	120	16	109	99
Neepawa	123	15	113	103
Ninette	106	16	95	85
Pierson	110	18	98	87
Pilot Mound	120	14	110	102
Pinawa	107	24	91	76
Portage la Prairie (1)	130	17	118	108
Portage la Prairie (2)	120	16	117	107
Reston	116	13	107	99
Rivers A.	115	15	105	95
Roland	120	15	110	100
Rossburn	113	14	103	94
Russell	102	19	89	77
Selkirk	124	15	114	104
Seven-Sisters	121	17	109	98
Souris	106	17	94	84
Sprague	88	25	71	56
Steinbach	115	17	103	93
Stonewall	121	15	111	101
Strathclair	98	33	75	54
Swan River	107	19	94	82
Virden	118	13	109	101
Waskada	103	19	90	78
Winnipeg A.	118	17	106	96

Table 9: Frost-Free Period (-2.2 C)

Station	Mean	Std.	25%	10%
Altona	150	19	137	125
Baldur	141	18	129	117
Beausejour	147	21	133	119
Bede	139	17	127	116
Birtle	122	20	108	96
Bissett	145	13	136	128
Boissevain	143	16	132	122
Brandon A.	133	15	123	113
Brandon CDA.	123	12	115	107
Camp Shilo	136	21	121	108
Carberry	140	14	130	121
Cypress River	136	16	125	115
Dauphin	133	16	122	112
Deerwood	141	16	130	120
Deloraine	134	17	122	111
Emerson	139	18	127	116
Eriksdale	129	20	115	102
Gimli	145	16	134	124
Grass River	133	13	124	116
Graysville	139	15	129	120
Great Falls	154	18	142	131
Hamiota	129	17	117	107
Indian Bay	135	12	127	119
Melita	125	16	114	104
Minnedosa	122	14	112	104
Moosehorn	124	20	110	98
Morden	147	19	134	122
Morris	139	17	127	117
Neepawa	144	19	131	119
Ninette	132	17	120	110
Pierson	133	17	121	111
Pilot Mound	140	18	128	116
Pinawa	136	16	125	115
Portage la Prairie (1)	153	14	143	135
Portage la Prairie (2)	148	19	135	123
Reston	131	15	121	111
Rivers A.	138	15	128	118
Roland	143	17	131	121
Rossburn	134	18	122	110
Russell	123	19	110	98
Selkirk	149	17	137	126
Seven-Sisters	149	16	138	128
Souris	126	15	116	106
Sprague	115	18	103	92
Steinbach	142	20	128	116
Stonewall	139	14	129	120
Strathclair	131	14	121	112
Swan River	131	18	119	108
Virden	138	16	127	117
Waskada	131	16	120	110
Winnipeg A.	140	12	132	124

Table 10: Corn Heat Units

Station	Mean	Std.	25%	10%
Altona	2594	219	2444.42	2306.89
Baldur	2369	215	2220.43	2080.69
Beausejour	2463	232	2303.38	2154.44
Bede	2378	180	2254.16	2138.96
Birtle	2094	275	1906.72	1736.23
Bissett	2433	243	2266.30	2111.51
Boissevain	2393	232	2235.24	2091.40
Brandon A.	2268	180	2144.70	2030.58
Brandon CDA.	2285	174	2166.51	2058.45
Camp Shilo	2440	255	2263.79	2098.05
Carberry	2364	225	2208.52	2062.28
Cypress River	2397	202	2259.64	2134.60
Dauphin	2314	259	2137.88	1977.56
Deerwood	2525	263	2344.06	2175.21
Deloraine	2369	231	2209.84	2061.08
Emerson	2579	239	2416.48	2268.54
Eriksdale	2315	189	2184.78	2063.06
Gimli	2360	209	2217.46	2086.84
Grass River	2330	172	2211.66	2101.58
Graysville	2434	193	2302.76	2183.29
Great Falls	2563	228	2407.73	2266.14
Hamiota	2255	196	2121.72	2000.20
Indian Bay	2359	224	2206.46	2067.35
Melita	2284	190	2153.66	2033.01
Minnedosa	2073	182	1949.24	1836.40
Moosehorn	2253	147	2084.30	1929.68
Morden	2627	214	2481.48	2349.01
Morris	2593	262	2414.84	2252.66
Neepawa	2373	217	2224.79	2088.73
Ninette	2391	220	2241.18	2104.56
Pierson	2295	233	2136.33	1991.63
Pilot Mound	2323	204	2183.67	2056.17
Pinawa	2330	201	2192.72	2067.09
Portage la Prairie (1)	2573	230	2415.45	2269.86
Portage la Prairie (2)	2517	219	2367.20	2228.80
Reston	2343	195	2208.84	2084.04
Rivers A.	2329	221	2178.06	2039.71
Roland	2501	217	2352.57	2215.43
Rossburn	2197	226	2041.96	1898.00
Russell	2074	201	1937.32	1812.90
Selkirk	2421	214	2272.91	2133.17
Seven-Sisters	2428	248	2257.38	2098.16
Souris	2328	186	2201.33	2085.83
Sprague	2147	215	2000.80	1867.72
Steinbach	2457	238	2293.73	2142.13
Stonewall	2397	226	2241.51	2096.42
Strathclair	2088	266	1904.19	1731.29
Swan River	2129	203	1990.76	1864.49
Virden	2372	212	2227.84	2096.61
Waskada	2340	233	2181.33	2036.40
Winnipeg A.	2483	208	2341.35	2211.98

Table 11: Growing Degree-Days

Station	Mean	Std.	25%	10%
Altona	1719	119	1637.72	1562.99
Baldur	1564	113	1485.92	1412.47
Beausejour	1589	112	1511.94	1440.04
Bede	1618	94	1553.33	1493.17
Birtle	1426	132	1336.11	1254.27
Bissett	1558	134	1466.08	1380.72
Boissevain	1566	143	1468.76	1380.10
Brandon A.	1536	104	1464.76	1398.82
Brandon CDA.	1577	123	1493.24	1416.85
Camp Shilo	1624	114	1545.23	1471.13
Carberry	1560	104	1488.14	1420.54
Cypress River	1619	133	1528.56	1446.23
Dauphin	1535	159	1426.88	1328.46
Deerwood	1661	119	1579.13	1502.73
Deloraine	1583	107	1509.28	1440.37
Emerson	1749	155	1643.60	1547.66
Eriksdale	1536	107	1462.28	1393.37
Gimli	1505	111	1429.30	1359.92
Grass River	1561	99	1492.89	1429.53
Graysville	1646	130	1557.60	1477.13
Great Falls	1632	130	1543.47	1462.74
Hamiota	1519	124	1434.68	1357.80
Indian Bay	1515	135	1423.06	1339.23
Melita	1582	139	1486.65	1398.38
Minnedosa	1397	131	1307.92	1226.70
Moosehorn	1471	140	1375.38	1287.74
Morden	1758	139	1663.48	1577.44
Morris	1740	188	1612.16	1495.79
Neepawa	1551	113	1473.82	1402.97
Ninette	1599	147	1498.89	1407.61
Pierson	1607	140	1511.66	1424.72
Pilot Mound	1531	117	1451.09	1377.96
Pinawa	1507	122	1423.67	1347.42
Portage la Prairie (1)	1676	121	1593.11	1516.52
Portage la Prairie (2)	1647	110	1571.76	1502.24
Reston	1609	113	1531.26	1458.94
Rivers A.	1533	123	1448.99	1371.99
Roland	1657	109	1582.44	1513.56
Rossburn	1454	122	1370.31	1292.59
Russell	1393	121	1310.72	1235.82
Selkirk	1581	132	1489.66	1403.46
Seven-Sisters	1549	119	1467.13	1390.73
Souris	1590	132	1500.11	1418.44
Sprague	1488	113	1411.16	1341.11
Steinbach	1611	112	1534.17	1462.82
Stonewall	1579	122	1495.06	1416.74
Strathclair	1366	132	1274.79	1188.99
Swan River	1431	112	1354.73	1285.06
Virden	1604	135	1512.20	1428.64
Waskada	1637	158	1529.40	1431.13
Winnipeg A.	1640	122	1556.92	1481.03

Table 12: Soil Moisture Amounts at Heading in Wheat

Station	Mean	Std.	25%	10%
Altona	28.29	34.92	4.44	-17.49
Baldur	39.49	38.88	12.62	-12.65
Beausejour CDA	35.51	29.23	15.40	-3.31
Beausejour	38.04	38.97	11.19	-13.91
Bede	-1.55	45.18	-32.63	-61.55
Birtle	29.70	37.26	4.33	-18.81
Bissett	40.13	22.45	24.71	10.38
Boissevain	48.81	29.29	28.86	10.65
Brandon A	17.94	38.73	-8.63	-33.30
Brandon CDA	27.28	42.82	-1.88	-28.47
Camp Shilo	-3.26	43.58	-33.42	-61.88
Carberry	3.43	33.45	-19.72	-41.56
Cypress River	29.83	41.07	1.90	-23.52
Dauphin	35.96	33.55	13.15	-7.65
Deerwood	54.79	38.82	28.04	3.04
Deloraine	36.12	44.68	5.20	-23.97
Emerson	26.27	41.33	-1.83	-27.42
Eriksdale	31.37	39.01	4.49	-20.63
Gimli	47.77	27.54	28.99	11.78
Grass River	30.25	40.51	2.38	-23.55
Graysville	25.51	41.98	-3.08	-29.15
Great Falls	44.02	28.96	24.27	6.20
Hamiota	30.70	32.85	8.36	-12.04
Indian Bay	49.81	32.17	27.90	7.89
Melita	29.69	30.36	8.86	-10.42
Minnedosa	40.11	34.20	16.79	-4.59
Moosehorn	40.91	32.53	18.59	-2.06
Morden	32.94	37.37	7.53	-15.06
Morris	27.56	36.01	3.00	-19.51
Neepawa	8.59	32.15	-13.37	-33.53
Ninette	31.36	41.40	3.17	-22.58
Pierson	15.13	40.53	-12.47	-37.68
Pilot Mound	57.50	39.09	-30.76	6.14
Pinawa	12.92	33.52	-9.97	-30.92
Portage la Prairie (1)	34.69	34.91	10.78	-11.32
Portage la Prairie (2)	36.00	35.84	11.49	-11.17
Rivers A	29.58	32.84	7.15	-13.41
Roland	33.95	36.70	8.85	-14.35
Rossburn	46.54	37.85	20.50	-3.80
Russell	37.03	34.48	13.58	-7.79
Seven-Sisters	38.32	36.57	13.12	-10.43
Souris	2.87	35.12	-21.05	-42.89
Sprague	31.76	44.57	1.45	-26.14
Steinbach	37.74	33.11	15.03	-6.06
Stonewall	36.11	38.39	9.66	-15.06
Swan River	26.91	30.56	6.07	-12.97
Virden	25.81	36.49	1.00	-21.59
Waskada	16.99	36.99	-8.24	-31.32
Winnipeg A	41.70	34.19	18.42	-2.85

Table 13: Soil Moisture Amounts at the Soft Dough Stage in Wheat

Station	Mean	Std.	25%	10%
Altona	-25.90	44.35	-56.19	-84.04
Baldur	-1.81	52.64	-38.18	-72.40
Beausejour CDA	-4.12	43.63	-34.14	-62.06
Beausejour	-3.13	46.04	-34.85	-64.50
Bede	-59.86	50.62	-94.69	-127.08
Birtle	-11.81	58.32	-51.53	-87.74
Bissett	-0.35	34.20	-23.85	-45.66
Boissevain	-3.33	42.93	-32.57	-59.27
Brandon A	-32.85	52.78	-69.06	-102.68
Brandon CDA	-30.83	53.31	-67.13	-100.24
Camp Shilo	-61.78	52.86	-98.36	-132.88
Carberry	-41.10	43.09	-70.92	-99.06
Cypress River	-24.46	49.08	-57.83	-88.21
Dauphin	-17.21	51.37	-52.14	-83.99
Deerwood	-11.22	50.58	-23.63	-56.20
Deloraine	-23.32	45.84	-55.04	-84.97
Emerson	-24.63	56.19	-62.84	-97.62
Eriksdale	-11.73	57.27	-51.19	-88.07
Gimli	6.93	33.92	-16.20	-37.40
Grass River	-20.98	57.96	-60.86	-97.95
Graysville	-32.11	48.84	-65.37	-95.70
Great Falls	-0.60	40.57	-28.27	-53.58
Hamiota	-21.37	50.41	-55.65	-86.95
Indian Bay	12.09	44.71	-18.36	-46.17
Melita	-30.00	45.53	-61.23	-90.15
Minnedosa	-11.75	50.46	-46.16	-77.70
Moosehorn	-18.80	37.25	-44.35	-68.01
Morden	-22.04	48.75	-55.19	-85.37
Morris	-32.34	44.25	-62.52	-90.17
Neepawa	-31.95	51.38	-67.04	-99.26
Ninette	-25.66	51.96	-61.04	-93.36
Pierson	-43.12	60.13	-84.07	-121.47
Pilot Mound	1.05	50.10	-33.22	-64.78
Pinawa	-50.96	43.86	-80.92	-108.33
Portage la Prairie (1)	-2.10	33.62	-25.13	-46.41
Portage la Prairie (2)	3.31	44.70	-27.26	-55.52
Rivers A	-7.85	52.58	-43.76	-76.68
Roland	-23.36	41.42	-51.69	-77.87
Rossburn	6.08	59.98	-35.19	-73.69
Russell	-20.23	52.52	-55.94	-88.51
Seven-Sisters	-7.22	44.63	-37.97	-66.71
Souris	-48.68	52.32	-84.31	-116.85
Sprague	-18.34	61.03	-59.84	-97.62
Steinbach	-12.81	40.59	-40.65	-66.51
Stonewall	-7.76	44.94	-38.72	-67.67
Swan River	-13.00	47.00	-45.05	-74.34
Virden	-28.32	52.61	-64.09	-96.66
Waskada	-42.80	52.84	-78.84	-111.81
Winnipeg A	-3.90	41.50	-32.16	-57.97

Table 14: Soil Moisture Amounts at Silking in Corn

Station	Mean	Std.	25%	10%
Altona	21.06	33.04	-1.54	-22.35
Baldur	44.01	44.17	13.49	-15.22
Beausejour CDA	37.19	35.56	12.72	-10.10
Beasejour	26.66	29.73	6.15	-13.09
Bede	-9.60	41.91	-38.43	-65.26
Birtle	27.82	46.71	-3.99	-33.04
Bissett	34.17	26.23	16.15	-0.58
Boissevain	41.90	31.92	20.13	0.21
Brandon A	17.68	45.28	-13.38	-42.23
Brandon CDA	14.41	43.36	-15.12	-42.04
Camp Shilo	-12.54	37.72	-38.64	-63.27
Carberry	6.05	43.22	-23.86	-52.08
Cypress River	22.67	43.23	-6.73	-33.53
Dauphin	30.53	42.55	1.60	-24.79
Deerwood	48.26	39.44	21.09	-4.31
Deloraine	30.43	35.29	6.01	-17.04
Emerson	4.21	45.29	-26.59	-54.67
Eriksdale	23.71	38.10	-2.54	-27.08
Gimli	41.35	26.54	23.25	6.66
Grass River	23.04	44.61	-7.65	-36.20
Graysville	12.13	40.73	-15.69	-41.14
Great Falls	40.60	30.52	19.79	0.74
Hamiota	25.96	38.88	-0.48	-24.62
Indian Bay	49.43	28.69	29.89	12.05
Melita	17.01	42.85	-12.39	-39.59
Minnedosa	32.69	35.30	8.62	-13.45
Moosehorn	26.12	27.94	6.90	-11.04
Morden	25.27	41.00	-2.61	-27.99
Morris	20.94	37.35	-4.57	-27.95
Neepawa	7.91	36.75	-17.19	-40.27
Ninette	21.90	43.09	-7.44	-34.29
Pierson	4.55	46.73	-27.27	-56.29
Pilot Mound	45.74	39.56	18.68	-6.24
Pinawa	4.55	36.66	-20.49	-43.40
Portage la Prairie (1)	29.69	35.62	5.29	-17.29
Portage la Prairie (2)	40.47	32.71	18.10	-2.58
Rivers A	30.73	36.70	5.66	-17.31
Roland	23.71	34.61	0.04	-21.84
Rossburn	46.53	43.02	16.93	-10.60
Russell	23.86	40.90	-3.95	-29.31
Seven-Sisters	33.70	31.62	11.91	-8.45
Souris	-4.98	41.59	-33.30	-59.17
Sprague	24.85	45.19	-5.88	-33.85
Steinbach	31.12	30.69	10.07	-9.48
Stonewall	31.28	38.78	4.56	-20.41
Swan River	26.70	37.02	1.45	-21.65
Virden	16.79	43.80	-12.99	-40.15
Waskada	8.24	37.26	-17.17	-40.46
Winnipeg A	35.00	33.48	12.20	-8.62

Table 15: Soil Moisture Amounts after the First Crop of Alfalfa

Station	Mean	Std.	25%	10%
Altona	-24.96	52.30	-60.73	-93.68
Baldur	-10.08	47.82	-43.12	-74.21
Beausejour CDA	-23.53	50.60	-58.34	-90.83
Beausejour	-16.76	44.42	-47.41	-76.15
Bede	-57.98	55.20	-95.96	-131.29
Birtle	-23.65	60.79	-65.05	-102.80
Bissett	-19.37	31.28	-40.86	-60.82
Boissevain	9.03	51.03	-25.77	-57.67
Brandon A	-34.18	55.56	-72.35	-107.80
Brandon CDA	-29.80	62.83	-72.59	-111.60
Camp Shilo	-54.36	52.32	-90.57	-124.73
Carberry	-42.54	42.28	-71.80	-99.41
Cypress River	-32.84	56.83	-71.48	-106.72
Dauphin	-12.85	57.46	-51.92	-87.55
Deerwood	3.12	59.17	-37.65	-75.75
Deloraine	-4.78	55.91	-43.47	-79.98
Emerson	-32.99	61.25	-74.64	-112.68
Eriksdale	-21.02	57.30	-60.50	-97.40
Gimli	-0.51	46.82	-32.44	-61.70
Grass River	-17.41	53.17	-53.99	-88.02
Graysville	-37.95	59.75	-78.64	-115.86
Great Falls	-14.83	37.54	-40.43	-63.86
Hamiota	-31.05	55.36	-68.75	-103.07
Indian Bay	-2.98	53.51	-39.43	-72.72
Melita	-36.75	68.32	-83.62	-127.00
Minnedosa	-21.73	56.68	-60.39	-95.81
Moosehorn	-7.30	38.84	-34.02	-58.88
Morden	-21.94	50.22	-56.09	-87.18
Morris	-35.36	54.30	-72.45	-106.55
Neepawa	-39.93	55.92	-78.12	-113.24
Ninette	-22.19	61.93	-64.43	-103.07
Pierson	-43.31	62.35	-85.77	-124.55
Pilot Mound	0.08	54.57	-37.18	-71.49
Pinawa	-53.83	53.15	-90.13	-123.35
Portage la Prairie (1)	-16.93	51.21	-52.01	-84.48
Portage la Prairie (2)	-5.62	43.71	-35.52	-63.14
Rivers A	-22.71	53.71	-59.39	-93.02
Roland	-18.40	51.22	-53.43	-85.81
Rossburn	-7.72	46.03	-39.39	-68.94
Russell	-24.48	46.96	-56.41	-85.53
Seven-Sisters	-11.37	44.87	-42.29	-71.18
Souris	-59.86	62.56	-102.46	-141.44
Sprague	-29.57	63.28	-72.60	-111.77
Steinbach	-4.79	43.66	-34.74	-62.55
Stonewall	-25.60	34.61	-49.45	-71.74
Swan River	-43.18	45.49	-74.20	-102.59
Virden	-39.33	56.06	-77.45	-112.21
Waskada	-39.33	52.90	-75.46	-108.52
Winnipeg A	-17.12	52.11	-62.61	-85.02

Table 16: Soil Moisture Amounts after the Second Crop of Alfalfa

Station	Mean	Std.	25%	10%
Altona	-148.84	76.93	-201.46	-249.93
Baldur	-115.88	88.30	-176.90	-234.29
Beausejour CDA	-118.17	96.40	-184.49	-246.38
Beausejour	-117.45	79.61	-172.38	-223.89
Bede	-178.65	90.25	-240.74	-298.50
Birtle	-124.53	105.37	-196.29	-261.72
Bissett	-116.16	58.70	-156.49	-193.94
Boissevain	-90.82	80.64	-145.82	-196.22
Brandon A	-160.28	89.21	-221.57	-278.48
Brandon CDA	-154.20	93.47	-217.85	-275.90
Camp Shilo	-171.97	87.72	-232.67	-289.95
Carberry	-155.82	80.41	-211.46	-263.97
Cypress River	-142.50	93.53	-206.10	-264.09
Dauphin	-122.47	90.79	-184.21	-240.50
Deerwood	-93.82	91.24	-156.68	-215.44
Deloraine	-120.21	98.64	-188.47	-252.88
Emerson	-145.10	100.15	-213.20	-275.40
Eriksdale	-140.66	90.24	-202.84	-260.95
Gimli	-77.96	76.02	-129.81	-177.32
Grass River	-144.03	98.90	-212.07	-275.37
Graysville	-156.22	112.38	-232.75	-302.76
Great Falls	-110.92	62.34	-153.44	-192.34
Hamiota	-156.22	89.74	-217.33	-272.97
Indian Bay	-72.63	84.94	-130.47	-183.31
Melita	-149.32	86.12	-208.40	-263.08
Minnedosa	-142.01	93.61	-205.85	-264.36
Moosehorn	-93.92	92.84	-157.79	-217.21
Morden	-138.05	83.75	-195.00	-246.84
Morris	-161.46	88.64	-222.00	-277.67
Neepawa	-146.06	81.95	-202.03	-253.50
Ninette	-129.41	92.17	-192.27	-249.78
Pierson	-180.58	92.07	-243.28	-300.55
Pilot Mound	-100.47	91.47	-163.04	-220.66
Pinawa	-187.80	96.05	-253.40	-313.43
Portage la Prairie (1)	-113.43	72.54	-163.12	-209.11
Portage la Prairie (2)	-97.45	77.88	-150.72	-199.94
Rivers A	-119.76	84.73	-177.63	-230.67
Roland	-145.80	85.39	-204.21	-258.17
Rossburn	-88.59	97.54	-155.70	-218.32
Russell	-142.87	93.12	-206.19	-263.93
Seven-Sisters	-104.33	92.64	-168.16	-227.82
Souris	-179.96	100.40	-248.33	-310.88
Sprague	-126.91	111.29	-202.59	-271.42
Steinbach	-105.47	70.41	-153.77	-198.62
Stonewall	-125.37	100.75	-194.79	-259.67
Swan River	-133.69	84.73	-191.48	-244.35
Virden	-152.54	96.83	-218.38	-273.42
Waskada	-177.21	90.38	-238.94	-295.43
Winnipeg A	-110.81	83.27	-167.52	-219.31

Figure 1: Dates after which the Risk of Occurrence of the Last Spring Frost (0 C) has been reduced to 25%.

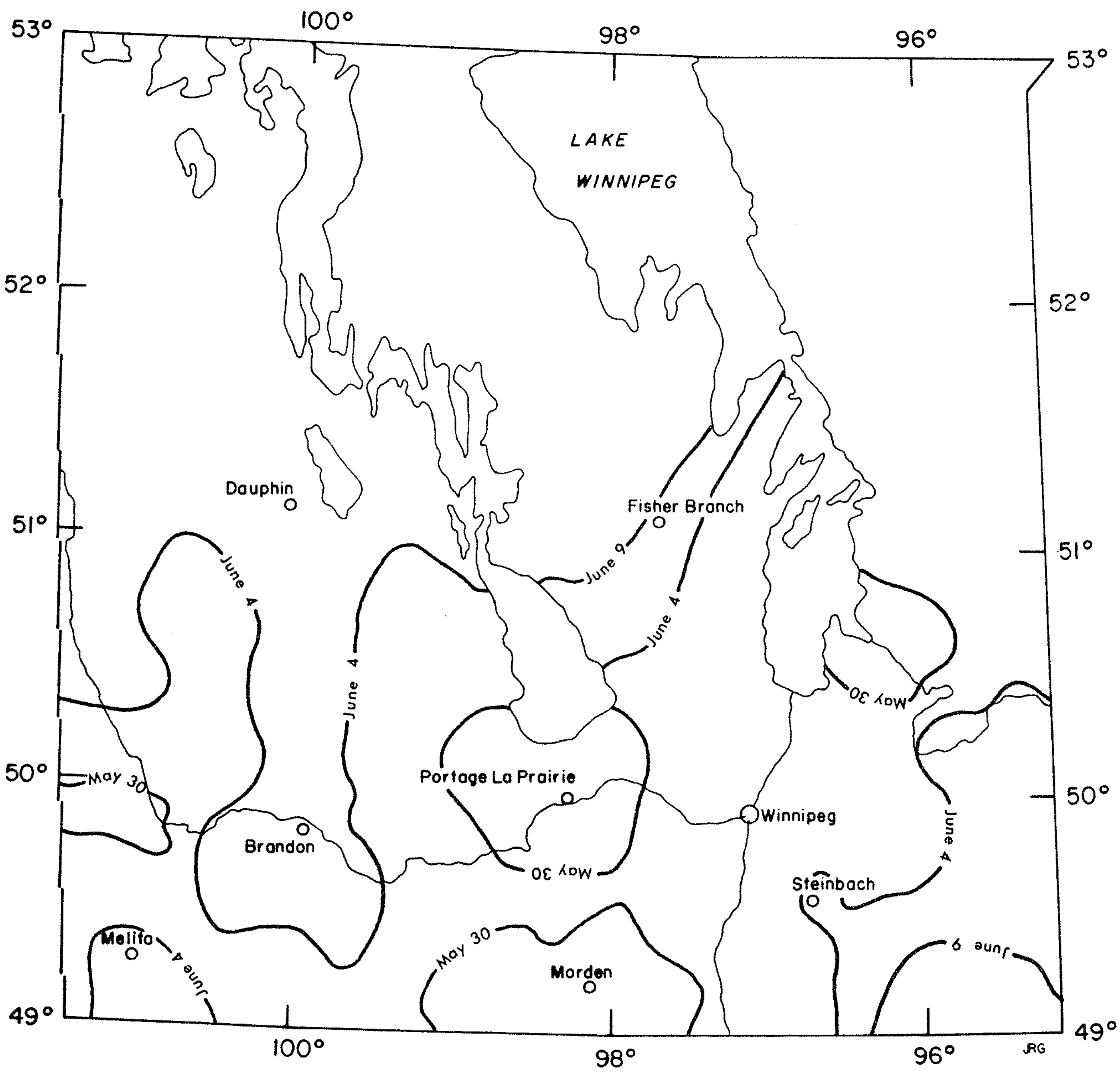

Figure 2: Dates after which the risk of occurrence of the Last Spring Frost (-2.2 C) has been reduced to 25%.

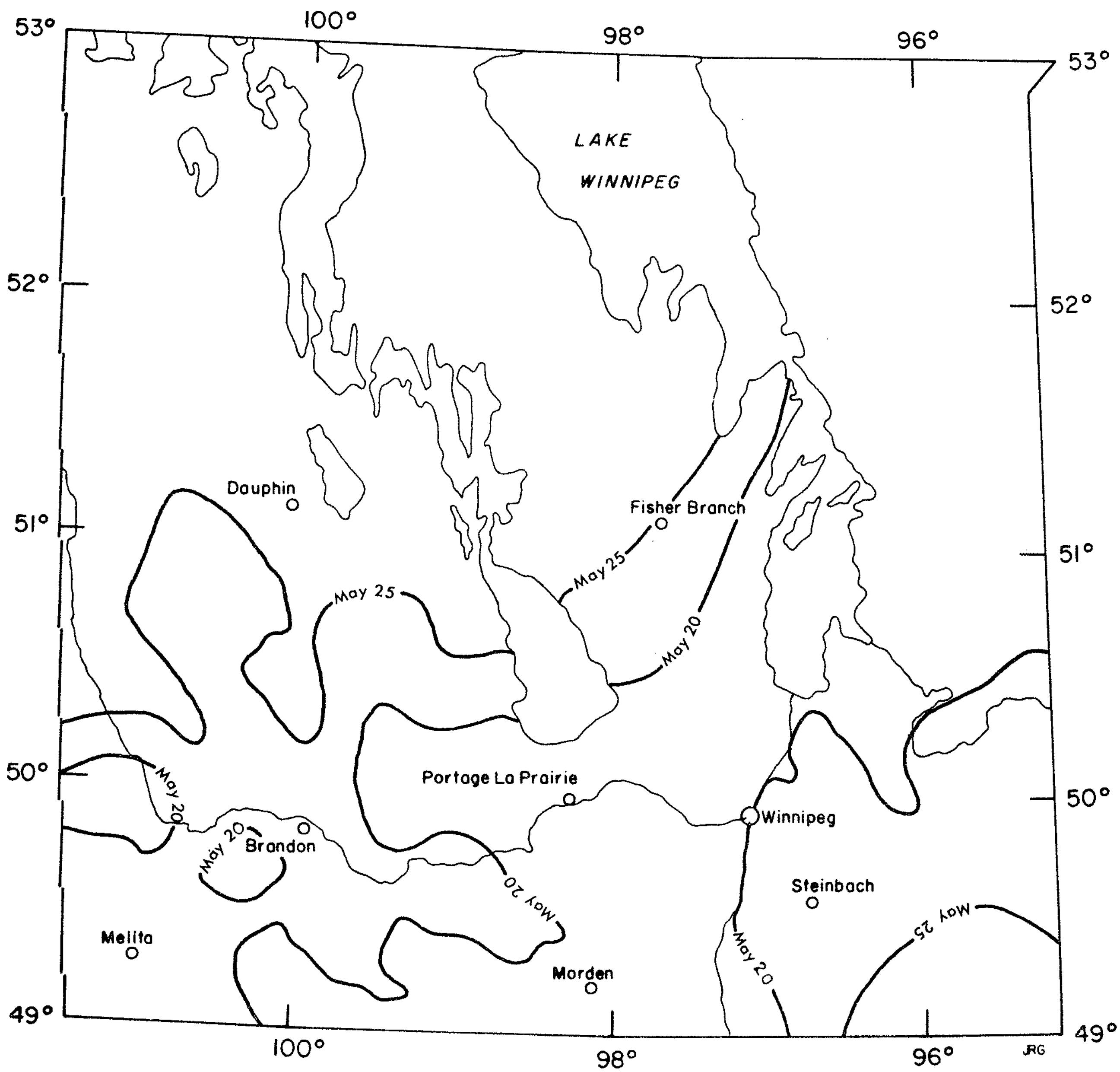

Figure 3: Dates after which the risk of occurrence of the Last Spring Frost (-2.2 C) has been reduced to 10%.

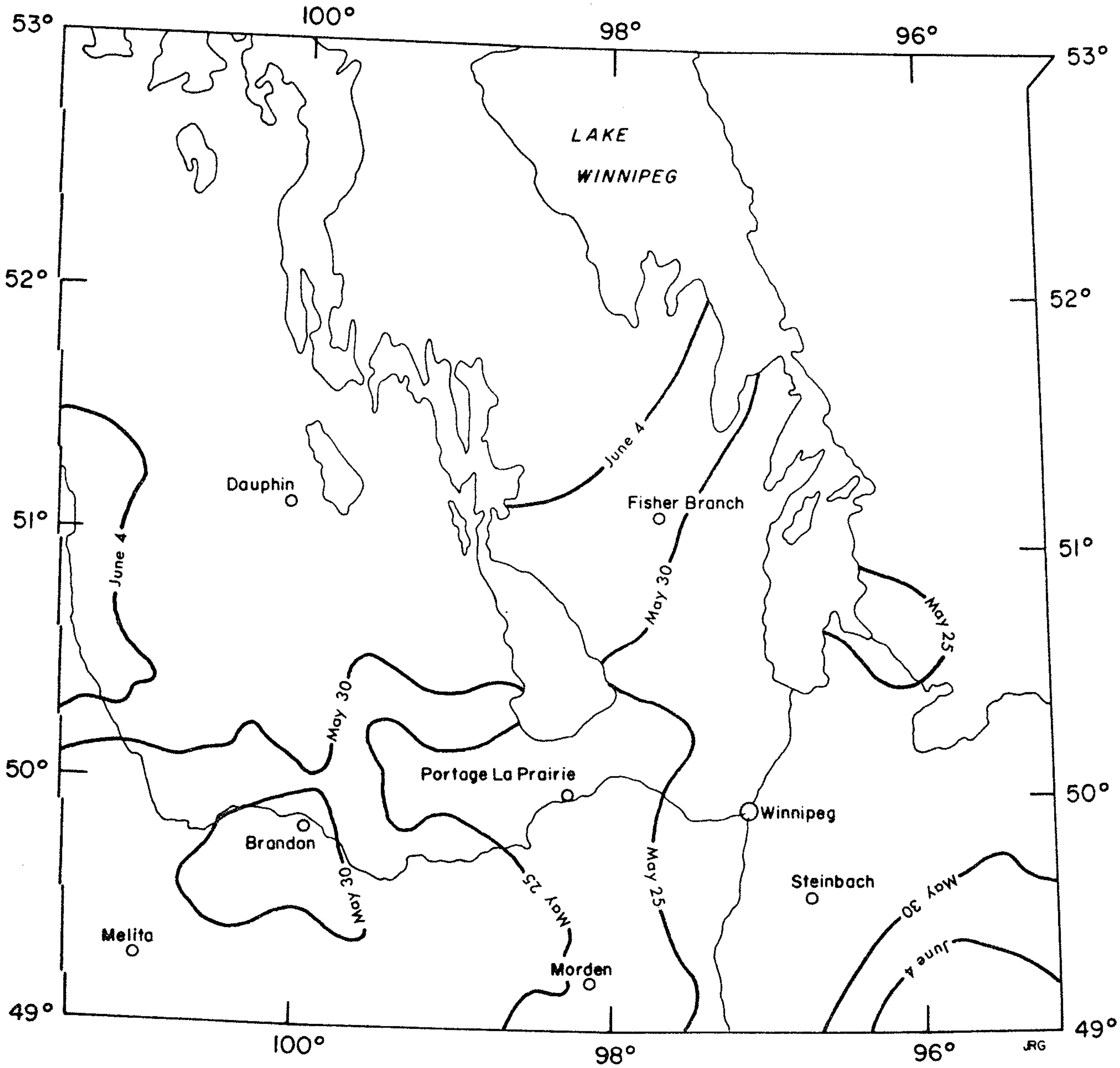

Figure 4: Dates before which the occurrence of the First Fall Frost (0 C) is at a 25% risk.

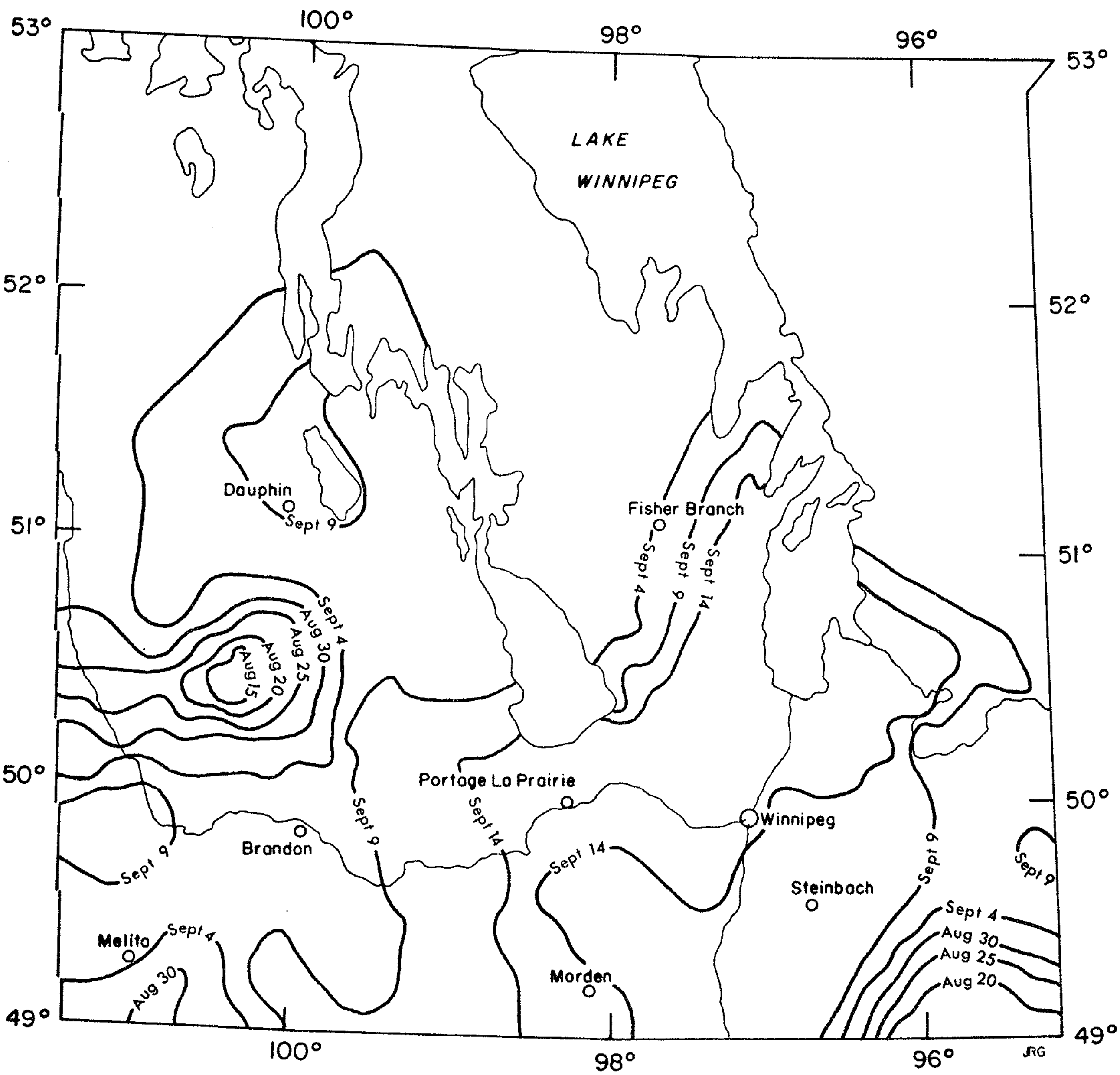

Figure 5: Dates before which the occurrence of the First Fall Frost (0 C) is at a 10% risk.

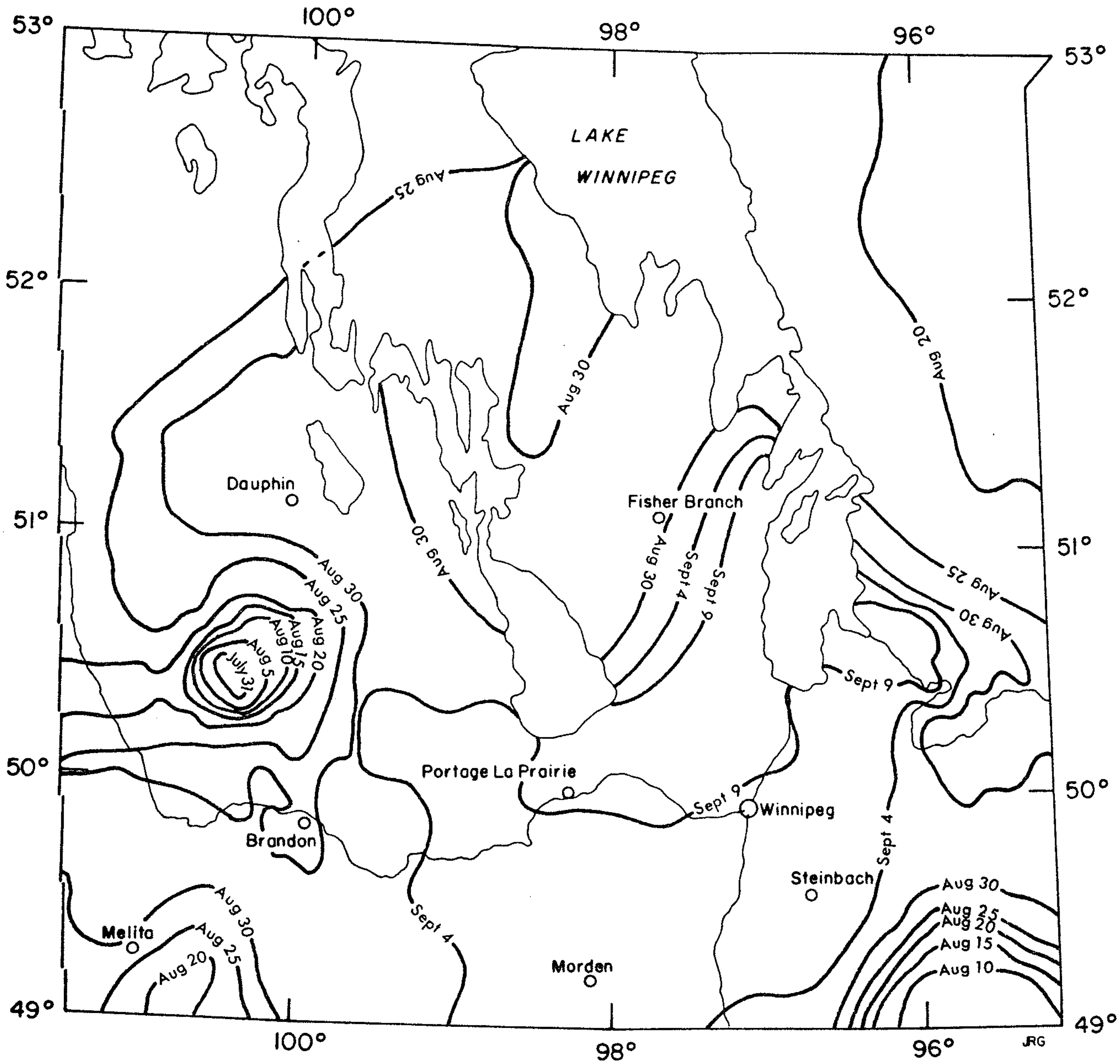

Figure 6: Average data of occurrence of the First Fall Frost (-2.2 C).

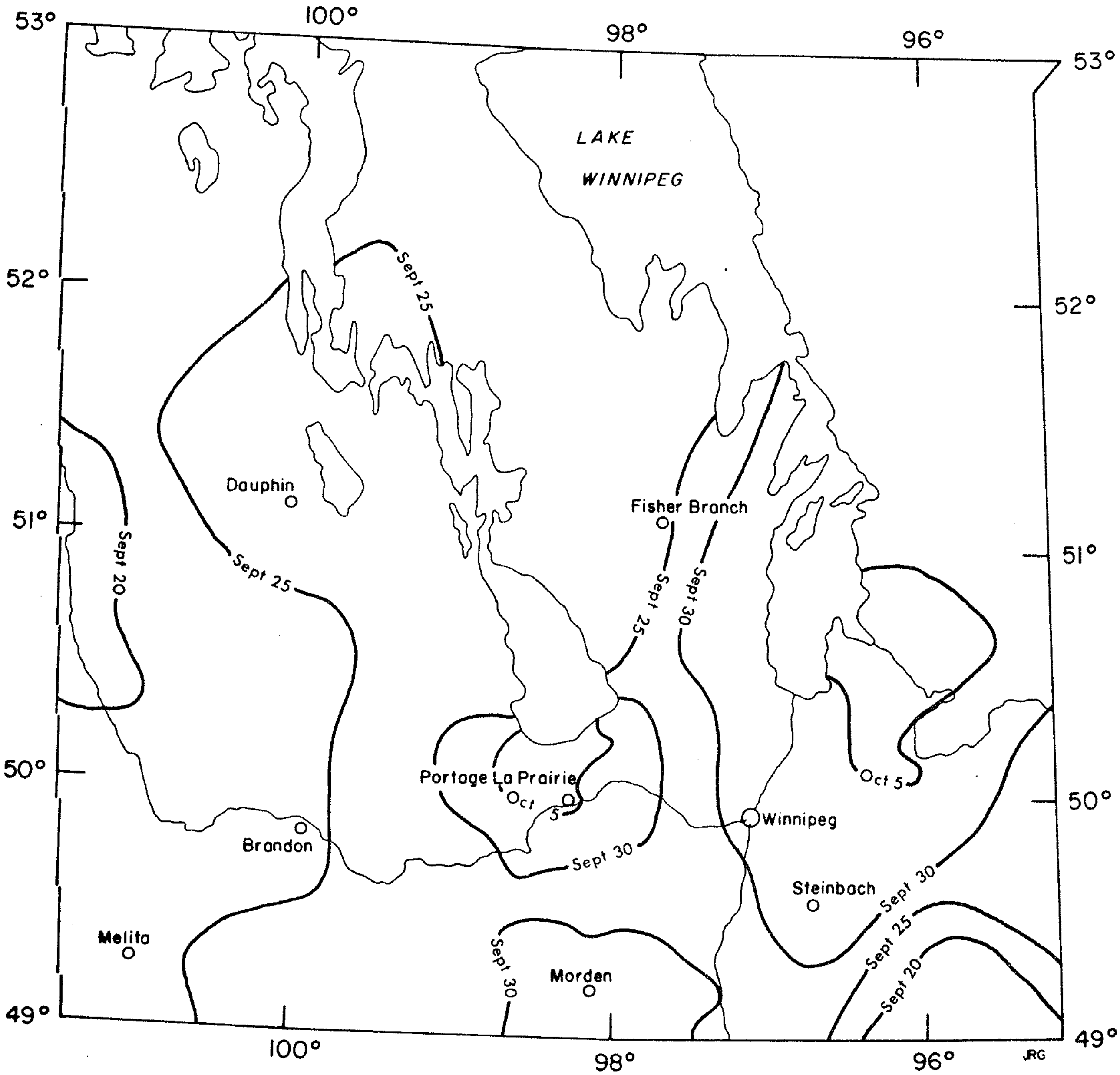

Figure 7: Dates before which the occurrence of the First Fall Frost (-2.2 C) is at a 25% risk.

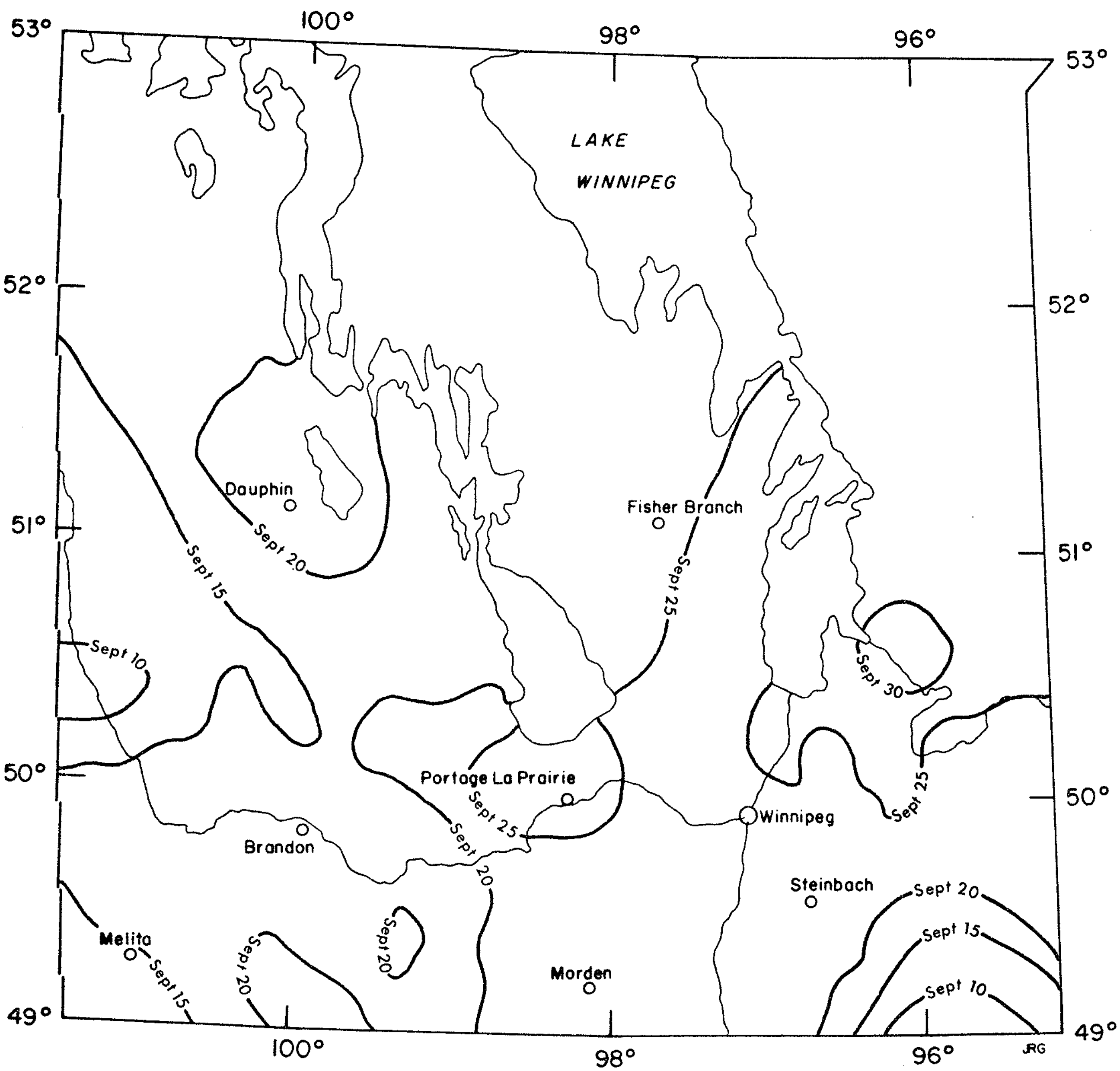

Figure 8: Dates before which the occurrence of the First Fall Frost (-2.2 C) is at a 10% risk.

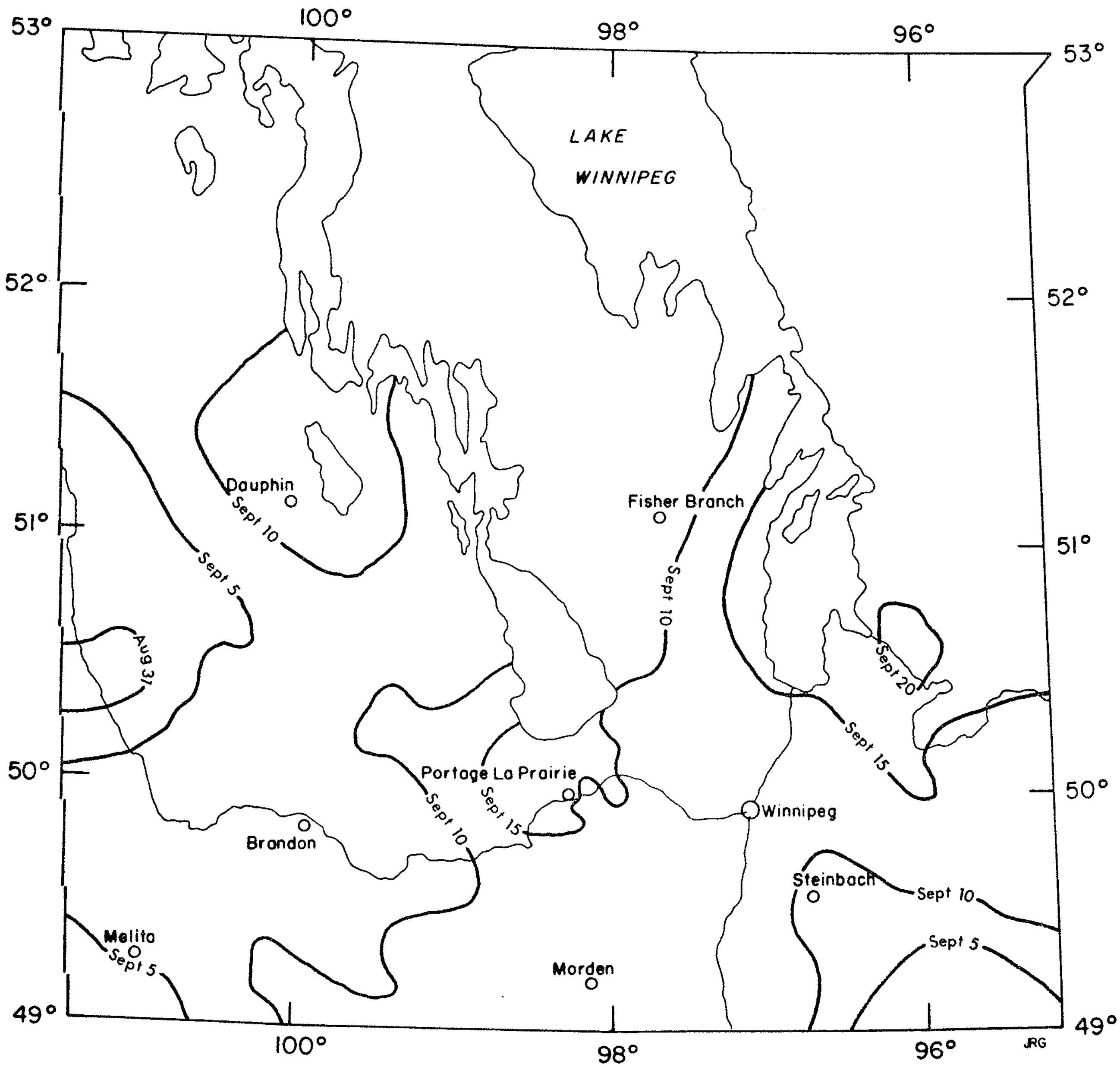

Figure 9: Length of the frost-free period (0 C) at a 25% risk.

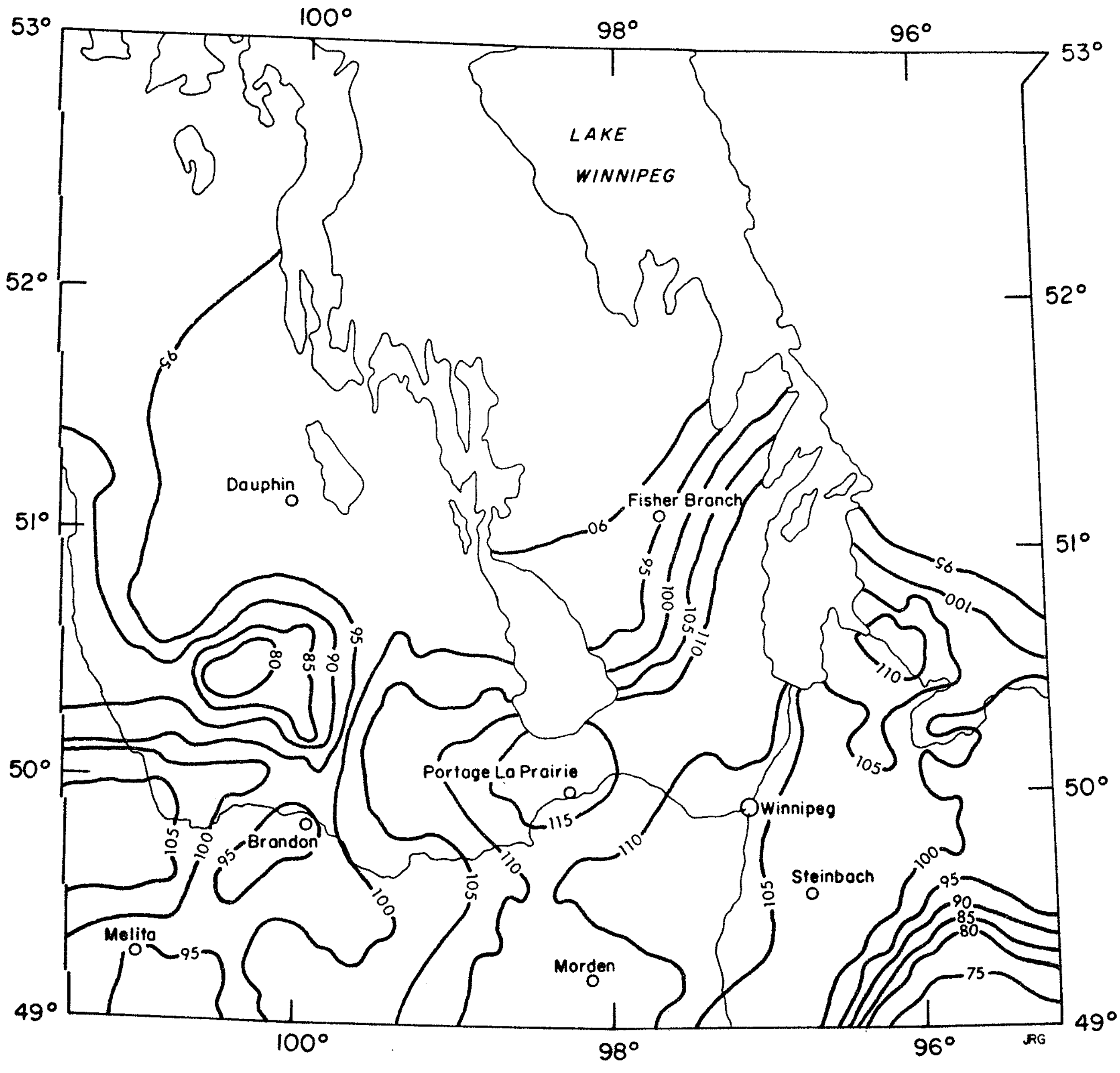

Figure 10: Length of the frost-free period (-2.2 C) at a 25% risk.

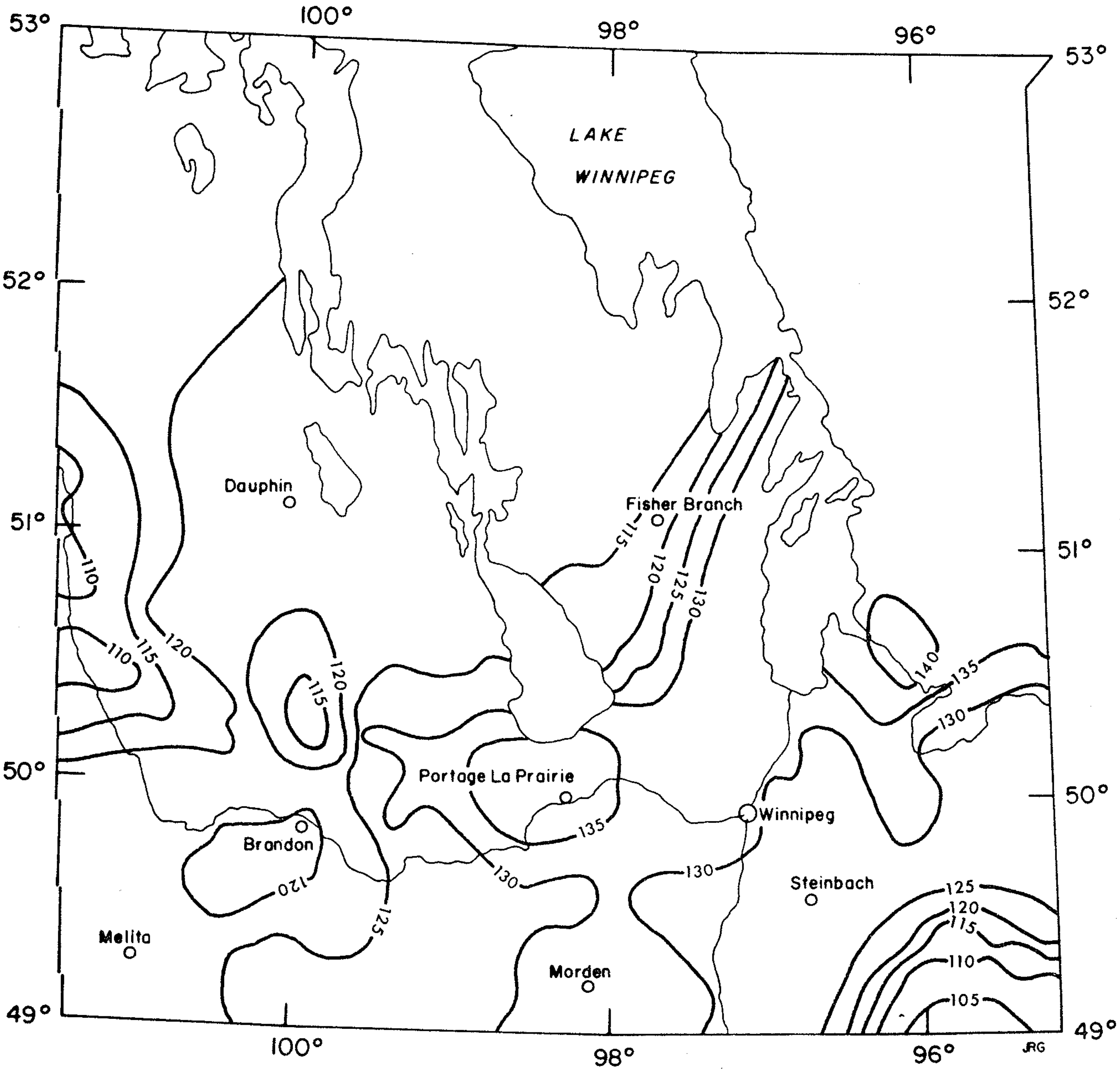

Figure 11: Length of the frost-free period (-2.2 C) at a 10% risk.

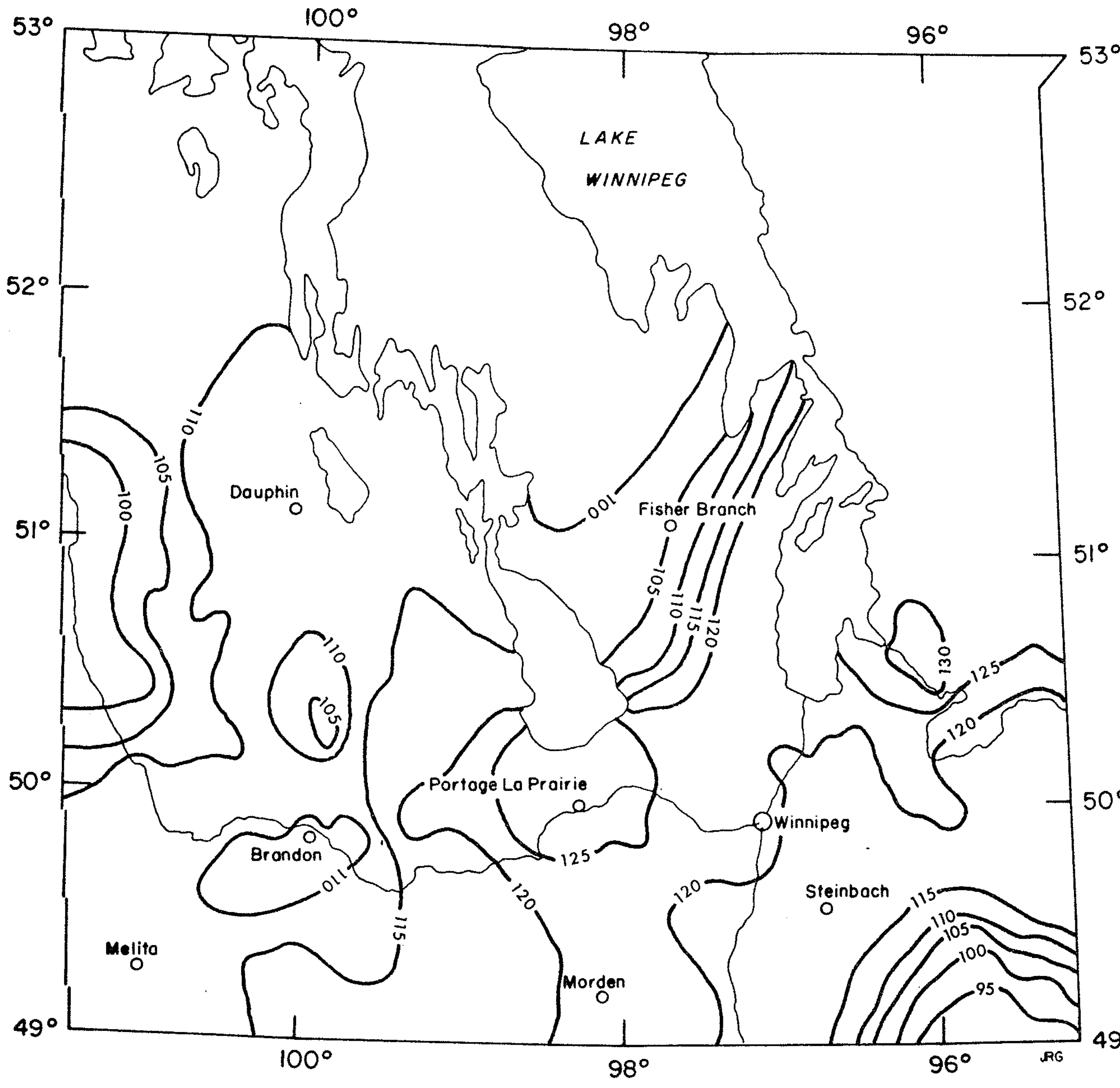

Figure 12: Minimum Accumulation of Corn Heat Units at a 25% Risk.

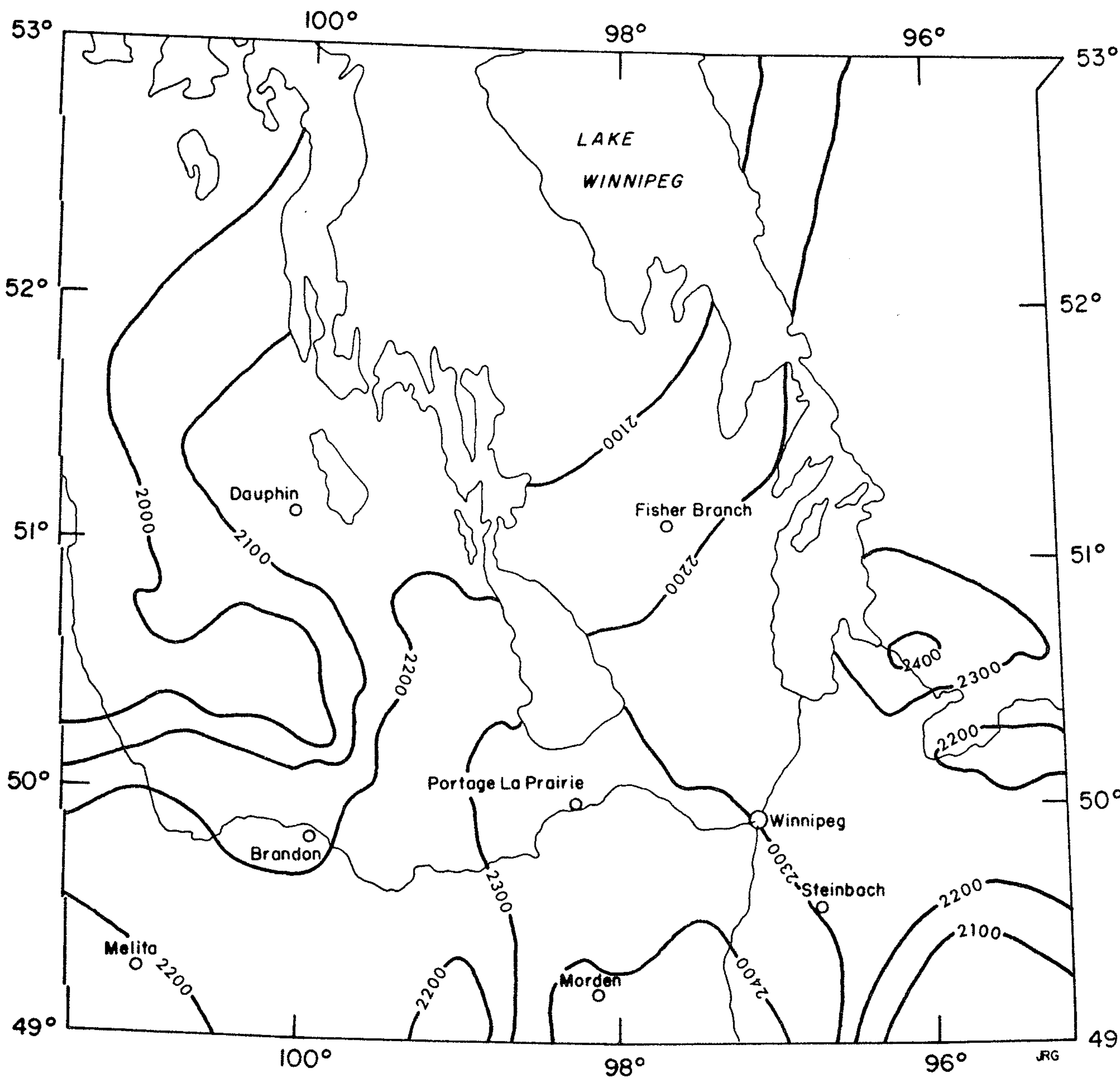

Figure 13: Minimum Accumulation of Growing Degree Days at a 25% Risk.

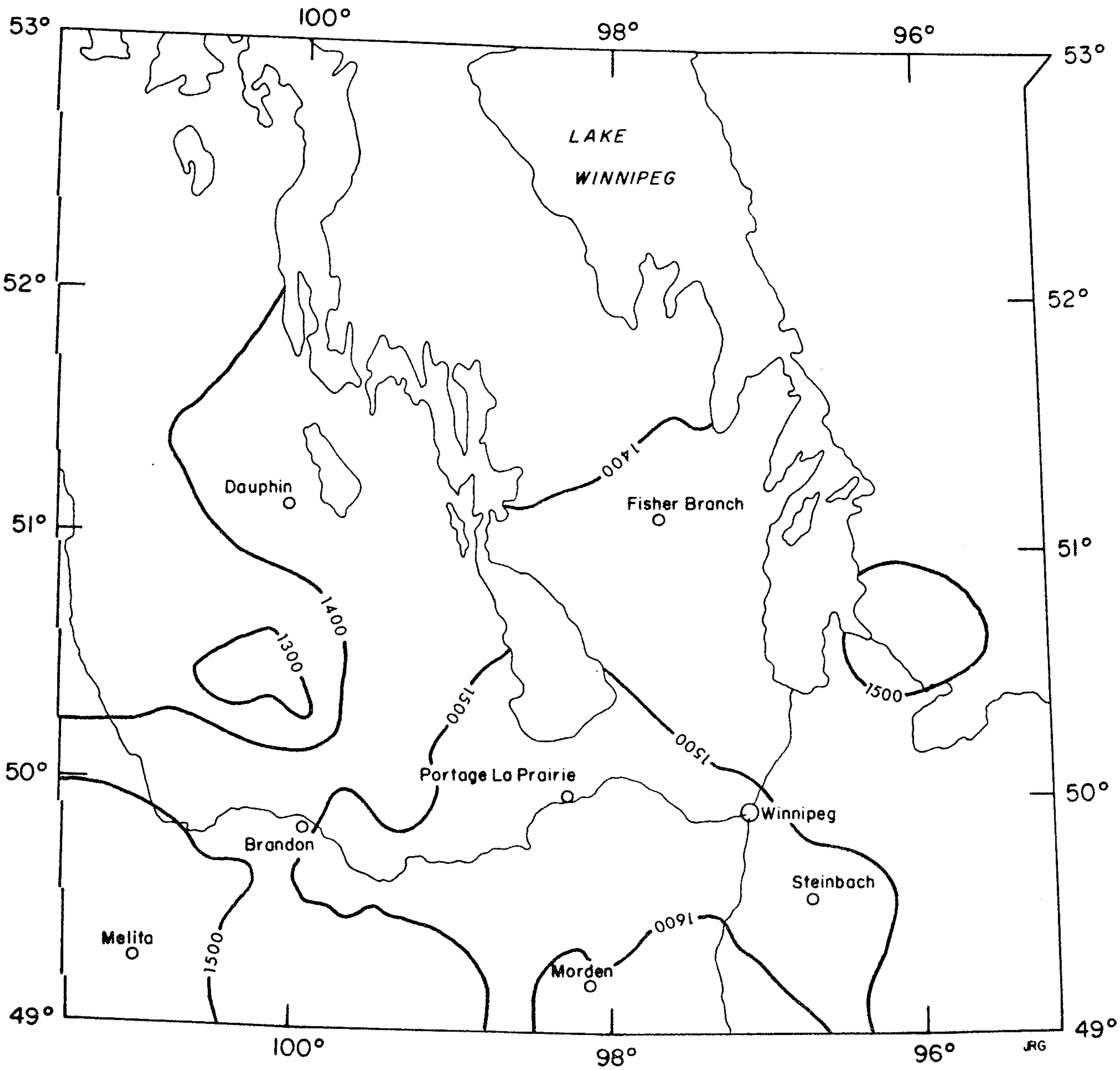

Figure 14: Minimum Accumulation of Growing Degree Days at a 10% Risk.

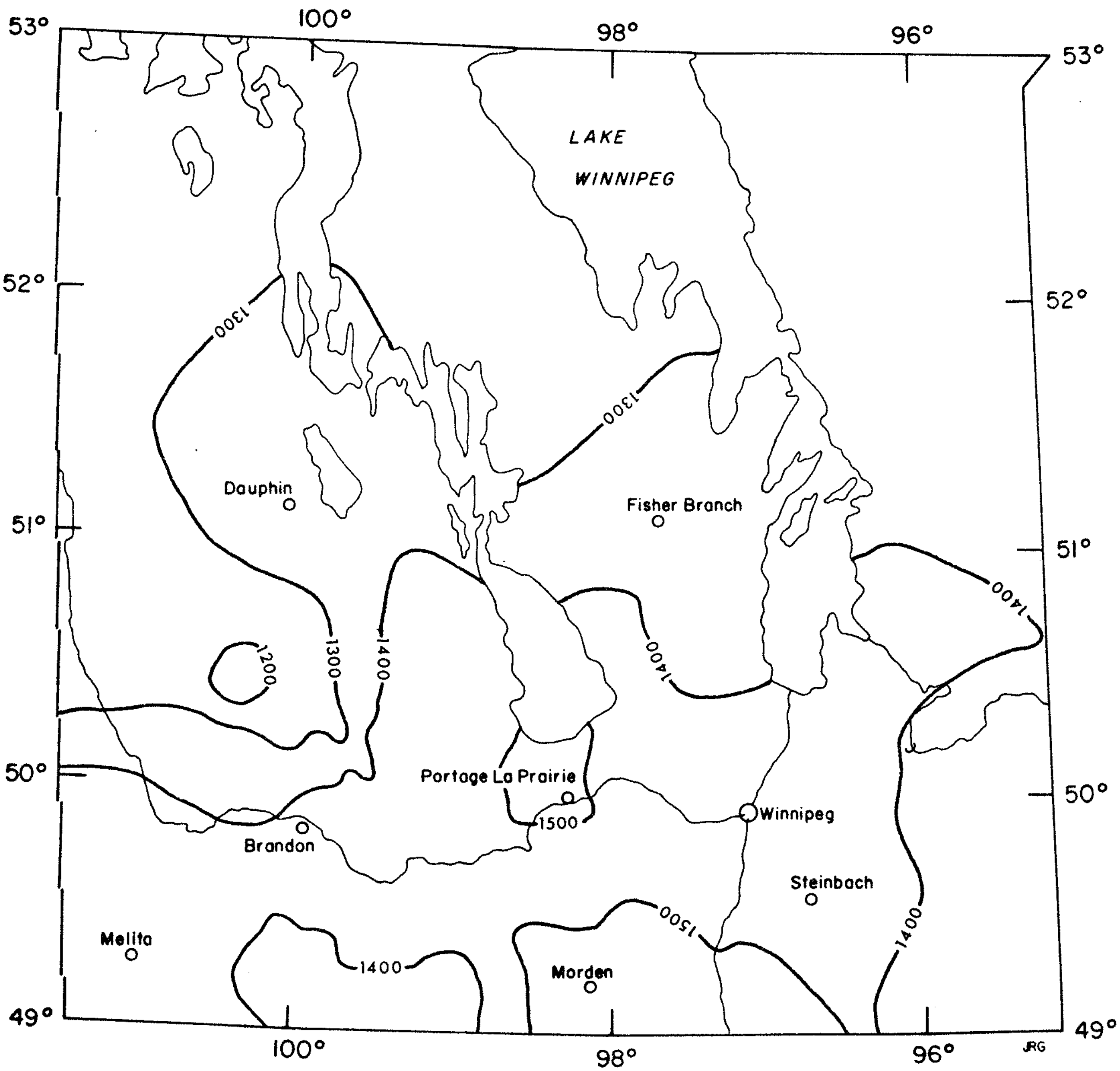

Figure 15: Soil Moisture Amounts at heading in wheat which can occur with a 25% risk.

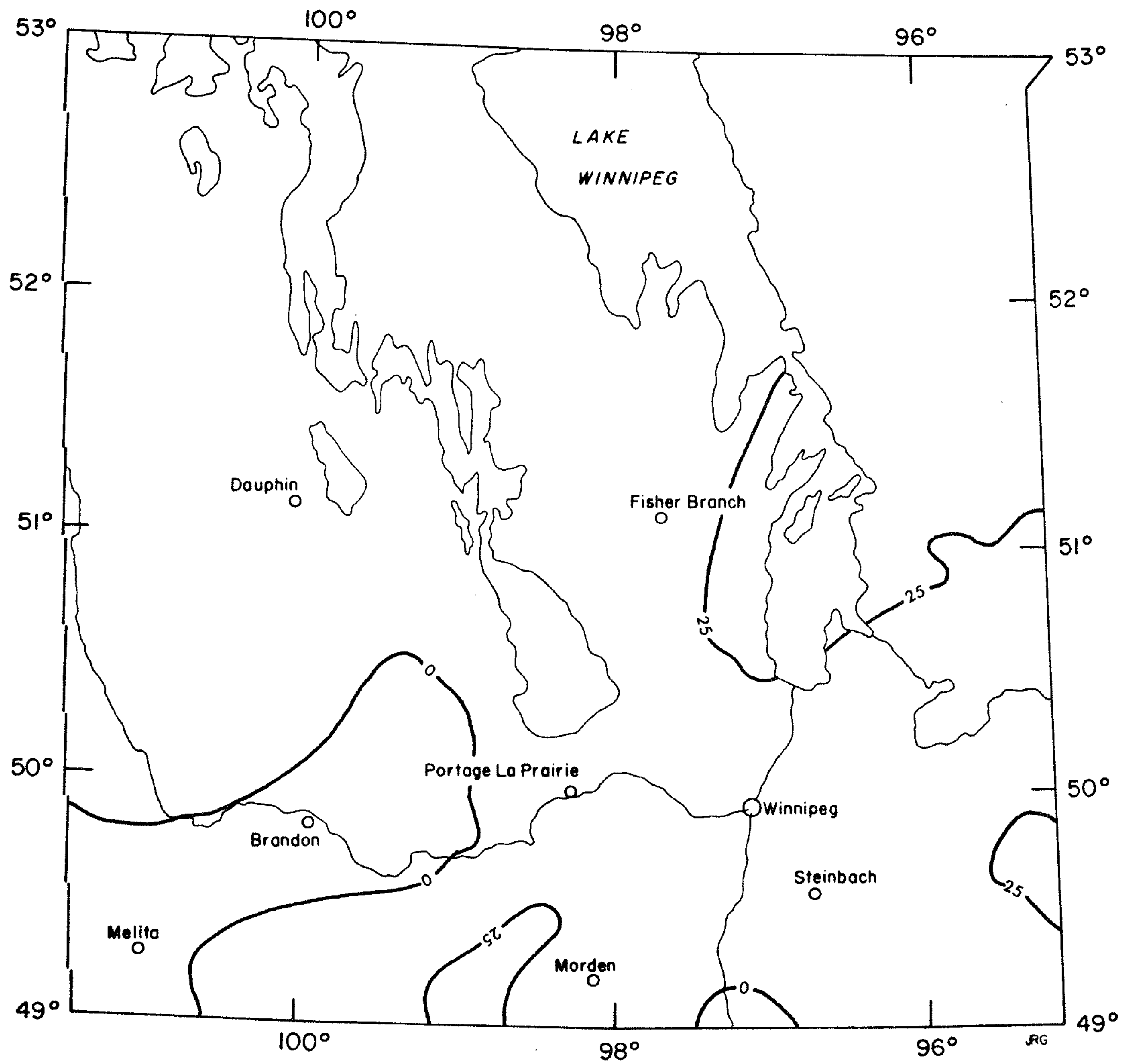

Figure 16: Soil Moisture Amounts at heading in wheat which can occur with a 10% risk.

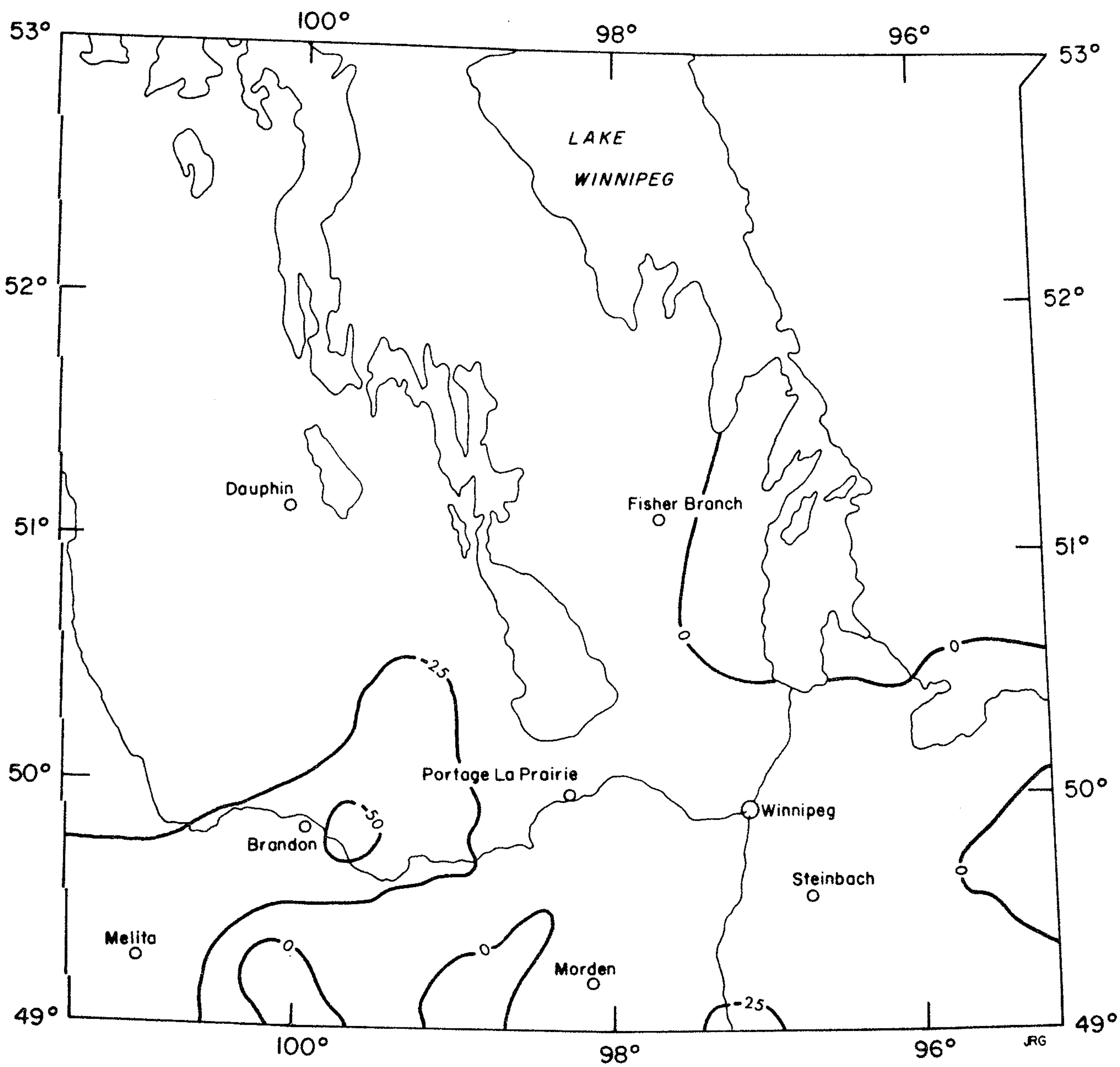

Figure 17: Soil Moisture Amounts at the Soft Dough Stage in Wheat which can occur with a 25% risk.

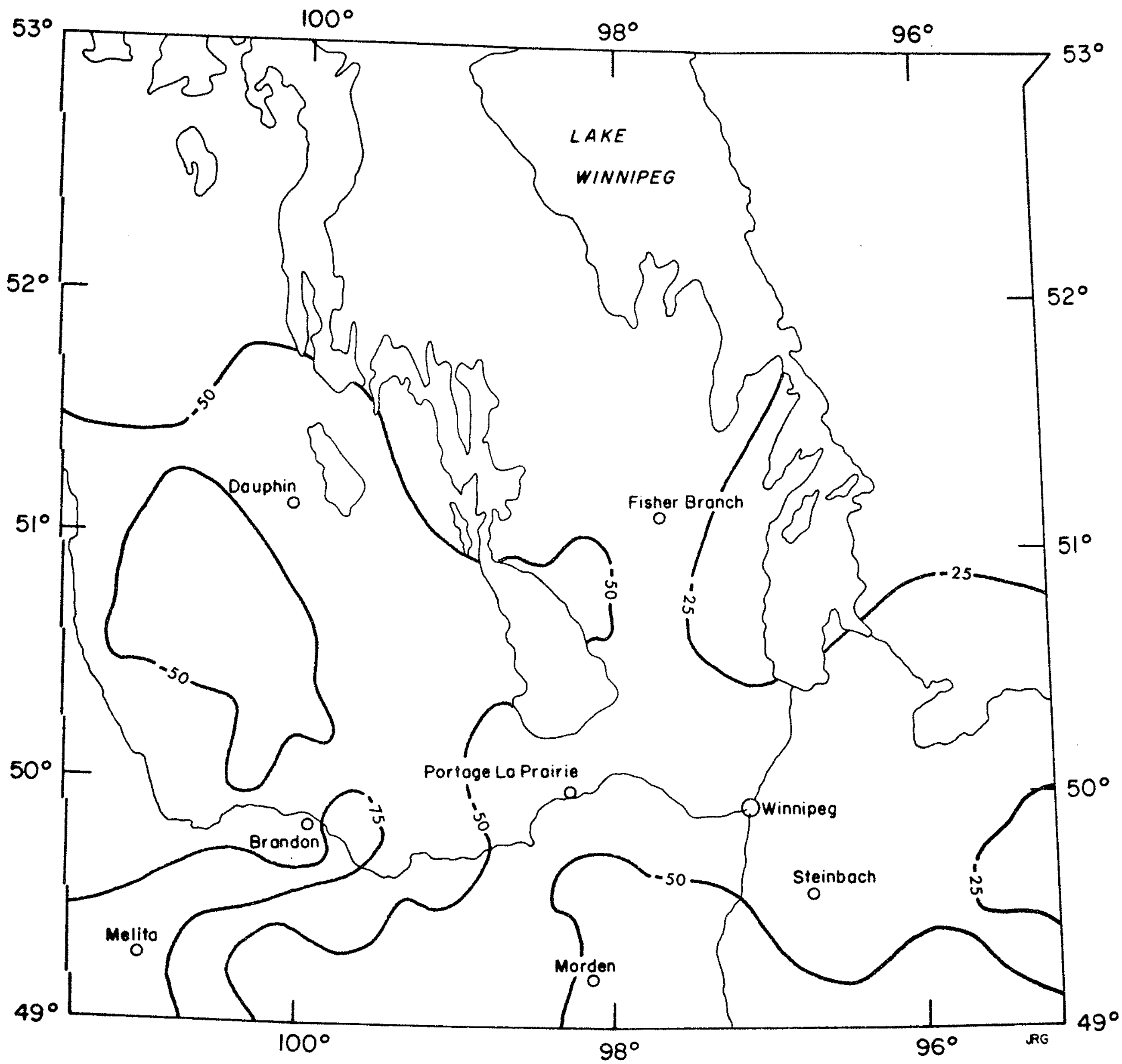

Figure 18: Soil Moisture Amounts at the Soft Dough Stage in Wheat which can occur with a 10% risk.

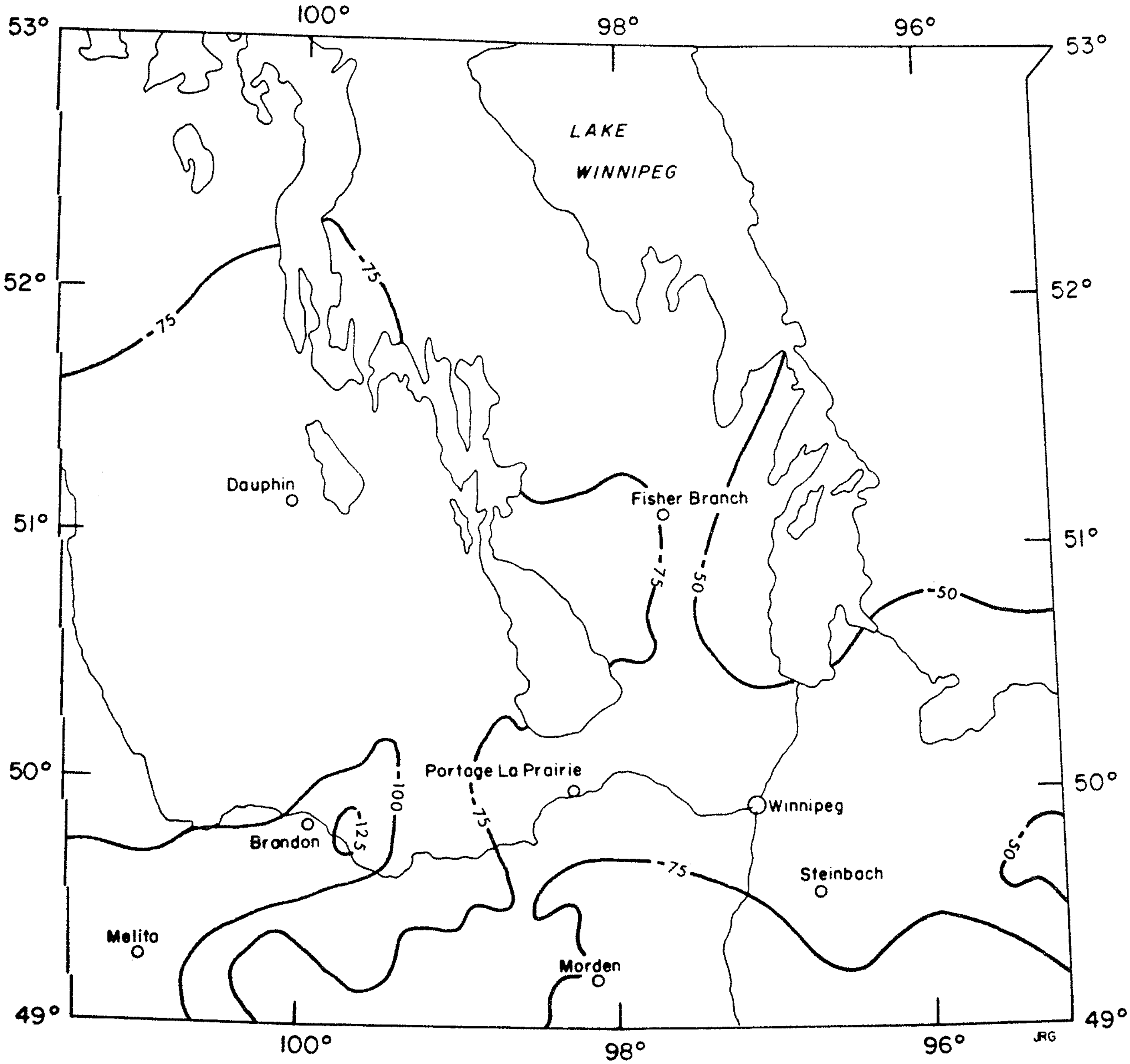

Figure 19: Soil Moisture Amounts at Silking in Corn which can occur with a 25% risk.

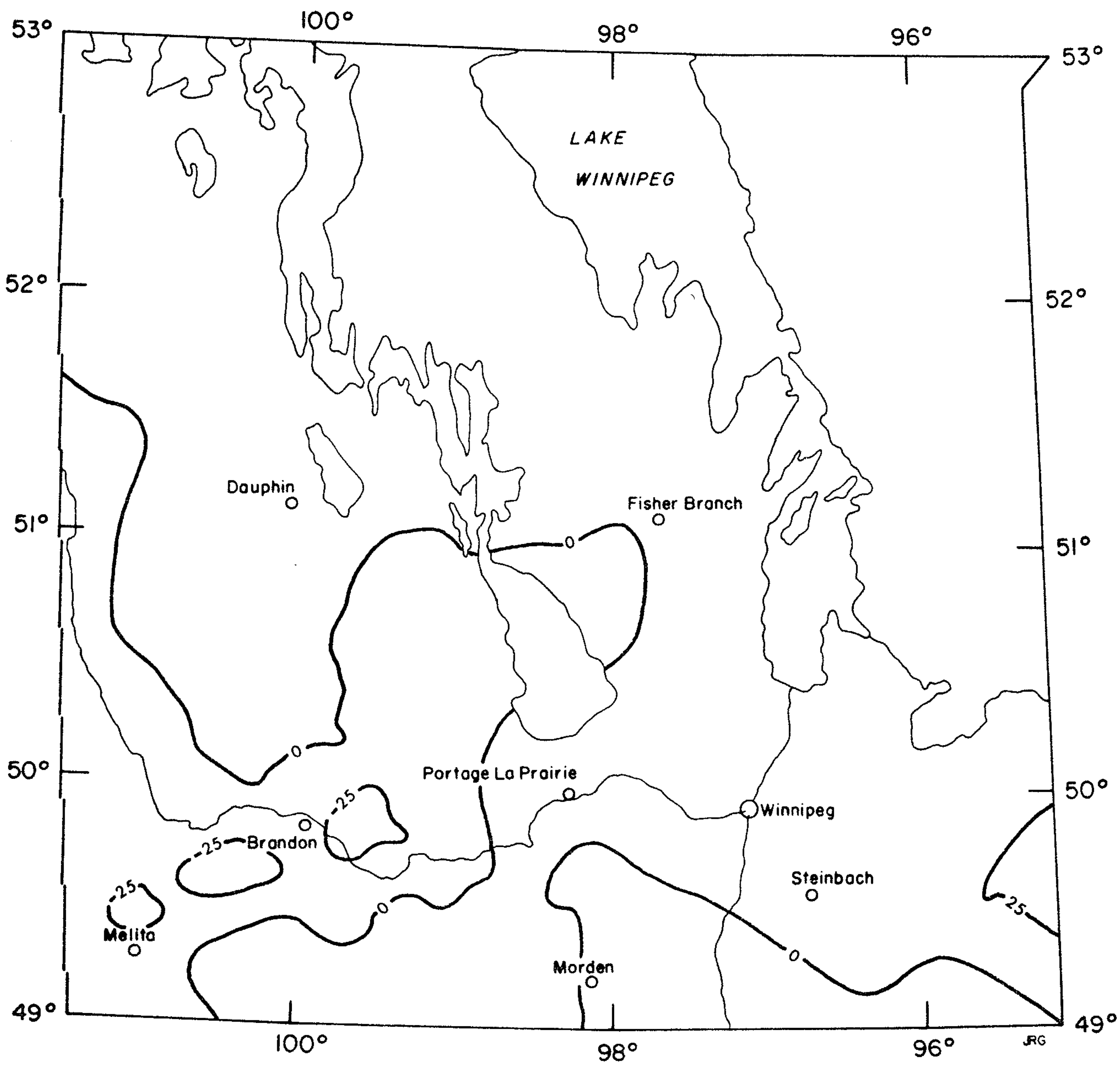

Figure 20: Soil Moisture Amounts at Silking in Corn which can occur with a 10% risk.

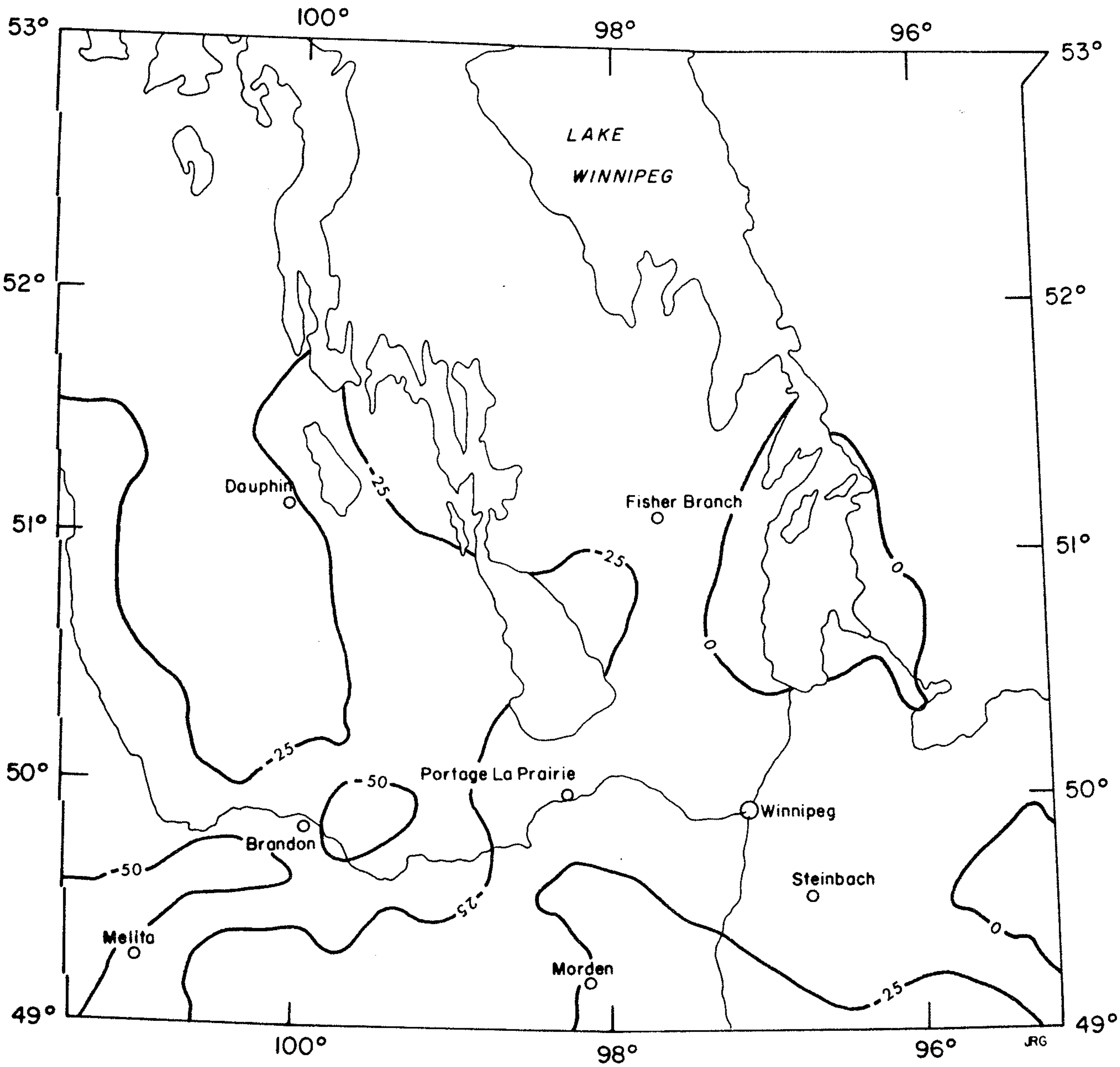

Figure 21: Soil Moisture Amounts after the First Crop of Alfalfa which can occur with a 25% risk.

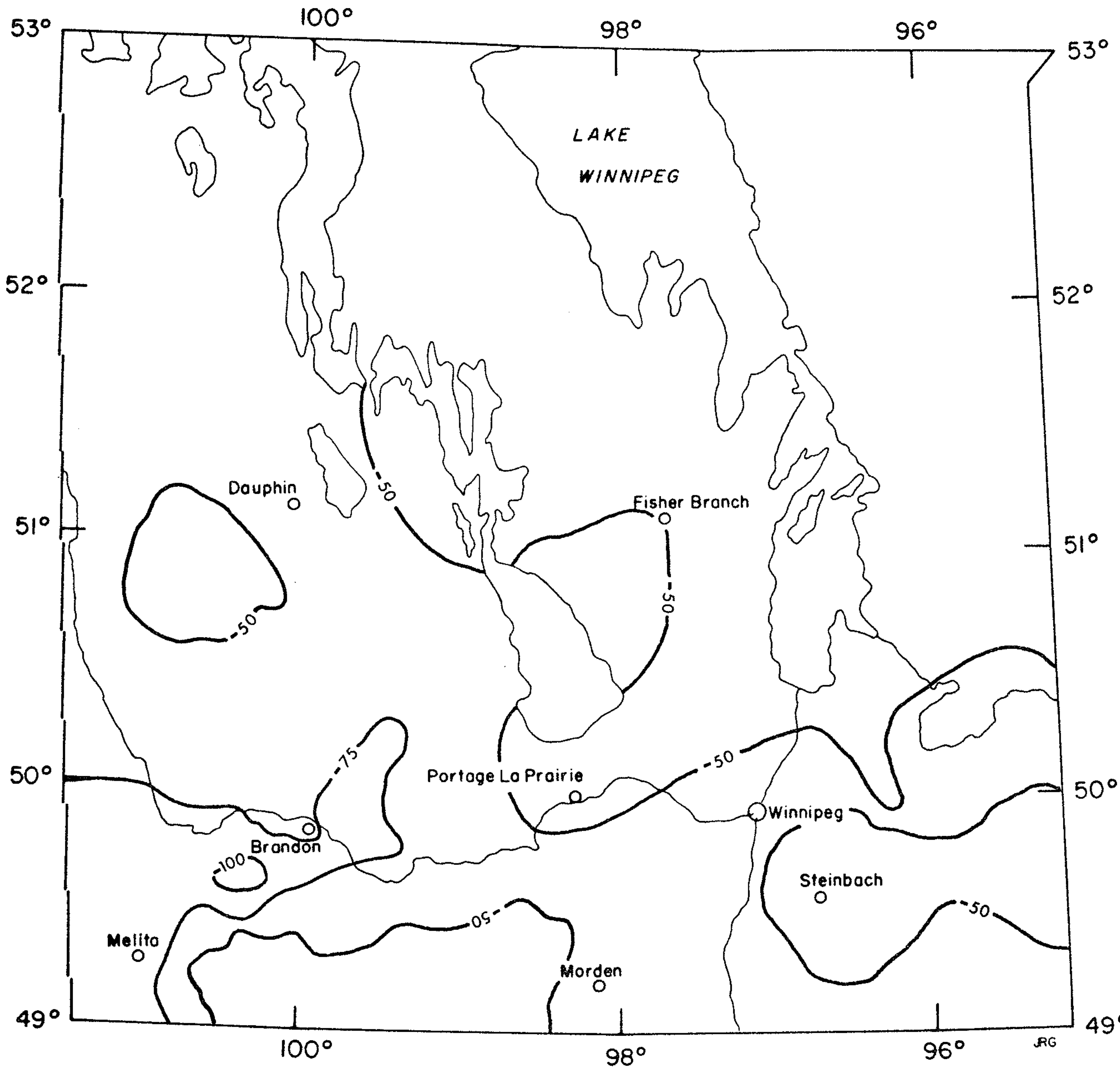

Figure 22: Soil Moisture Amounts after the First Crop of Alfalfa which can occur with a 10% risk.

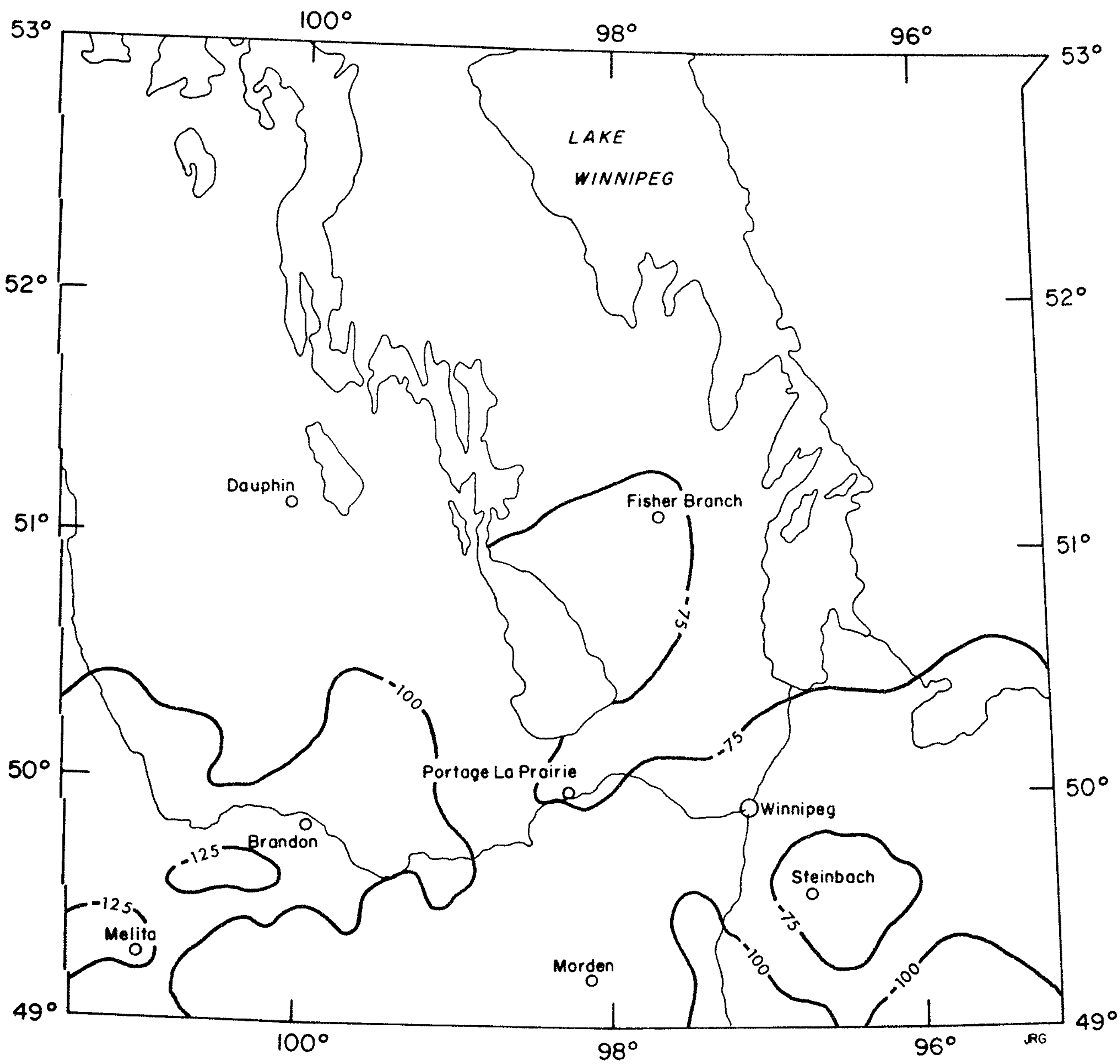

Figure 23: Soil Moisture Amounts after the Second Crop of Alfalfa which can occur with a 25% risk.

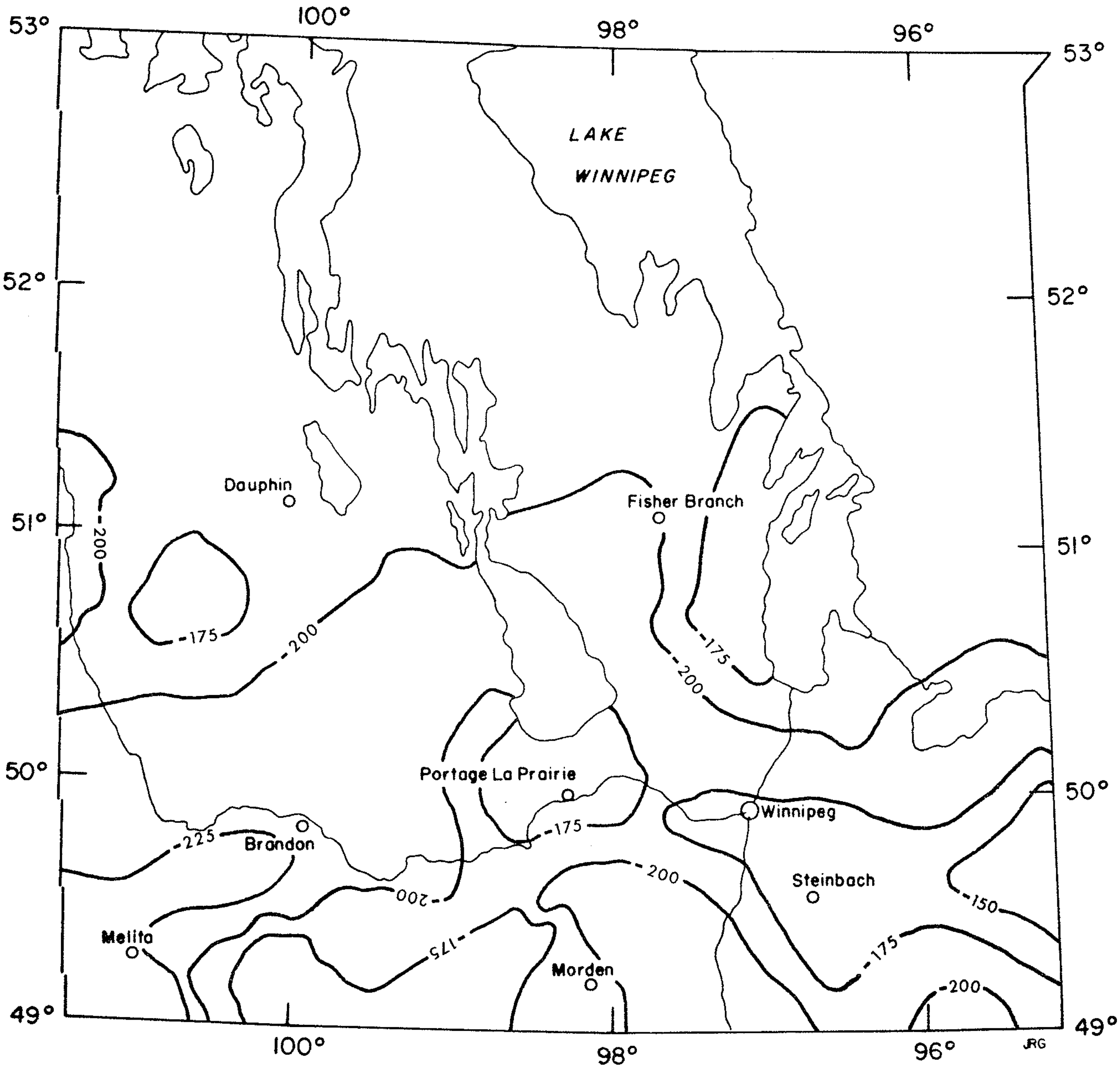

Figure 24: Soil Moisture Amounts after the Second Crop of Alfalfa which can occur with a 10% risk.