THE ECONOMIC IMPACTS OF A 2*CO_2 GREENHOUSE SCENARIO ON THE AGRICULTURAL SECTOR WITHIN MANITOBA

BY

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ABSTRACT

Increased concentrations of gasses such as carbon dioxide (CO_2) and chloroflorocarbons (CFCs), amongst others, in the atmosphere have led some scientists to propose that a warming of the earth's climate may be occurring. This effect is commonly referred to as the Greenhouse effect. This will have an impact on agricultural practices which are sensitive to factors such as temperature and precipitation. The province of Manitoba is very reliant upon agriculture and agriculturally related industries for revenue creation and employment and therefore it is important for farmers, policy makers and Manitobans in general to improve their knowledge of the potential impacts of climatic warming in order that they can plan for the future more effectively.

The study has four objectives:

i) To estimate how yields of existing crops will change in response to an altered climate,

ii) to suggest new enterprises which could be introduced as a result of the climate change,

iii) to evaluate the potential economic consequences of climate change for the agricultural sector in Manitoba,

iv) to consider new cropping pattern that may occur as a result of climate change.

These objectives were achieved using models and procedures to estimate future yields, which were then incorporated into a simple linear programming model from which the economic impacts and changes in cropping patterns were obtained.

Results show beneficial effects in terms of gross margins achieved by the crop sector in Manitoba as a result of greenhouse warming. An increased growing season accompanied by an increase in heat units received throughout the province facilitated expanded production of some existing crops, for example soybeans, sunflowers and corn, to commercial levels; as well as the introduction of crops totally new to production such as sorghum and potentially winter wheat, in addition to an expansion of agricultural practices further north.

Several conclusions can be drawn from the findings of this study. It would appear that greenhouse warming will be beneficial to the agricultural sector in Manitoba. New cropping patterns could be introduced, changing the relative profitability of different areas of the province, and agriculture extend further north.

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CHAPTER ONE

INTRODUCTION

1.1 Background

During the past century, some scientists have predicted a warming trend which could result in a significant change in the earth's climate. Agricultural practices are very dependent on climate therefore any changes will have important implications for food production and supply. The importance of successful agricultural practices to man's survival and to the health of many economies, should not be underestimated and as a result, scientists, policy makers and governments require an indication of the potential effects of climatic warming on agriculture (among other sectors) and strategies to minimise any disruptions or capitalise upon the benefits it may endow.

The province of Manitoba, Canada, is very reliant upon agriculture and agriculturally related industries. In 1987, approximately 55% of the value of agricultural production was obtained from crop oriented practices (Manitoba Agriculture 1987), which stretch to the limits of possible productive areas; as such these marginal areas are likely to exhibit noticeable responses to climate change. Therefore, knowledge relating to the effects of climate change on agriculture and possible responses to these changes is essential for Manitobans as well as people engaged in agriculture all over the world. This study will consider the possible effect of different climate change scenarios on crop yields in Manitoba, and the responses required by farmers to maintain economically optimal (or close optimal) production patterns.

1.2 The Greenhouse Effect

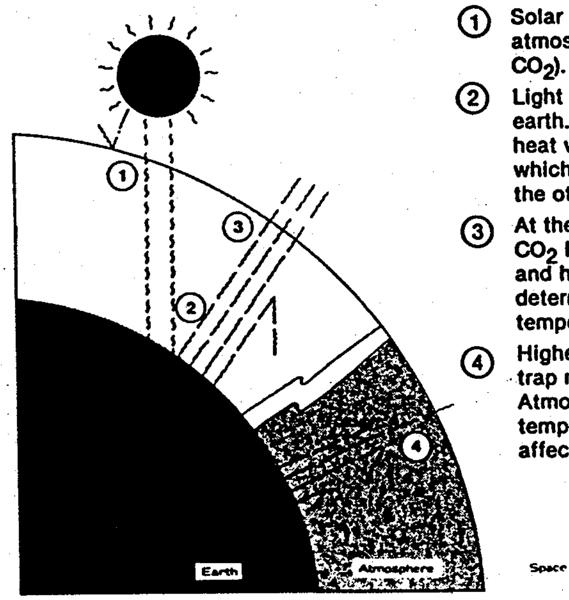
Several theories have been propounded to explain the observed warming trend. These can be divided into two categories; those considering natural and those considering man made phenomena. Cyclical warming and cooling of the Earth's climate has been observed for many years; for example the last major warming occurred approximately 12,000 years ago (Schneider 1986) bringing an end to the last ice age. These types of climate change are considered related to natural events such as changes in the terrestrial carbon or hydrological cycle, or the earth's orbit and declination (Newman 1980). However, since the early 1970's greater importance has been given to the role of man's activities as a factor influencing climatic change. There is increasing evidence to suggest that climatic warming may be occurring as a result of burning fossil fuels, large scale destruction of the rainforests and man's total agricultural, industrial and transport activities which increase the atmospheric concentration of carbon dioxide (CO_2), methane, chloroflurocarbons (CFCs) and nitrous oxide particles (among others). Short wave radiation emitted by the sun is able to penetrate through the earth's atmosphere and reach its surface. When radiation strikes the earth, some is reflected and some absorbed and converted into heat energy. As the earth warms, it also emits radiation back up into the atmosphere. This radiation is of a much longer wavelength than that received by the earth and is easily absorbed and reflected back by many of the gases in the atmosphere, for example CO_2. Therefore, there is concern that the documented increase in the concentrations of CO_2 and other atmospheric gases are causing more energy to be trapped and temperatures to rise (See

Fig. 1.1). This warming trend is commonly referred to as the Greenhouse effect, and the gases referred to as the Greenhouse gases. Of all the gases, CO_2 is considered the major contributor to the greenhouse effect with CFCs a close second (Fig. 1.2). CO_2 is the major contributor due to its volume while CFCs, though not present in such great quantities, contribute substantially because of their potent greenhouse characteristics.

1.3 Speed of Climatic Warming

There are wide ranging estimates available which predict the speed of CO_2 increase in the atmosphere. Among the most rapid increase projected is a doubling of CO_2 (to approximately 600 ppm)[1] by the years 2035 to 2040. More conservative projections predict a doubling by the year 2075 or beyond (White 1985). Large scale general circulation models (GCMs), such as GFDL (Geophysical Fluid Dynamics Laboratory) and GISS (Goddard Institute for Space Studies), are being used to predict the effects of the observed CO_2 increase on the Earth's climate. Most studies have suggested that there will be a greater increase in temperature in the high latitudes and mid-continental regions than in the tropics (Arthur 1988, Manabe and Weatherald 1980 cited in White 1985), but no general consensus has been reached concerning the effects of increased CO_2 on precipitation. Most models predict an overall increase in precipitation with greenhouse warming, but the monthly and regional distributions are unknown (Arthur 1988). Oram (1985) states that, "temperature effects of a secular climatic change are likely to have a greater impact on production systems in colder regions of the

[1]. ppm - parts per million.



① Solar energy enters the atmosphere (unimpeded by CO_2).

② Light is absorbed by the earth. It is reradiated at longer heat wavelengths, some of which are captured by CO_2; the others escape into space.

③ At the normal atmospheric CO_2 level the quantity of light and heat escaping into space determines the earth's temperature and climate.

④ Higher concentrations of CO_2 trap more reradiated heat. Atmospheric and surface temperatures increase, affecting weather and climate.

Figure 1.1 The Greenhouse Effect: how it works.

Source: Environment Canada, Atmospheric Environment Service, Fact Sheet "The Greenhouse Gasses", 1986.

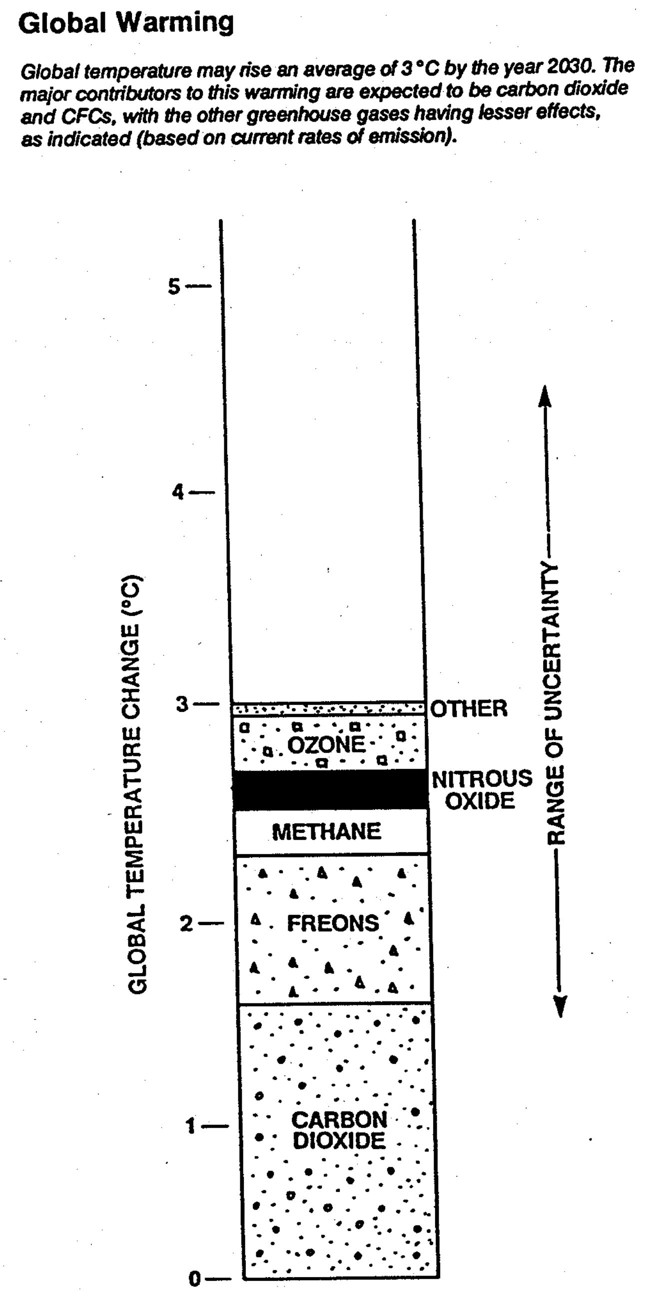


Figure 1.2 Amount of Global Warming Attributed to Each of the Greenhouse Gasses.

Source: Environment Canada, Atmospheric Environment Service, Fact Sheet "The Greenhouse Gasses", 1986.

while the effects of a change in total precipitation or its distribution will be most pronounced in lower latitudes". However, Manabe and Weatherald suggest that there will still be a substantial increase in precipitation in the higher latitudes (47N and above) because of the greater poleward transfer of water vapour (Manabe and Weatherald 1980, cited in White 1985). It should be noted that the province of Manitoba lies within these bounds. Its large reliance on agriculture for revenue and employment make it important to investigate and understand the implications of a changed climate.

1.1.3 Magnitude of Change

The extent of precipitation and temperature changes predicted by the GCMs are variable. The estimates presented in Table 1.1 relate only to Manitoba, it should be remembered that different areas of the world are likely to be affected to different extents. Each of the GCMs differ slightly in the way they model the atmosphere and their degree of resolution (Table 1.2), which could account for a large part of the variation between their predictions, (Table 1.1). Although their results differ, in general "virtually all theoretical studies suggest that increasing CO_2 concentrations would significantly increase average global temperatures" (White 1985,).

1.4 Choice of GCM

Each GCM has slightly different predictions for temperature and precipitation changes that will occur as a result of doubling CO_2 in the atmosphere. The choice of GCM is therefore important as its predictions will have an effect on the final conclusions of the study. The GCM results used in this study are those given by the

Table 1.1

Changes in Existing Temperature and Precipitation Predicted for Manitoba by Three General Circulation Models under a 2*CO2 Climate Change Scenario

Temperature Change in C

	Deloraine GFDL (a)	Deloraine OSU (b)	Deloraine GISS (c)	Portage (d) GFDL	Portage OSU	Portage GISS	Niverville GFDL	Niverville OSU	Niverville GISS	Arborg GFDL	Arborg OSU	Arborg GISS	The Pas GFDL	The Pas OSU	The Pas GISS
January	5.91	4.30	5.80	6.61	4.42	5.50	6.22	4.56	5.60	7.00	4.42	5.40	6.96	4.08	7.30
February	7.46	3.60	5.90	8.45	3.72	6.00	7.81	3.72	6.00	9.10	3.88	6.00	8.38	4.03	5.70
March	7.53	3.80	5.22	7.95	3.92	5.20	7.61	3.97	5.30	8.30	3.90	5.30	8.50	3.45	5.20
April	7.85	3.40	5.70	8.14	3.12	5.50	7.38	3.02	5.30	8.90	3.08	5.50	10.17	3.68	5.30
May	4.96	3.20	3.10	4.91	3.28	2.70	4.52	3.27	2.70	5.30	3.27	2.60	6.61	3.08	3.70
June	8.68	3.70	3.30	9.14	3.90	3.20	9.28	4.03	3.30	9.00	3.93	3.20	8.29	3.60	2.90
July	8.79	3.30	3.04	8.94	3.34	3.00	9.08	3.42	3.00	8.80	3.36	2.90	7.74	3.45	3.40
August	8.21	3.30	2.84	8.21	3.50	2.60	8.42	3.68	2.80	8.00	3.50	2.40	6.96	3.03	2.40
September	7.12	3.50	4.54	7.78	3.42	4.20	7.75	3.42	4.50	7.80	3.42	4.00	6.82	3.55	4.00
October	6.37	3.20	4.41	7.27	2.88	4.20	7.04	2.62	4.20	7.50	2.72	4.20	6.79	2.45	4.50
November	5.94	3.20	6.13	6.12	3.12	6.10	6.23	2.97	6.10	6.00	2.83	6.10	5.72	3.05	6.80
December	6.86	2.80	5.30	7.48	2.88	5.30	7.37	2.87	5.30	7.60	2.74	5.20	7.36	3.05	5.90

Pecipitation % Change in mm

	Deloraine GFDL (a)	Deloraine OSU (b)	Deloraine GISS (c)	Portage (d) GFDL	Portage OSU	Portage GISS	Niverville GFDL	Niverville OSU	Niverville GISS	Arborg GFDL	Arborg OSU	Arborg GISS	The Pas GFDL	The Pas OSU	The Pas GISS
January	111.74	140.00	108.40	113.77	141.60	103.00	119.54	137.08	103.00	108.00	137.58	101.00	114.22	124.00	119.00
February	127.96	108.00	123.70	125.62	111.60	122.00	124.23	114.89	120.00	127.00	113.00	125.00	124.30	118.00	133.00
March	115.54	130.00	131.50	108.38	127.24	125.00	109.77	122.84	124.00	107.00	129.23	123.00	109.77	131.48	152.00
April	113.98	123.00	103.80	104.00	113.80	107.00	113.00	110.22	108.00	95.00	110.82	108.00	117.48	120.00	113.00
May	104.43	88.00	105.40	92.77	87.60	99.00	95.54	86.02	99.00	90.00	89.57	97.00	97.87	91.00	113.00
June	77.25	106.00	106.00	72.08	105.60	111.00	68.15	102.75	112.00	76.00	106.92	114.00	89.92	114.75	120.00
July	66.30	146.00	120.00	73.38	135.60	118.00	68.77	126.53	115.00	78.00	124.50	120.00	75.37	98.25	124.00
August	68.67	142.00	122.00	70.23	128.00	124.00	73.46	119.14	123.00	67.00	121.03	126.00	86.32	124.75	110.00
September	82.11	100.00	72.00	79.85	103.32	91.00	81.69	105.40	100.00	78.00	106.88	72.00	111.83	108.50	91.00
October	99.85	127.00	117.00	98.77	132.20	120.00	122.23	134.33	114.00	105.00	131.78	126.00	114.86	127.50	126.00
November	141.30	127.30	138.00	143.00	128.38	133.00	143.00	122.85	127.00	143.00	128.45	136.00	120.13	119.55	131.00
December	126.73	100.00	108.00	142.85	96.36	112.00	135.69	94.93	115.00	150.00	96.21	113.00	124.24	105.00	113.00

Source: Linear Interpolation from GCM Results provided by Atmospheric Environment Service, Agriculture Canada.

(a) Geophisical Fluid Dynamics Laboratory.
(b) Oregon State University.
(c) Goddard Institute for Space Studies.
(d) Portage La Prairie.

Table 1.2 The General Characteristics of Five GCM Models

	GFDL	GISS	NCAR	OSU	UKMO
Gridcell dimentions (lat *long)	4.44^{o} * 7.5^{o}	7.83^{o} * 10.0^{o}	4.44^{o} * 7.5^{o}	4.0^{o} * 5.0^{o}	3.0^{o} * 330km
Approx gridcell area ($1000km^2$)	330	650	330	190	110
Vertical resolution (layers)	9	9	9	2	11
Cloud distribution in troposphere influence on radiation	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer
Insolation	Seasonal cycle	Seasonal and diurnal cycles	Seasonal cycle	Seasonal cycle	Seasonal and diurnal cycles
Land/ocean distribution	Realistic	Realistic	Realistic	Realistic	Realistic
Topography	Realistic	Realistic	Realistic	Realistic	Realistic
Ocean	Mixed layer is 50m deep	Mixed layer with seasonally depth is prescribed from climatology but with a maximum allowed depth of 65m prescribed seasonal ocean heat convergence	Mixed layer is 50m deep	Mixed layer is 60m deep	Mixed layer is 50m deep; prescribe ocean heat heat convergence

GFDL Geophysical Fluid Dynamics Laboratory
GISS Goddard Institute for Space Studies
NCAR National Centre for Atmospheric Research
OSU Oregon State University
UKMO United Kingdom Meteorological Office

Source: Kellogg, W.W. and Z. Zhao. 1988.

1988 run of the Goddard Institute for Space Studies (GISS) model[2]. This particular model was chosen above the others for several reasons; previous versions of the model have been used to predict climate change on the Prairies in past studies (Williams et al 1988, Arthur 1988) thus some continuity in climate change research would be maintained, it was recommended by experts in the field of climate change studies[3] and filled several criteria deemed desirable by Bach (Bach 1988). He considered that for climate impact analysis upon agriculture the GCM used should ideally meet the following specifications:

a) be based on a realistic geography and topography,

b) have a high spatial resolution,

c) have an adequate temporal resolution,

d) incorporate a coupled model of the atmosphere-ocean circulation,

e) simulate realistically the patterns of the observed climate (Bach 1988).

Bach discovered that none of the GCMs available at present fulfilled all of these requirements. However, in his estimation, the GISS model came the closest, its major disadvantage being its degree of resolution.

Modellers and those conducting research into the impacts of climate change should always bare in mind that predictions from the current GCMs are not very realistic, therefore research must be considered in terms of possible scenarios rather than predictions of future events.

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[2] 2*CO_2 is selected due to the wide availability of GCM model results for this scenario. The effects of other greenhouse gases, or other CO_2 concentrations have not been widely simulated.

[3] Personal Communication with J.B. Harrington, Climate Change and the Environment Conference, May 11, 1989, Winnipeg.

1.5 Agriculture and Climate

Agricultural systems are closely related to climate. Different systems have evolved throughout the world as a result of climatic differences and climatic influences on factors such as soil type. These factors determine the crops that can be produced successfully in different areas. Climatic changes are likely to affect both the magnitude of production and the efficiency of the production system (White 1985). The profitability of crops that are presently grown will change as yields are altered, resulting in new boundaries between cropping zones and an evolution of new production systems. The crop mix in many areas may have to change over time, crops which were once profitable being rejected as unsuitable for the new climate while previously infeasible and unprofitable crops could be introduced.

If changes in crop variety and type need to occur, it is likely they will come about gradually as the climate begins to change. Farmers need to be educated to produce these new crops, and markets must be explored and opened for the products. The speed of adoption may well relate to the risk preferences of the farming community. That is, the more risk averse the farmer, the slower new technology or cropping practices will be adopted unless sufficient education and information are available. Social and economic factors react with technology and climate and are likely to have a major influence in determining which crops will be preferred by producers among the range feasible. Greater awareness of the need for changes and the rationale behind them reduces the perceived riskiness of adopting new practices and could smooth and quicken the period of change for the agricultural sector.

GCM climatic change results have indicated that large areas of the Canadian Prairie

Provinces at present unsuitable for agricultural practices could become usable should the climate change as predicted as a result of doubling CO_2. For the Prairie Provinces as a whole, one estimate predicts that 4 million hectares of mineral soils and 3.1 million hectares of organic soils would become suitable for agricultural production (Arthur 1988). At present many of these soils are in areas climatically unsuited to agriculture due to climatically limiting factors such as growing season length and number of heat units received. Other areas are at present suited for crop production but input costs exceed those in the south of the province making these areas less economically viable. Additional areas where soils are also limiting for example: Cryosols, could also be freed for production as with a milder climate their structure would change over time making them suitable for marginal agricultural practices (Dept. Agricultural Economics and Farm Management 1985).

The combination of yield and crop type changes coupled with an extended agriculturally productive area could have significant beneficial effects throughout the Manitoba economy. Many sectors, for example the transport sector, financial markets, agricultural services and machinery manufacturers, have strong linkages with agriculture (Arthur and Freshwater 1986). Therefore any changes in the agricultural sector will also have an impact on the well being or otherwise of these other sectors.

CHAPTER TWO

PROBLEM STATEMENT AND SPECIFICATION OF OBJECTIVES

2.1 Problem Statement

The recent trend of increased global temperatures, corresponding to higher concentrations of certain gasses in the atmosphere, suggest that a change in the earth's climate may be occurring. Agricultural practices will be directly affected by any such change because of the strong linkages between plant growth and development with climate.

Agriculture and its support industries are an important part of the Manitoba economy. Global warming will lead to changes in the relative profitability of crops, perhaps making it necessary to introduce new crops or different varieties of existing crops into Manitoba to maintain economic production practices. It is important that farmers become informed of likely future events so that they can plan for them. Decisions at the farm level have important implications for other sectors too, as any change in farming practices will affect the rest of the agricultural industry and the economy as a whole because of the close interlinkages between different sectors. Agricultural chemical manufacturers, seed merchants, chemical distributors and machinery manufacturers and suppliers will be particularly affected by any changes in the farm demand for their products. If new crops are introduced, a need for different chemical treatments, extension advice and perhaps even different machinery and equipment will arise. The requirements of existing crops could also change to some extent as their yield relationships to inputs such as fertiliser alter. It is important to consider what changes may occur and what responses would be appropriate to these changes. In any situation of change, markets diminish in size and others open up. The manufacturing and service sectors must be aware of the potential contractionary and expansionary markets in order to remain competitive against each other and outside foreign competition. There is a danger that ill advised or informed action; or slow responses to changing demands and new markets, could lead to market take over by more experienced firms in other areas of Canada, or by foreign competitors already experienced in meeting these demands giving them an edge in competition. If this were the case, job losses within the province would result, having a detrimental effect on the economy of the province as a whole. Predictions of the likely economic consequences of climatic change are required by farmers, researchers and policy makers alike to enable them to plan for the future.

At present there is some dispute as to the exact nature of the climatic change, due to the differing predictions of GCMs. The uncertainty of these predictions make it necessary to consider more than one possible climate scenario so that a number of different situations can be explored and appropriate responses considered. Once modelling techniques have been improved and more reliance can be placed on their predictions, appropriate courses of action will have already been discovered and their implications explored.

2.2 Objectives

1. To estimate how yields of existing crops will change in response to an altered climate, using one GCM.

2. To suggest new enterprises which could be adopted as a result of climate

change.

3. To formulate a simple linear programming (L.P) model in order to study the potential economic consequences of climate change for the agricultural sector within Manitoba.

4. To use the economic model to project changes in cropping patterns resulting from climatic changes.

Attainment of these objectives will add to the body of knowledge relating to impacts of climate change, by considering its effects and possible reactions to these effects.

CHAPTER THREE

REVIEW OF RELEVANT LITERATURE

Many different approaches can be used to assess the impacts of climate change upon agriculture. This study focuses upon the impacts of climate change on crop production in Manitoba, therefore methods used to estimate yield changes, crop region movements and the economic impacts of these changes are of most interest.

Several techniques have been used in previous studies to estimate yield changes and crop area movements. Crop migration is often estimated by matching the 2*CO_2 climate, predicted by GCM runs, for one region with the present climate in another region. The crops presently grown in the analogous region are considered to be suitable for production in the first area under a 2*CO_2 climate. This method enables researchers to estimate at least two things. Firstly, the new crops which could be grown under a 2*CO_2 climate and those existing crops which would be no longer suitable for production; secondly, the direction of yield changes likely to occur in existing crops that are still suited climatically. For example, if spring wheat is produced under the present climate in the area of interest and is also produced in the analogous area but with higher yields, it is likely that with climatic warming spring wheat will still be produced in the first area and yields will increase. Unfortunately this method cannot account for differences in factors such as soil type and daylength between areas which affect the suitability of these areas for crop production and the yields that can be achieved. However, these drawbacks can be minimised as long as the researcher is aware of some of the consequences of these differences. In general, the simplicity of this approach makes it a useful tool for impact assessment although care must be taken to weigh the feasibility of the results in order to prevent unlikely generalisations arising. Rosenzweig (1985), Newman (1980) and Fraser (1984) use variations of this approach in their climate impact assessments. Each of their approaches are described and discussed in section 3.1.

The method of analogous regions can give some indication of yield changes in response to climate, however there are other techniques available that are also commonly used. A large number of climatic impact studies have tended to favour the use of biological simulations or statistical weather-yield relationships to estimate yield changes. Both of these methods have a number of disadvantages. Yield regression equations are developed using empirical observations of yield response to climate in a particular geographical location and over a certain weather range. Outside the data set and location for which they were estimated, their predictions become less accurate as not all factors affecting crop growth can be accounted for simultaneously. Therefore, under a climate change scenario the accuracy of yield predictions from regression equations is diminished. In addition, the opportunities to explore the performance of new crops are very limited because regression equations tend to be location specific. Biological simulations of crop development and yield in response to a different climate tend to be quite demanding in terms of data requirements, a further limitation is that only a few crops are well modelled. Arthur (1988), Wilkes (1988) and Williams et al (1987), are examples of studies using these approaches for climate impact assessment and are discussed in Section 3.2.

This study is primarily concerned with the impacts of climate change on the agricultural sector of the Manitoba economy. Therefore, once the effects of climate change upon crop yield and type have been estimated, the economic consequences of these changes need to be followed through. Past studies such as Arthur (1988), Williams et al (1987) and MacGregor and Graham (1988), have used input output analysis and programming techniques for economic impact estimation and are described in section 3.3. Input output analysis though extremely useful in terms of assessing the effects of climate change on different sectors of the economy and illustrating the linkages and multiplier effects between each of these sectors, tends to be demanding in its data requirements. Programming techniques, such as linear programming are less demanding in terms of data required and can be fairly easy to build. Although a number of simplifying assumptions are associated with this technique, for example linearity and determinism, models can still give a good indication of the economic consequences of yield and crop changes.

3.1 Crop Movement using the Technique of Analogous Regions

The following papers (Rosenzweig 1985, Newman 1980 and Fraser 1984), attempt to estimate the extent of crop migration as a result of climate change. No common method is used in these papers but in general, present climates and cropping patterns are compared to those in the past and the relationship between previous climate change and crop movement estimated.

Rosenzweig (1985)

Rosenzweig considers the effects of climate change, caused by doubling CO_2 on the geographic location of wheat production in areas of North America. The environmental requirements of winter, spring and fall sown wheats in North America were collected and compared to temperatures predicted by the control run, ($1*CO_2$), of the Goddard Institute for Space Studies (GISS) general circulation model (GCM) and observed precipitation[4]. This data was used to generate a simulated map of current wheat producing regions which agreed substantially with the actual pattern of wheat production (Figs. 3.1.1 and 3.1.2).

The $2*CO_2$ GISS GCM runs indicated that under a situation of doubled CO_2 levels, average temperatures in the eastern U.S. would increase by 4.2°C. In central and western areas, average temperatures were predicted to increase by 4.9°C. These figures are at the upper end of temperature changes predicted by the GCMs; therefore study results likely provide an upper bound to the sensitivity of studied wheat regions to CO_2 induced warming.

The $2*CO_2$ GISS model scenarios were matched with environmental requirements of wheat. The results suggested that there would be a substantial extension of the winter wheat belt into Canada due to moderated temperature variables, lengthened growing season, and increased mean minimum January temperatures (Figs. 3.1.3 and 3.1.4). Her results suggest that acreage of fall and winter wheat will move northward and acreage of spring wheat decline. This could be a result of the increase in production of fall and winter wheat. The fall sown spring wheat region was expected to extend further north and eastward than its present situation, with greater acreage in southern latitudes due to warmer winter temperatures. No estimates were given concerning the degree of movement north.

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[4] Precipitation changes from climatic change are not well understood, although some modellers feel that there is not adequate grounds for ignoring the precipitation predictions of GCM's (Schlesinger).

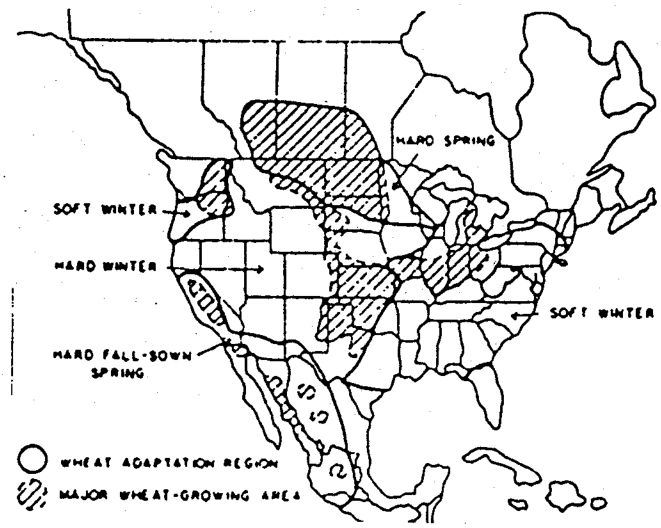

Figure 3.1.1 The Major Wheat Growing Areas of North America

Source: U.S. Wheat Associates and Foreign Agricultural Service, USDA.

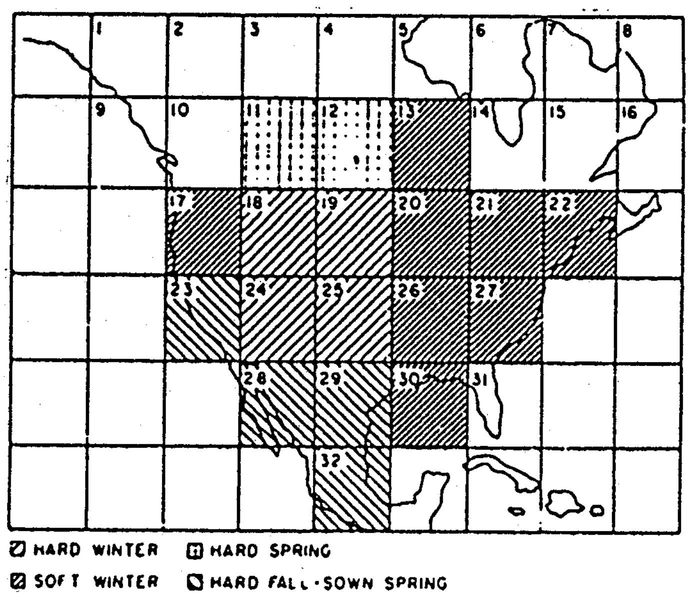

Figure 3.1.2 Actual Wheat Growing Regions of North America on the GISS GCM Grid

Source: Rosenzweig 1985.

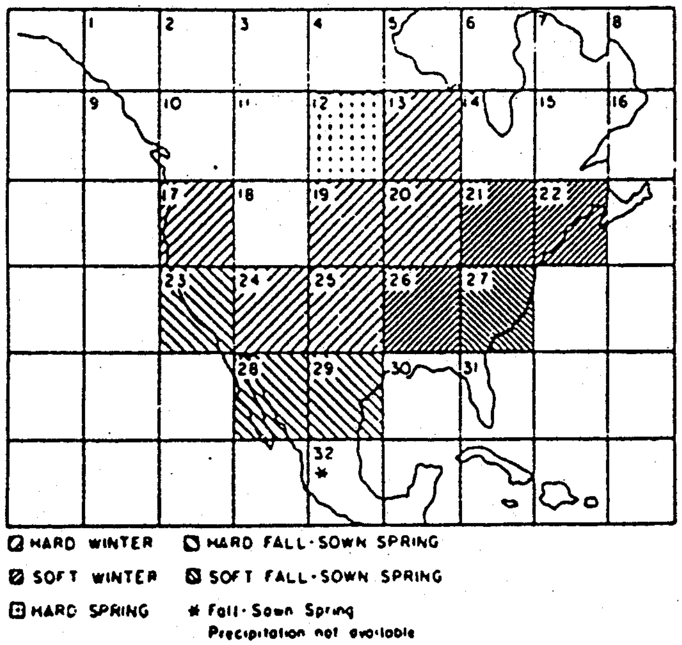

Figure 3.1.3 Simulated North American Wheat Regions using the GISS GCM Control Run
Source: Rosenzweig 1985.

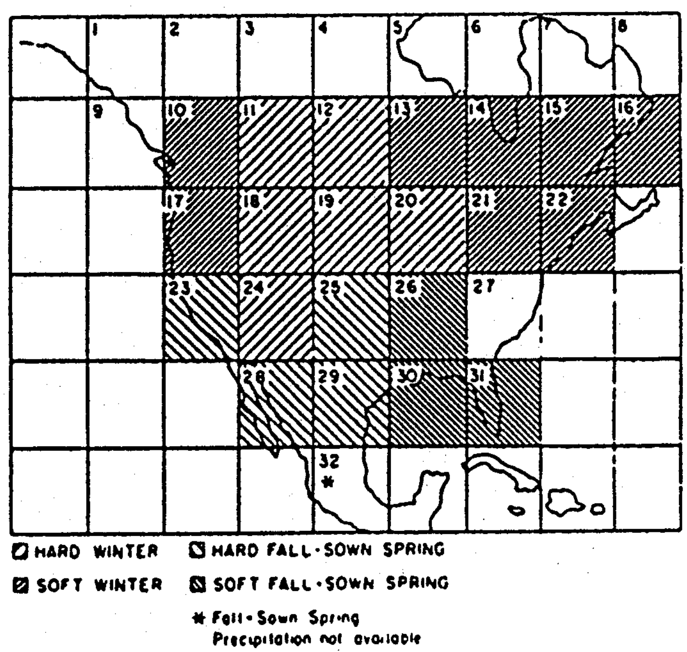

Figure 3.1.4 Simulated Wheat Regions using GISS GCM Doubled CO_2 Run
Source: Rosenzweig 1985.

This method adopted by Rosenzweig would seem to be a reasonable way of estimating the suitability of crops for production in different areas of the world. However care must be taken to consider factors such as daylength, and its effect on plant development, amongst others when considering the results. Use of this technique is limited as the input data describing minimum requirements for crop growth are not readily available for the majority of crops. In addition, it cannot distinguish between regions with different soil types, topographical characteristics and daylength, all of which alter the suitability of areas for production of specific crops.

Newman (1980)

Newman used estimates of historical climate change and predictions of future climate, to forecast the potential effects of climatic change on the location of the North American corn belt. Shifts in the northern limits of historical maize cultivation were documented and validated using a computer simulation. The geographical movements of the simulated seasonal thermal unit changes[5] were found to be similar to changes in the location of historical corn fields. It was found that for every 1°C change in the temperature, the corn growing regions shifted on average by 144km (Fig. 3.2.1).

The effect of temperature changes on the annual change in potential evapotranspiration (PE) was estimated using a second computer simulation. For every degree centigrade change in temperature, a west-east shift of approximately 100km in annual PE values was predicted.

The two results reported above were combined to estimate the geographical shift

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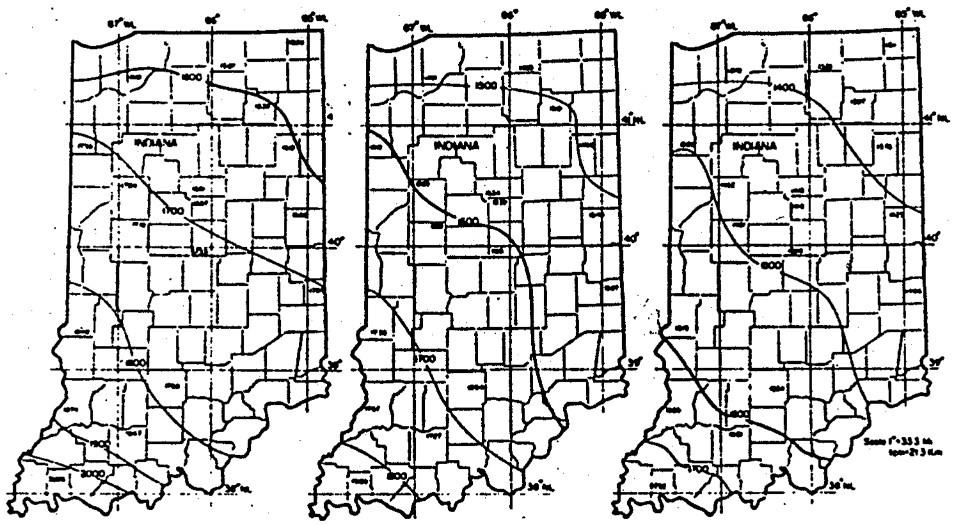
[5] Measured in growing degree days, (GDD). GDDs are a daily time-temperature level index value of thermal units used to estimate crop thermal requirements.



a b c

a) GDD normals (base 10°C, modified) 1969-1978 GDD in °C + 1°C deviation,
b) GDD normals (base 10°C, modified) 1969-1978 GDD in °C no deviation,
c) GDD normals (base 10°C, modified) 1969-1978 GDD in °C - 1°C deviation.

GDD = Growing Degree Days

Figure 3.2.1 Shift in the North American Corn Belt as a Result of Temperature Changes

Source: Newman 1980.

in the corn belt per 1°C climate change. The simulated displacement gradient was calculated as being 175km/°C in a SSW-NNE direction. A warmer and drier climate displaced the corn belt toward the north east whilst a warmer and wetter climate displaced the corn belt north and slightly to the west (Fig. 3.2.2). Newman did not make any comment on yield changes, however it is implicit that yields must be less favourable in areas left by corn growers and be more favourable in the new areas adopted. Similar to Rosenzweig, Newman's method cannot account for differences in factors such as daylength and soil type.

Fraser (1984)

Fraser examines long term climatic data for North America to forecast the future Prairie climate resulting from doubling CO_2 in the atmosphere. Using an average of climate change predictions from several GCMs, Fraser considers it reasonable to expect a warming of 5°C during the winter and 3°C during the summer months on the eastern Prairies (Fraser 1984, 197). Maps of present temperature in North America during January and July (Figs. 3.3.1 and 3.3.2) were utilised to locate areas where the present climate approximates that of the Prairies in the future. The areas selected as the most representative were the Dakota's and Montana[6]. This prediction is roughly consistent with those of other literature using the method of analogous regions.

The prediction of future moisture levels is a little more uncertain, mainly because modelling techniques are not as reliable as those available for temperature prediction. Fraser considers work completed by Kellogg and Schware (1982) in his estimations.

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[6] Fraser, p.197.

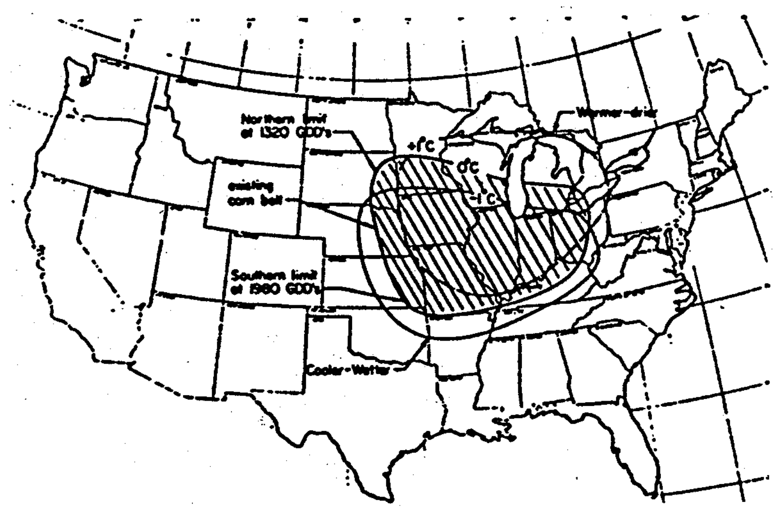

Figure 3.2.2 Simulated Goegraphical shift in the US Corn Belt Based on Frost Free Growing Season Thermal Units. (Thermal units in growing degree days - GDDs in °C)

Source: Newman 1980.

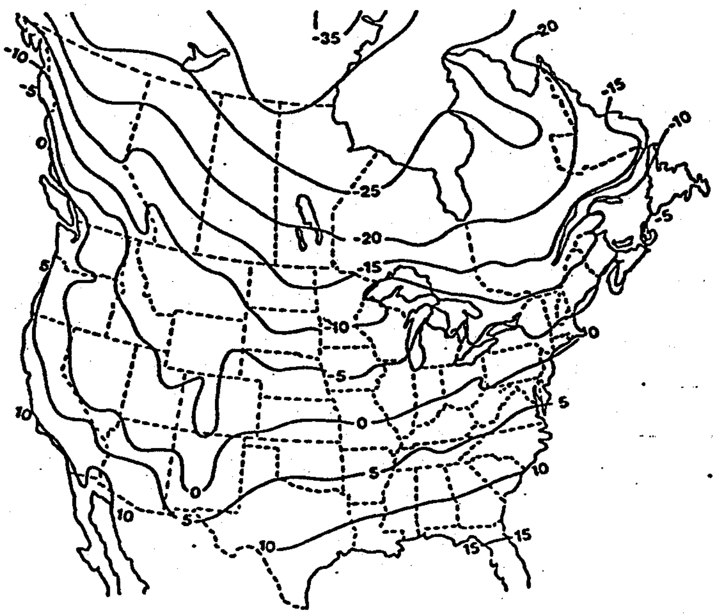

Figure 3.3.1 Mean January Temperatures °C - North America
Source: Fraser 1884.

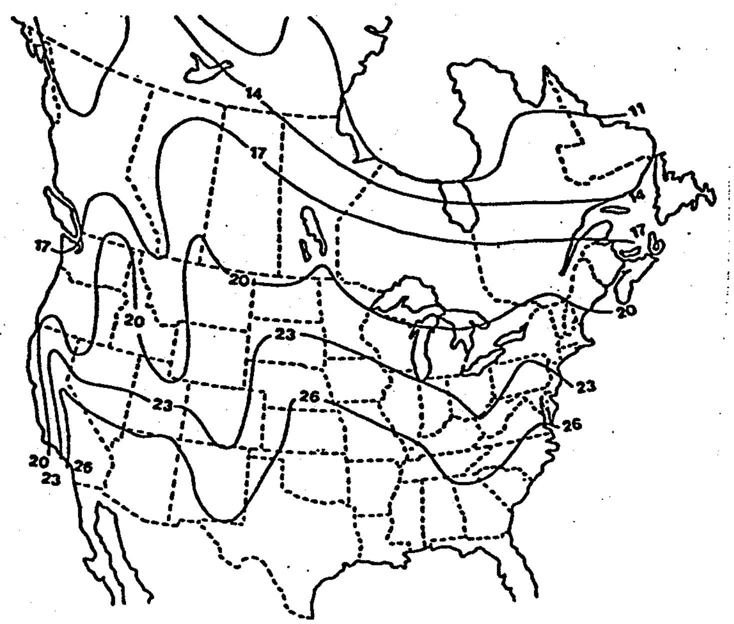

Figure 3.3.2 Mean July Temperatures °C - North America
Source: Fraser 1984.

Their study suggested that the central plains of North America would have lower soil moisture, perhaps extending far enough for an effect to be felt on the Prairies (Fig. 3.3.3) (Kellogg and Schware 1982, cited in Fraser 1984).

In terms of the effect of the described climate change on agriculture, Fraser is optimistic. He stresses the possibilities for a northward shift in agriculture to areas previously limited by temperature, despite soil limitations, and considers it possible for agricultural practices to adapt to the new climate.

3.2 Yield Changes using Biological and Statistical Models

Over the past few years, a number of studies have attempted to go beyond predicting simple crop movement; instead they use biological simulations and statistical regression equations to estimate the changes in yields expected as a result of changing climate. There are many weather-crop yield models available throughout the world[7], varying in degree of complexity and suitability to different problems. The techniques used in the following studies were considered to estimate the effects of climate change on crop yields in Manitoba.

Williams et al (1987)

This study is one of five studies used by IIASA/UNEP (International Institute for Applied Systems Analysis/ United Nations Environment Programme) to assess the impacts of climate change and variability on food production. It considers the effect of climate change on the agricultural sector in Saskatchewan.

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[7] For a good review of those available, their applications and limitations see Robertson 1983.

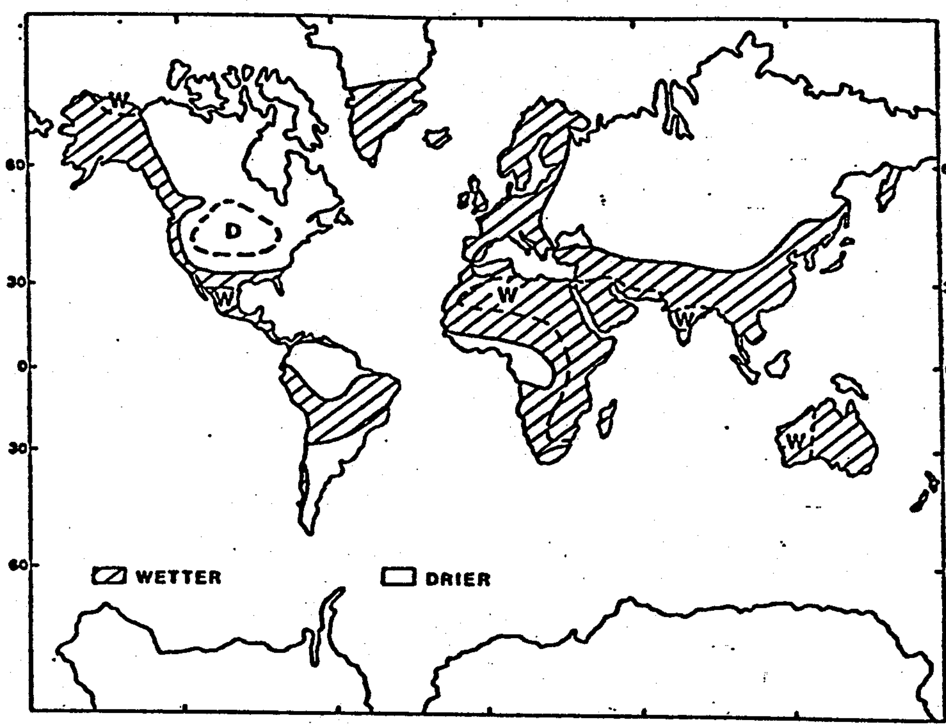

Figure 3.3.3 Soil Moisture Patterns on a Warmer Earth
Source: Kellogg and Schware 1982.

The study can be considered in three distinct stages; the first being the calculation of the new climate scenario, the second the estimation of spring wheat yields under that changed scenario and lastly an assessment of the economic impacts on various sectors of the economy resulting from yield changes (described in Section 3.3).

The control run (1* CO_2) of the GISS model was compared to historical climate normals for Saskatchewan but was found to bear little resemblance (Williams et al 1987, 19). However, the study assumed that changes recorded from the 1*CO_2 to 2*CO_2 GISS runs would approximate to changes expected in the Saskatchewan climate with a CO_2 doubling. Climatic normals were altered accordingly to give what was considered to be a better representation of a 2*CO_2 climate for Saskatchewan.

The climate change results indicated that Saskatchewan should expect a warmer and wetter climate under a 2*CO_2 scenario[8]. However, after reviewing literature which indicated that higher temperatures were historically associated with lower rainfall, Williams et al decided to consider a doubled CO_2 scenario with only increased temperature and fix precipitation at its historical normal levels[9].

The results from the climate model were then fed into a crop yield model to estimate the effects of climate change on spring wheat yield in Saskatchewan. The model used was a crop growth model previously developed for land use purposes by Dumanski and Stewart (Dumanski and Stewart 1983). The yield calculations are based on methodology developed by the F.A.O (Food and Agriculture Organisation) and utilise tabulated results from the De Wit (1965) photosynthesis model to compute

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[8] "Wetter" meaning that precipitation will increase from historical levels.

[9] They were later criticised for this, particularly by Schlesinger.

constraint free yields (Williams et al 1988, 50). That is, initially it is assumed that there are no moisture, pest or other constraints to crop growth. These yields are then adjusted by agroclimatic constraint indices and net biomass and dry matter yields calculated. Wheat yields on both stubble and fallow were calculated. Results indicated that the overall effect of a climate change would be to decrease yields between 18% to 28%, depending on moisture availability[10].

For the economic model, changes in the yields of other grain crops were assumed to be the same in percentage terms. It should be noted that in reality these ratios would not remain the same as many crops respond at different rates and in different ways to climatic stimuli. It is important to discover the relative responses of each crop to climate change as this may help to indicate more accurately which crops would be more suitable for growth in the future.

Arthur (1988)

Climate change scenarios from GFDL (Geophysical Fluid Dynamics Laboratory) and GISS (Goddard Institute for Space Studies) GCMs were used as input into several models simulating different aspects of plant growth, in order to estimate the effects of climate change on Prairie agriculture.

The design of the study is similar to that of Williams et al in that a series of interlinked models are used to estimate yield changes. Firstly, daily temperatures and precipitation changes were extrapolated from the monthly results of both GCMs. Then

[10] When precipitation increases predicted by GISS were ignored, yields in Saskatchewan decreased by 10% more than when GISS precipitation predictions were accounted for (Williams et al 1987, 67).

a seeding date algorithm was used to forecast the effect these differences would have on the planting date of various crops. From the new planting dates and climatic information, a biometeorological time scale (BMTS) was developed in order to map the daily progress of a crop toward maturity (Robertson 1968).

The results obtained from the BMTS were then used to estimate soil moisture stress using the Versatile Soil Moisture Budget Model (VSMB) developed by Baier, yer and Sharp (Baier, Dyer and Sharp 1987). The figures for soil moisture stress were then used in yield regression equations to estimate changes in yields as a result of the 2*CO_2 climates. In addition to soil moisture stress, many other factors affecting yield were incorporated into the yield equations.

Yield changes were found to be varied over crop and province. In general, slight reductions in crop revenue were predicted (although Manitoba experienced slight increases in revenues under most of the scenario's examined).

Wilkes (1988)

Wilkes used results from the Oregon State University (OSU) GCM in conjunction with physiological simulation models similar to those used by Williams et al (1987) to estimate the possible effects of doubling CO_2 on wheat and corn (maize) yields in three North American cropping regions. He found that yields of both crops decreased in the areas considered, suggesting that a movement of growing areas further north might be advantageous.

The results indicated that there would be some changes in the geographical location of the cropping regions considered, mainly because of yield changes. Corn yields were found to increase in areas presently limited by insufficient temperatures, mainly the northern sectors of the three regions studied, and decrease in warmer areas. Simulation results indicated that the area of the continent well adapted to grain corn production might increase to the north as heat limitations were reduced, although the study did not give any estimates determining the extent of crop movement. Corn yields were estimated to decrease in the warmer southern areas, however they did not decline to the same extent as wheat yields, probably because corn is more tolerant to heat.

3.3 Economic Impacts

Once yield alterations as a result of climate change have been assessed, their economic implications must be considered. In the following sections, the methods used by different studies to measure these impacts on farming systems are reviewed.

Williams et al (1987)

The economic impacts of yield changes calculated using the F.A.O. model under a 2*CO_2 scenario were considered in two stages, at the farm level and at the provincial level. Firstly, the effects of yield changes on farm production were estimated using simulation models for five different farm types; crops; beef-forage-grain; grain; hog-grain; dairy-forage-grain and poultry (Williams et al 1987, 70). Farm operators had to choose between a number of alternative production methods based on varying management practices and resource availabilities. These individual farm results are then aggregated to provincial totals and incorporated in a regional input-output model (I-O), and employment model.

These models used by Williams et al were considered unsuitable for use in this study for several reasons. Firstly, the I-O and employment models are beyond the focus of this study as they consider the effects of climate change on several sectors of an economy whilst this study only considers its impacts on the agricultural sector in Manitoba. Therefore the models of most interest to this study are the farm level simulation models. Although these models did give plenty of scope for choosing alternative plans, the institutional and resource constraints are based on present practices and levels. In a future scenario, these could develop differently, affecting the most reasonable production plan. For these reasons, it would seem appropriate to use a model with fewer constraints which does not simulate present conditions quite as closely and allows greater flexibility in production decisions.

Arthur (1988)

In the final section of Arthur's study, the economic impacts of yield changes estimated using yield regression equations on the agricultural sector of the economy were estimated using a linear programming model. The changes predicted where then used as inputs into an input-output (I-O) model, in order to determine the effects of a 2*CO_2 scenario on the other sectors of the economy. The linear programming technique is of most interest for this particular study as it concerns the effects of yield changes on the agricultural sector only. The model used predicted yields to adjust cropping patterns in order to maximise net crop revenues, given physical, biological and economic constraints on the sector (Arthur 1988).

Linear programming is a very flexible tool which can give a great degree of scope in modelling different scenario's with relative ease. One drawback of this model is the constraints relating to present conditions which could change without too many problems in the future and significantly alter the final outcome.

MacGregor and Graham (1988)

Although this study does not consider climate change impacts, the model is of interest in terms of its potential for use in this area. There are several different techniques available for estimating the economic consequences of input or output changes on the agricultural sector. Their study used a comprehensive aggregate linear programming model (C.R.A.M.), developed by Webber, Graham and Klein[11], to measure the effects of persistently lower grain prices on regional and provincial production patterns, export levels, resource values and associated changes in farm value-added for the grains and oilseeds sector within Canada.

Canada was divided into 29 crop producing regions and domestic demand was specified at the provincial level. Grains and oilseed production was broken into several commodities including wheat, barley (including oats and rye), flax, canola, grain corn and soybeans. Other crops were aggregated and expressed in value rather than quantity terms. Land types were assumed to be homogeneous for each region.

Model results for two separate periods, 1985-1986 and 1990-1991 crop years, were compared to reveal production responses. Predictions from the first run, i.e 1985-1986, were close to recorded actual events which validated the predictive capacity of the model. The model was run for the second period incorporating lower prices for the commodities. Cropping practices in all areas were observed to change, providing an indication of producer response to lower prices. Summer fallow increased from 8Mha in 1885-86 to 12Mha in 1990-91. In addition, 24% of the total cropland shifted

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[11]Details of the Model can be found in Webber, Graham and Klein 1986.

from stubble to fallow cropping.

The main limitations of the model were the assumptions that land in various regions was a homogeneous resource and the inadequate representation of the quality differences of grain. In addition the cost incurred by shifting grain land to forage production was not represented. However, the construction of the model is of interest, particularly the crop section, and shows promise of adaptability for climate impact assessment in terms of its flexibility.

CHAPTER FOUR

METHODOLOGY AND THEORY SUPPORTING ANALYSIS

This study is composed of the three integrated parts. The first is the determination of the 2*CO_2 temperature and precipitation values for Manitoba from data provided by one of the major GCMs. The second involves predicting how yields of major prairie crops might alter as a result of the new climate, and the new crops that could be introduced, and the third considers the economic consequences of predicted changes in crop types and yields on the agricultural sector of Manitoba.

The following techniques and procedures were chosen for climate impact assessment in Manitoba after considering the literature reviewed in Chapter Three. The rationale supporting each of the choices is presented in the following sections. The F.A.O. model used by Williams et al was chosen to estimate yield changes. Similar to Newman, Rosenzweig and Fraser, the method of analogous regions was chosen to predict crop migration and indicate the new crops that could be introduced. In each of the aforementioned studies, different methods were used to estimate the extent of crop migration, suggesting that at present there is no generally accepted technique available to do this. This study will use a different method, cluster analysis, to assess the similarity between the 2*CO_2 climate for Manitoba and other climates. The economic model is largely based on the crop section of C.R.A.M. (Webber, Graham and Klein 1986), although modified extensively to make it better suited to the problem studied.

4.1 Estimation of Climate Change Using GCM Results

Data indicating changes in temperature and precipitation between 1*CO_2 and 2*CO_2 GCM climates were obtained from Environment Canada for the 1988 GISS GCM run. Within Manitoba there were only three reference values available; additional values were calculated for Deloraine, Elm Creek, Brandon, Dauphin, Arborg, Niverville, Swan River, The Pas and Thompson using linear interpolation between these points and other neighbouring points[12]. In total, nine grid points were used to estimate precipitation and temperature anomalies in Manitoba as a result of doubling CO_2 (Figs. 4.1 and 4.2).

Williams et al (1987), compared older 1*CO_2 GISS model results against 30 year climatic normals for Saskatchewan. They found that that particular GISS 1*CO_2 climate was not a very accurate representation of the actual climate. Temperatures were significantly higher in winter and significantly lower in summer than observed (Fig. 4.3), while precipitation was far greater than normally experienced (Fig. 4.4). To reduce these inaccuracies, Williams et al (1987) assumed that changes in temperature and precipitation between the 1*CO_2 and 2*CO_2 GISS results corresponded to changes that might occur in the observed climate due to a doubling of CO_2. Historical climate normals were used as a base scenario and combined with differences between 1*CO_2 and 2*CO GISS model results to predict a doubled CO_2 climate in Saskatchewan. Arthur (1988) also took the same approach. The underlying rationale for this approach is described in Williams et al (1987, section 1.5.2). The same approach was used to estimate the 2*CO_2 climate in Manitoba.

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[12] Simple linear interpolation between points was suggested in a personal communication to Dr. Louise Arthur, University of Manitoba, from Tom Agnew, Environment Canada.

January

*9.3	*9.6	*14.8
*6.3	*5.5	*5.0
*7.3	*6.5	*6.2

February

*5.2	*5.5	*9.7
*6.5	*5.9	*6.6
*4.1	*5.6	*5.5

March

*3.2	*5.5	*6.6
*3.8	*5.2	*4.8
*6.1	*6.1	*5.2

April

*3.6	*5.0	*2.8
*4.4	*5.7	*5.0
*5.0	*4.7	*5.1

May

*3.4	*4.7	*2.1
*3.6	*2.9	*1.5
*3.3	*3.5	*2.6

June

*3.3	*2.6	*1.7
*3.4	*3.1	*3.5
*3.7	*3.7	*3.7

July

*3.5	*4.0	*4.0
*2.6	*3.0	*2.6
*2.7	*3.6	*2.2

August

*3.6	*2.2	*4.6
*3.7	*2.3	*2.8
*4.3	*4.2	*3.8

September

*3.4	*3.7	*4.9
*5.9	*4.0	*4.0
*6.5	*5.5	*7.0

October

*4.5	*4.7	*4.9
*5.2	*4.3	*3.9
*5.2	*4.2	*3.8

November

*7.8	*7.4	*6.3
*6.5	*6.2	*5.9
*4.5	*5.9	*6.2

December

*7.8	*6.6	*12.4
*5.7	*5.2	*5.4
*5.1	*5.5	*5.9

Figure 4.1 Nine grid Points showing Temperature Anomalies in °C between 1*CO_2 and 2*CO_2 GISS model runs, used to adjust historical climate data to obtain a 2*CO_2 climate for Manitoba.

January

*135	*133	*144
*124	*105	*88
*118	*110	*118

February

*133	*140	*156
*150	*125	*124
*107	*104	*104

March

*162	*183	*120
*132	*130	*100
*139	*136	*127

April

*142	*125	*100
*100	*103	*121
*103	*110	*104

May

*110	*129	*94
*126	*100	*86
*128	*110	*111

June

*142	*136	*138
*103	*108	*132
*120	*98	*107

July

*130	*119	*114
*123	*128	*96
*111	*90	*112

August

*129	*95	*113
*100	*122	*138
*225	*120	*96

September

*130	*124	*122
*56	*67	*188
*125	*95	*69

October

*142	*124	*111
*133	*126	*125
*96	*73	*87

November

*115	*115	*106
*153	*142	*116
*152	*110	*96

December

*145	*117	*155
*118	*106	*135
*107	*111	*126

Figure 4.2 Nine grid Points showing Precipitation Anomalies in percentage changes between 1*CO_2 and 2*CO_2 GISS model runs, used to adjust historical climate to obtain a 2*CO_2 climate for Manitoba.

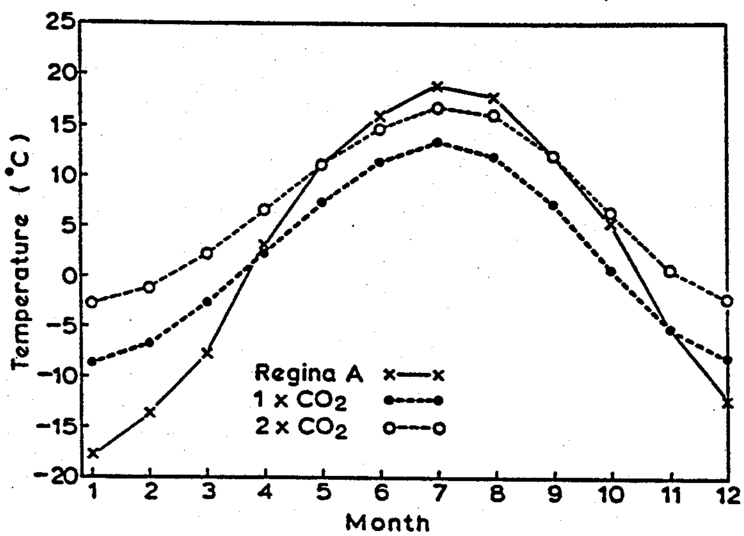

Figure 4.3 Comparison of Regina 1951-1980 normal mean monthly Temperature with GISS $1*CO_2$ and $2*CO_2$ results for 50°N Latitude, 105°W Longitude.
Source: Williams et al 1987.

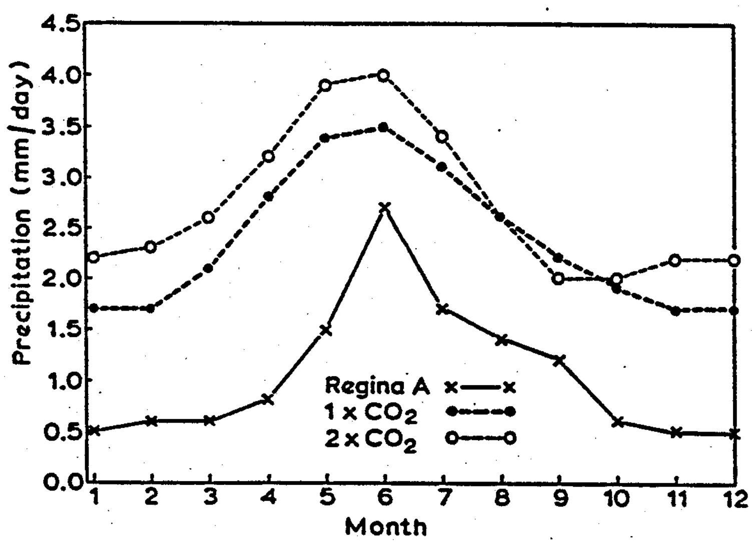

Figure 4.4 Comparison of Regina 1951-1980 normal Monthly Precipitation rate with GISS $1*CO_2$ and $2*CO_2$ results for 50°N Latitude, 105°W Longitude.
Source: Williams et al 1987.

Historical temperature and precipitation normals are adjusted using two different methods. Historical temperature normals are adjusted to reflect a $2*CO_2$ scenario using differences. That is, the difference between $1*CO_2$ and $2*CO_2$ temperature results are added to historical temperature averages to simulate $2*CO_2$ temperatures for Manitoba as follows:

$$T2CO = CTN + TA$$

Where,
T2CO = Estimate of monthly temperature in Manitoba as a result of CO_2 doubling.
CTN = Monthly temperature normal.
TA = Temperature anomaly between $1*CO_2$ and $2*CO_2$ GISS runs.

Historical precipitation normals are adjusted to obtain estimates reflecting a doubled CO_2 scenario using ratios as follows:

$$P2CO = PC * PN$$

Where,
P2CO = Estimate of monthly precipitation in Manitoba as a result of CO_2 doubling.
PC = Ratio of $2*CO_2$ to $1*CO_2$ values predicted by the GISS GCM model.
PN = Monthly precipitation normal (Williams et al 1988).

4.2 Estimation of Yield Changes in Existing Crops

4.2.1 Choice of yield model

When selecting any type of model, care must be taken to ensure that it is suitable for the purpose intended. It must be compatible with the data available and provide relatively reliable results. A large number of crop-weather models have been developed over recent years, each of differing complexity, data requirements and applicability. A good survey of many of these models is available from the W.M.O. (See Robertson

1983)

There are only a few weather-crop yield models readily available in Canada. Two possibilities were considered for use in this study. The first uses yield regression equations based on several variables such as soil moisture, fertilizer use, pest and variety selection, to estimate yield under changing conditions. The second is a dynamic model that estimates potentially attainable yields and then adjusts these estimates according to production constraints to estimate agroclimatically attainable yields. Both of the models considered have a number of drawbacks. The first uses regression equations which are limited in the range over which they are considered to give good results. They are generally most accurate for the data set, location and technology for which they were originally developed (Robertson 1983, 4). The accuracy of yield predictions is therefore diminished under a changed climate scenario. The second model also suffers from a number of limitations; for example, it uses average phenological characteristics, is based on growing season averages and does not take into account management variations (Robertson 1983, 31). In addition, the rate of development between different growth stages is derived using functions which are empirically determined. Similar to the first model, this presents drawbacks as these rates may not remain constant over different climates[13]. However these rates are developed with the general case in mind and may not present such drawbacks as the more specific yield regression equations.

Despite its limitations the second model was chosen for use in this study for the

[13] There is evidence to suggest that increased concentrations on CO_2 gas raises the photosynthetic rate of most crops. See Rosenberg et al pp 297-98 for a brief discussion of its effects.

following reasons. Firstly, input data was readily available (current regression models require daily weather data which is highly detailed for such a long run scenario); secondly, it was recommended over the first by experts in the field of yield modelling and climate change[14]; and thirdly Agriculture Canada personnel offered to run the model for the study.

4.2.2 Description of Yield Model

Only a brief outline of the model is given in the following paragraphs. Those who wish to obtain more detailed information are referred to Stewart (1983). The methodology used to estimate crop yields is based on procedures developed by the F.A.O. (1978). The procedure can be considered in three stages: the calculation of constraint free yields, the calculation of agroclimatic constraint indices and the estimation of expected net biomass and dry matter yields. In the calculation of constraint free yields, it is assumed that there are no moisture, nutrient, weed, pest or disease limitations to crop growth. The equation used is:-

$$B_N = 0.36b_{GM}/(1/N - 0.25C_T)$$

Where:
B_N is the potential constraint free biomass production,
b_{GM} is the crop seasonal rate of maximum gross biomass production and is calculated based on deWit (1965),
C_T is a temperature function defining the crop maintenance respiration loss developed by Mc Cree (1974),
N is the growing season length.

The deWit (1965) methodology for calculating b_{GM} was adapted by the FAO to represent crop growth more accurately. In the calculation of b_{GM}, the maximum gross

[14] Personal communication with Jim Dyer, Agriculture Canada.

biomass production of a crop is determined using characteristics relating to de Wits "standard crop". A standard leaf area index of 5.0 is assumed and biomass production determined essentially by considering photosynthesis and its relationships with biomass production on both clear and overcast days. C_T is calculated using a previously determined maintenance respiration coefficient at 30°C and measures of temperature. McCree (1974) observed values for maintenance respiration coefficients in legume and non legume crops at 0.0283 and 0.0108 respectively (Stewart 1983, 6). Once the values of b_{GM} and C_T are estimated, potential constraint free biomass production can be obtained by inserting the appropriate growing season length. The growing period (N) is defined as, "the period in days during the year when the mean minimum air temperature is greater than or equal to 5°C" (Stewart 1983, 3). The 5°C isotherm is used for the start and end of the growing season. These are calculated from 30 year climatic normals, and represent with 50% probability the average date for the last spring and first fall frost (Sly and Coligado 1974, cited in Williams et al 1987).

The potential net dry matter yield (B_y) is calculated from net biomass production (B_N) and the harvest index (H_I) for the crop.

So that, $B_y = B_N * H_I$

The harvest index is that fraction of the crop net biomass production that is economically useful, that is the grain component (Williams et al 1988, 5). Values of H_I can vary considerably due to factors such as the genetic potential of the crop, moisture conditions and farming practices. Typical values for several crops are presented in Table 4.1. The values of B_y represent long term average yields that could occur with little or no agronomic constraints within the growing period (FAO 1978, cited in Stewart 1983, 3). However we know that in reality there are many factors

Table 4.1

Harvest Index for Several Crops Considered in Potential Net Biomass and Yield Calculations

Crop	Growing Season Length (Days) 75-89	90-119	120-149	150-179	180
Spr. Wheat	0.11-0.28	0.29-0.40	0.40	0.40	0.40
Maize	0.22-0.15	0.15-0.35	0.35	0.35	0.35
Soybean	0.20-0.29	0.30	0.30	0.30	0.30
Potatoes	0.45-0.59	0.60	0.60	0.60	0.60
Phaseolus Bean	0.19-0.29	0.30	0.30	0.30	0.30

Source: Table 2, Stewart 1983,11.

which constrain plant growth. This figure must be adjusted to take into account yield reducing factors. Only moisture stress and field workability are assessed quantitatively, other constraints are considered to have a negligible effect on crop yields in the long run.

The effect of moisture stress on yield was calculated from the following expression:

$$MSF = 1 - K_y(1 - AE/PE)$$

Where,
K_y is an empirically derived yield response factor,
AE is actual evapotranspiration, and
PE is potential evapotranspiration.

Values of K_y are taken from Doorembos and Kassam (Doorembos and Kassam 1979, cited in Williams et al 1987). Typical values for several crops are presented in Table 4.2. It is assumed that for moisture deficits up to 50%, there is a linear relationship between relative yield and relative evapotranspiration. Where moisture deficits exceed this limit it is assumed that the linearity of these relationships remain constant. PE is calculated using the Penman method (Penman 1963, cited in Williams et al 1987). AE is calculated using PE in procedures developed by Ritchie, which describe the partitioning of evapotranspiration between soil evaporation and plant transpiration (Ritchie 1972, 1974, cited in Williams et al 1987).

The constraints imposed by workability were derived from estimates of fall workday probabilities obtained from a model developed by Baier et al (Baier, Dyer and Sharp 1979, cited in Williams et al 1987). The workday concept defines the risk associated with the minimum number of days required to complete harvest before the onset of inclement weather. There is generally considered to be an inverse relationship between the length of the growing season and risk.

Table 4.2

Yield Response Factor (Ky) to Moisture for Canadian Crop Conditions

Crop	Yield Response Factor (Ky)
Spr. Wheat	1.15
Maize	1.25
Soybean	1.20
Potatoes	1.10
Phaseolus Bean	1.15

The anticipated net biomass production (B_{ye}) is calculated using the following formula:

$$B_{ye} = B_y * MSF * WP$$

Where,
MSF represents moisture stress, and
WP represents workability.

This final formula calculates the long term crop production capability under near optimal conditions.

4.3 Defining Analogous Regions

4.3.1 Choice of Technique

It is apparent from the literature reviewed that there is no standard technique for estimating crop migration as a result of climate change. Many different methods have been used in recent work, for example, documentation of historical climate change and corresponding shifts in crop production areas (Newman 1980, Fraser 1984); the analysis of environmental requirements of existing crops and matching these with new temperature and precipitation values (Rosenzweig 1985). In this study an alternative technique, cluster analysis, is used to match the future $2*CO_2$ climate of Manitoba with climates in five U.S. states[15]. This particular method was chosen as it provides a way to group observations together according to their degree of similarity.

4.3.2 Cluster Analysis

This technique has been used extensively in many disciplines when the need arises

[15] North Dakota, South Dakota, Montana, Minnesota and Iowa were chosen based on results of previous studies using the method of analogous areas.

for classification, description of complex data sets and grouping of observations. A set of individuals/observations are allocated to a set of groups, such that individuals/observations within groups are similar to one another while individuals in different groups are dissimilar (Chatfield and Collins 1980, 212).

Cluster analysis can be used to divide data in many ways, one of the most common being the hierarchical tree, often obtained by using a single link clustering procedure. In single-link clustering, groups are compared according to the distance between their closest members. In effect this means that only one link is required to join two groups (Chatfield and Collins 1980, 221). Other procedures have also been developed whereby groups are linked on the basis of different criteria. Some of these alternatives are described briefly in section 4.3.4. A clustering algorithm is used to link observations together which eventually form a tree. There are two common types of algorithm, agglomerative and divisive. The agglomerative algorithm starts with **n** groups of one individual and finishes with one group of **n** individuals. The divisive algorithm is the opposite, starting with one group of **n** individuals and finishing with **n** groups of one individual.

4.3.3 Example of an Agglomerative Algorithm[16]

Table 4.3 is a dissimilarity matrix representing the dissimilarities between various makes of car. The clustering procedure first looks for the smallest dissimilarity between the different cars. In this case it is between cars 4 and 5 where the dissimilarity is 0.69. These cars are joined to form a single group at a threshold

[16] Taken from Chatfield and Collins 1980 ch.11.

Table 4.3 Dissimilarity Matrix for five cars

Car	**1**	**2**	**3**	**4**	**5**
1	--	.725	.925	.950	.935
2		--	.975	.940	.960
3			--	.955	.945
4				--	.690
5					--

Table 4.4 Revised dissimilarity matrix

Car	**1**	**2**	**3**	**4/5**
1	--	.725	.925	.935
2		--	.975	.940
3			--	.945
4/5				--

Source: Chatfield, C. and A.J. Collins, Introduction to Multivariate Analysis, Ch.11 (1980).

distance of 0.69. The dissimilarity between this group and the others is then calculated. That between car 1 and the group consisting of cars 4 and 5 is min(0.95, 0.935) which equals 0.935. The matrix table is then revised accordingly (Table 4.4). The procedure now looks for the smallest dissimilarity again, in this case between cars 1 and 2. These are merged at a threshold distance of 0.725 and the matrix revised accordingly. In this manner, a hierarchical tree is formed (Fig. 4.5). It is apparent that the larger the threshold distance at joining, the less similar are the objects joined. Therefore it is beneficial to consider groups formed at the lowest threshold distances for analytical purposes.

4.3.4 Clustering Methods Available

There are several different clustering methods available: for example, average linkage; Ward's minimum variance and the centroid method to name but a few[17]. Each of these methods differ in the manner in which distance between clusters is calculated. The centroid method considers the distance between the centres of two groups as a measure of the similarity between them. Ward's method is slightly different, using within-group sums of squares as a procedure for defining groups. The number of groups is reduced by one at each stage by combining the two groups giving the smallest increase in the total within-group sum of squares. Average linkage considers the average of the dissimilarities between the pairs of individuals in each group so that there is effectively only one individual in each group (Chatfield and Collins 1980, 224).

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[17] Various clustering techniques are discussed in standard references on cluster analysis such as, Anderberg 1973, Hartigan 1975, Everitt 1974.

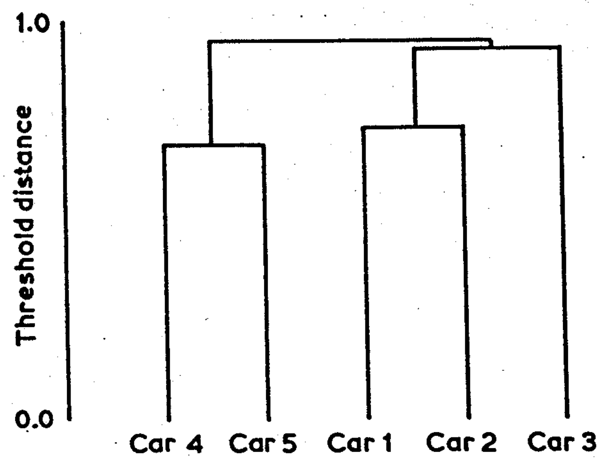

Figure 4.5 The Hierarchical Tree for the Data in Table 4.3.
Source: Chatfield, C and A.J. Collins 1980.

4.3.5 Average Linkage

The mathematical representation of the procedure used by average linkage, a commonly used method, is described below. In the explanation, it is assumed that clusters C_K and C_L are merged to form C_M and a formula is given for the distance between the new cluster C_M and any other cluster C_J (SAS Institute Inc. 1985, 263).

The distance between two clusters (D_{KL}) C_K and C_L is defined as:

$$D_{KL} = \Sigma_{i \varepsilon CK} \Sigma_{j \varepsilon CL} \mathbf{d}(x_i, x_j)/(N_K N_L)$$

If $\mathbf{d}(\mathbf{x},\mathbf{y}) = \|\mathbf{x}-\mathbf{y}\|^2$ then

$$D_{KL} = \| \bar{\mathbf{x}}_K - \bar{\mathbf{x}}_L \|^2 + W_K/N_K + W_L/N_L$$

The following combinatorial formula is gives the distance between the new cluster C_M and any other cluster C_J.

$$D_{JM} = (N_K D_{JK} + N_L D_{JL})/N_M$$

Where

D_{KL} = any distance or dissimilarity measure between clusters C_k and C_L
C_K = Kth cluster, subset of {1,2,..,n}
C_L = Lth cluster, subset of {1,2,..,n}
C_M = Cluster M, formed by merging C_K and C_L
i = observation in Cluster C_K
j = observation in Cluster C_L
ε = element within the set
x_i or $\mathbf{x}_i$ = ith observation in C_K
x_j or $\mathbf{x}_j$ = Jth observation in C_L
N_K = number of observations in C_K
N_L = number of observations in C_L
$\|\mathbf{x}\|$ = euclidean length of the vector **x**, that is the square root of the sum of the squares of the elements of **x**
$\|\mathbf{y}\|$ = euclidean length of the vector **y**, that is the square root of the sum of squares of the elements of **y**
$\bar{\mathbf{x}}_K$ = mean vector for cluster C_K
$\bar{\mathbf{x}}_L$ = mean vector for cluster C_L
W_K = $\Sigma_{i \varepsilon CK} \| \mathbf{x}_i - \bar{\mathbf{x}}_K \|^2$
d(x,y) = any distance or dissimilarity measure between observations or vectors **x** and **y**

Therefore the distance between two clusters is the average distance between pairs of observations over each cluster. This method was considered by Lorr to perform slightly better than most other clustering techniques in many cases (Lorr 1983). One caution with this particular method is that it tends to join clusters with small variances and is biased toward producing clusters with the same variance (SAS Institute Inc. 1985, 263). This has significant implications if the technique tends to join clusters on the basis of relatively insignificant variables which may have lowered the variance of the variables for each observation. In this case, groupings would be biased toward forming clusters with greater weighting to lesser important variables. This problem need not be severe depending on the type of data being clustered and can be overcome by preselecting important variables for clustering. In this study, thirty year climatic normal temperature data are clustered for several stations in the states with the 2*CO_2 temperatures predicted for Thompson, The Pas, Swan River, Brandon, Dauphin, Deloraine, Elm Creek, Arborg, Portage la Prairie and Niverville Manitoba. Temperature has been preselected as an important variable on the basis of results obtained in other studies, therefore groupings on this basis should form relatively reasonable clusters.

4.3.6 Choice of U.S. States

Climate data from North Dakota, South Dakota, Iowa, Minnesota and Montana were included in the analysis. These states were selected on the basis of results reported in previous studies which gave some indication of the direction and magnitude of climate movement. Several stations in each of the states were included in the analysis, their names and positions are listed in Table 4.5.

Table 4.5 List of U.S. Weather Stations used in Cluster Analysis.

NAME	STATE	LAT Deg-Min	LONG Deg-Min
Bismark	ND	N4646	W10046
Carrington	ND	N4727	W09908
Dunn Center 2SW	ND	N4721	W10239
Gackle	ND	N4638	W09908
Leeds	ND	N4817	W09926
Lisbon	ND	N4626	W09740
Mayville	ND	N4730	W09719
New England	ND	N4633	W10252
Park River	ND	N4823	W09745
Powers Lake 1N	ND	N4834	W10238
Turtle Lake	ND	N4731	W10053
Upham 3N	ND	N4837	W10044
Aberdeen WSO	SD	N4527	W09826
Academy	SD	N4328	W09905
De Smet	SD	N4423	W09733
Fort Meade	SD	N4424	W10328
Hot Springs	SD	N4326	W10328
Marion	SD	N4325	W09715
Milesville 5NE	SD	N4431	W10137
Miller	SD	N4431	W09859
Redig 11NE	SD	N4523	W10323
Timber Lake	SD	N4526	W10104
Webster	SD	N4520	W09732
Wood	SD	N4330	W10029
Cascade	IA	N4218	W09101
Clarinda	IA	N4044	W09501
Corydon	IA	N4045	W09319
Decorah 2N	IA	N4319	W09147
Harlan	IA	N4139	W09519
Iowa City	IA	N4139	W09132
Iowa Falls	IA	N4231	W09315
Keosauqua	IA	N4044	W09158
Newton 1E	IA	N4141	W09302
Storm Lake 2E	IA	N4238	W09511
Austin 3S	MN	N4337	W09300
Babbitt 2SE	MN	N4741	W09155
Baudette	MN	N4843	W09437
Bemidji Airport	MN	N4730	W09456
Cambridge St Hosp.	MN	N4534	W09314
Faribault	MN	N4418	W09316
International Falls	MN	N4834	W09323
Moose Lake 1SSE	MN	N4627	W09245
Morris WC School	MN	N4535	W09555
Pine River Dam	MN	N4640	W09407
Springfield 1NW	MN	N4415	W09459
Wadena 3S	MN	N4624	W09509
Windom	MN	N4352	W09507
Fort Benton	MT	N4749	W11040
Hysham	MT	N4618	W10714
Trident	MT	N4557	W11129
Trout Creek R. Sta.	MT	N4752	W11537
Vida	MT	N4750	W10529

4.4 Estimation of Economic Impacts on Agriculture in Manitoba

The main issue addressed by this study is how agricultural systems will change in response to a differing climate. It is desirable that structural changes occur in a way that allocate resources efficiently. Different techniques can be used to determine the way in which resources are allocated. The choice of technique is dependent upon the problem considered and the information required from the results. In this particular case the goal was considered to be one of determining the optimal pattern of resource use. However if this were not the case and only changes in the pattern of resource usage were required, techniques other than those mentioned below could be used; for example simulation modelling.

There are numerous mathematical programming techniques available today which are used to solve such optimisation problems: for example, linear programming; quadratic programming; non-linear programming and stochastic programming, to name but a few[18]. The technique chosen to solve this particular problem is linear programming (LP). This was chosen above the others because it has been used with success in the past to solve similar production problems and because of its computational ease[19]. Given the hypothetical nature of the scenario it is better not to

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[18] Discussion of these other techniques can be found in Hazell, P.B.R. and Norton, R.D. 1986.

[19] C.R.A.M. was originally developed "to evaluate the economic impacts of the introduction of medium quality wheat on Prairie and Canadian Agriculture and to examine the impacts of alternative freight rate structures for moving Prairie grain on the agricultural economics of both eastern and western provinces". - Webber, Graham and Klein 1986. Changes in yields can be considered to be a similar problem to changing prices and costs as the end effect is the same, namely a change in the returns obtained by farmers.

over invest in modelling, until improvements in the estimation of primary agricultural responses have been achieved.

4.4.1 Linear Programming

In common with the majority of modelling techniques, LP provides us with a simplified world/environment within which events are assumed to occur with certainty. In the following pages, a linear programming maximisation model is described.

The basic process involves maximising an objective stated as a functional form: for example, maximising the sum of production revenues received minus variable costs, for each of the enterprises undertaken, subject to a number of resource constraints. For a unit of an enterprise to be included in the solution the amount it adds to the objective function value must exceed that possible by any other enterprise and must still result in a feasible solution.

The common L.P model consists of two distinct parts. An objective function and a number of corresponding constraints. The objective function is composed of the problem activities (or decision variables) and a coefficient reflecting their per unit value or contribution to the objective function: for example, positive contributions to revenue or negative contributions via costs. The technical constraints represent the maximum or minimum resources available for use by the activities and the quantity of each resource required for the production of one unit of each activity. The general form of the maximisation problem with **m** constraints and **n** activities, is as follows:

Max $Z = \Sigma^{n}_{j=1} C_j x_j$

Subject to,

$\Sigma^{n}_{j=1} a_{ij} x_j \ (\leq, =, \geq) b_i$ for all i all $x_j \geq 0$

Where:

Z = objective to be maximised, for example revenues minus variable costs.
i = resources, $i = 1......m$
j = activities, $j = 1......n$
C_j = objective function coefficient for each activity.
a_{ij} = quantity of resource i needed to produce a unit of activity j.
b_i = maximum quantity of resource i available.
x_j = quantity of activity j incorporated in the final solution.
n = number of activities.
m = number of constraints.

Similar to most models, linear programming operates on the basis of several assumptions for the sake of simplicity. These are optimisation, where an appropriate objective function is maximised or minimised. Fixedness, where at least one of the right hand side values of the constraints must be non zero. Finiteness, meaning that there are a finite number of activities and constraints. Determinism, all objective function coefficients, resource requirements and resource availability are known with certainty. Continuity, resources can be used and activities produced using fractional units. Homogeneity, all resources and activities are of equal quality. Additivity, there is no interaction between activities leading to economies of scale and finally proportionality which assumes that the objective function coefficients and resource requirements are constant regardless of the level of activities used (Hazel, P.B.R. and R.D. Norton 1986, 13). One drawback of simple L.P is the assumption of determinism, which means that risk cannot be taken account of in the decision making process. Risks are inherent in most business ventures and there is a need to balance potential profits with the riskiness of each enterprise; by ignoring risk there is a danger that the L.P model solution, although optimal in terms profit or revenue maximisation, may be too risky for practical use. However, drawbacks of this nature can be overcome by the modeller through the use of alternative LP formulations such as stochastic programming or MOTAD. Drawbacks of this nature in simple LP can be compensated for by the ease with which problems can be formulated and solved, allowing a number of alternatives to be tested using sensitivity analysis and the stability of the solution determined.

4.4.2 The Model

The linear programming model used to assess the economic impacts of climate change on the agricultural industry of Manitoba is developed in such a way that it could be altered with ease to accommodate the special needs of different scenarios. The objective of the model is to maximise the sum of revenues minus variable costs over the range of activities entered. The model is developed with very few constraints because of the long time periods associated with climate change. Factors such as technology, capital, input availability, markets and managerial resources are difficult to determine for the future. However it is likely that in the long run they will not be constraining and are treated as such in the model. The two factors considered to be the most limiting form the constraint set these are land (although for one model run this constraint is relaxed by the addition of another potential crop area further north) and some of the major disease/pest relationships between crops that govern crop rotations[20]. No government subsidies or production quotas are included in the model because it is difficult to forecast these for the future. Inclusion of old schemes would likely distort model results to favour production of crops grown in the past.

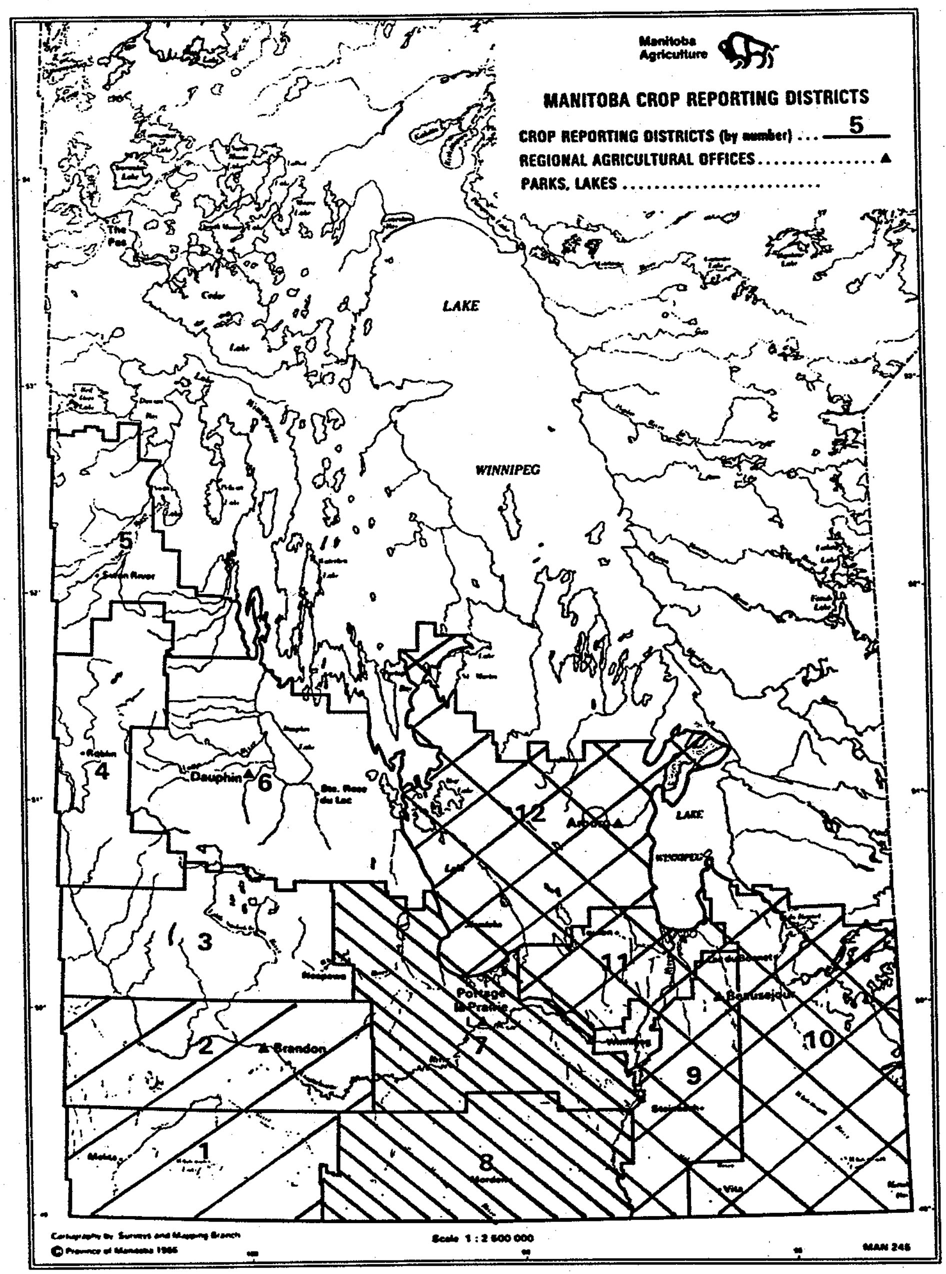
[20] In the long run some of these constraints might be relaxed. See the following discussion.

Representation of present quotas might preclude the inclusion of crops that should be produced because markets may have expanded.

The baseline model consists of nine different crops produced in four areas (Fig. 4.6). The fifth area indicated on the map relates to an expanded land base included in a later model run. Yields differ between the same crops grown in different areas in an attempt to reflect variations in factors such as soil type and moisture availability. Forty three constraints are incorporated to reflect land availability, basic feed demands by the livestock sector and rotational cropping practices. Four of these constrain the land available for crop production in each area. Two represent the basic demands of the livestock sector[21] in Manitoba during 1986-87 for feed barley and feed wheat[22]. Nine constraints limit rotational practices for the majority of crops produced. These rotational constraints appear in each region (10 in region 4) and make the final 37 constraints. Rotations were defined in four year blocks, grains such as wheat, barley and oats were each allowed to occupy 50% of the land in each region, meaning that each one of these crops could be produced in two out of four years in the rotation or any combination of these crops could be produced for all four years. Each of the specialty crops such as flax, canola, potatoes, soybeans and sunflowers were constrained in such a way that each activity could only occupy a maximum of 25% of the land available in each of the regions. This means that each of these crops can only be

[21] Feed demands of the livestock sector represent the total demand from all livestock enterprises across the province of Manitoba.

[22] It was assumed that minimum feed demands from this sector would not change under a 2*CO_2 scenario.



Field 1. South West Manitoba. ⁄ ⁄
Field 2. North West Manitoba.
Field 3. Interlake and South East Manitoba. ╳╳
Field 4. South Central Manitoba.⧹⧹⧹
Field 5. Northern Manitoba. Areas surrounding The Pas and Thompson (not shown on the map) Manitoba.

Figure 4.6 The Linear Programming Model Areas
Source: Map from Manitoba Agriculture.

grown once every four years[23]. In order to prevent the total acreage being seeded to at least four specialty crops which tend to have higher returns associated with them but also higher risk, an additional constraint was added which allows only 50% of the land to be seeded to these crops in total, constraining specialty crops to be grown only two years out of four on any particular land base. A special activity was included in the activity set to represent a five year corn-canola rotation (corn was produced for four years then a year of canola). This activity was constrained to occupy different percentages of land depending on the risk involved with successful corn production in that particular region. The full model specification is presented in Appendix 1.

4.4.3 The Aggregation Issue

When formulating an aggregate regional linear programming model, the researcher should be aware that aggregation bias is likely, as not all farm units are identical. "The aggregate regional approach involves aggregating the resources of a homogeneous region or area (not necessarily involving contiguous land) and modelling these aggregated variables as a single large farm" (Hazell and Norton 1986, 144). Hazell and Norton illustrated that aggregation bias is always in an upward direction because it overstates resource homogeneity and mobility. As a result, farms/units are able to combine resources in proportions unavailable on an individual basis. In aggregated models, it is implicitly assumed that each of the farms have access to the same technology for production.

If farms are rigidly classified into groups or regions which satisfy strict theoretical

[23] There may be potential for one in three year rotations for canola and other specialty crops if disease constraints are relaxed.

requirements of homogeneity, the aggregation bias can be minimised, and in some instances avoided altogether. According to Hazel and Norton (1988), the most comprehensive conditions for successful aggregation have been established by Day (1966). He set down three requirements which must be fulfilled:

a) technological homogeneity - each farm must have the same production possibilities, the same resources and constraints, the same technology and managerial ability,

b) pecunious proportionality - individual farmers within a group must hold expectations about unit activity returns that are proportional to average expectations,

c) institutional proportionality - the constraint vector of the programming model for each individual farm should be proportional to the constraint vector of the average or aggregate farm.

To ensure strict unbiasedness, two other criterion must be satisfied:

d) the representative farm be defined as the arithmetic mean farm,

e) none of the individual farm models be degenerate. That is, there must not be more than one possible incoming activity at a given iteration and any incoming activity can enter the basis at a level greater than zero. Degeneracy may lead to cycling whereby the same iterations are repeated. This can cause problems with large, interconnected models (Hazell and Norton 1986, 30).

The conditions laid down by Day (1966), are extremely demanding in terms of model specification and data collection. Other authors, for example Miller, and Lee, have worked with less stringent conditions (Miller 1966, Lee 1966, both cited in Hazell and Norton 1986). They reason that there is normally a range for each coefficient over which it can be varied without inducing a change in the optimal basis. The solution vectors for the average/aggregate farm may be proportional as long as the individual farms have solutions lying within the tolerated range.

In practice, farms are grouped according to factors such as resource endowments, enterprise activities and technology. Data limitations are often such that this is the best method of grouping that can be accomplished. The model described in section 4.4.2, aggregates farms on the basis of resource endowments such as moisture availability and soil type. For the sake of simplicity and ease of data collection, Manitoba was broken into four different crop areas. These areas were chosen on the basis of soil water status[24] as moisture is generally considered to be the factor most limiting plant development in Manitoba[25]. Figure 4.5 shows the four "fields" included in the LP model, and the crop reporting districts (CRDs) they contain. Field 1 includes CRDs 1 and 2; Field 2 contains CRDs 3, 4 and 5; Field 3 covers CRDs 9, 10, 11 and 12 the remaining CRDs, that is 7 and 8, make Field 4. Field 5 is an area further north than present CRDs and includes several different parcels of land within the area indicated which are not necessarily continuous. Yields of the same crop were taken to be different in each area in an attempt to represent other resource factors such as soil type. Technology is assumed to be "recommended" rather than "average", due to the long run nature of the scenario.

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[24] Indications of soil water status can be obtained from Southern Manitoba's Climate and Agriculture 1984, Manitoba Agriculture.

[25] Personal communication with Dr. C. Shaykewich, Dept., Soil Science, University of Manitoba, Winnipeg, Manitoba.

CHAPTER FIVE

RESULTS AND MODEL DATA COLLECTION

5.1 2*CO_2 Climate for Manitoba

Tables 5.1 and 5.2 show the thirty year historical normals, differences between 1*CO_2 and 2*CO_2 GISS model runs and the new 2*CO_2 temperatures and precipitation predicted for Deloraine, Brandon, Dauphin, Elm Creek, Arborg and Swan River Manitoba. These figures are presented graphically in Appendix two. These data indicate that 2*CO_2 temperatures are consistently higher than those presently experienced. During the winter, warming of between 5.2°C and 6.4°C is predicted, with an increase of 2.5°C to 3.5°C over the summer. Temperature increases predicted by the GISS model are nearly 50% higher in winter than in summer. Warmer winter temperatures could lengthen the growing season and have a positive effect on agricultural practices presently constrained by an insufficient frost free period. As temperature is increased, it is likely that the growing season will lengthen and heat requirements will become less of a constraint for crop growth. The increase in available heat units will likely cause existing crops to mature faster and allow the introduction of longer maturing, higher yielding varieties. This could have particularly beneficial effects in the more northerly areas of Manitoba where climatic factors rather than soils limit crop production (Mills 1980). An increase in temperatures could also increase the number of growing degree days in all areas of the province, allowing certain special crops to be grown in wider areas: for example, corn production is limited to those areas receiving 2300 CHUs (corn heat units) per season; this area

Table 5.1

Thirty Year Monthly Temperature Normals and 2*CO2 Scenario Temperature Predictions for Selected Stations in Manitoba

Month	Deloraine(a) Normals C	Deloraine 2*CO2-1*CO2 GISS (b)	Deloraine 2*CO2 C	Brandon CDA Normals C	Brandon CDA 2*CO2-1*CO2 GISS	Brandon CDA 2*CO2 C	Dauphin Normals C	Dauphin 2*CO2-1*CO2 GISS	Dauphin 2*CO2 C
January	(17.60)	5.80	(11.80)	(19.30)	5.60	(13.70)	(19.50)	5.50	(14.00)
February	(13.80)	5.90	(7.90)	(15.20)	5.90	(9.30)	(15.60)	5.90	(9.70)
March	(6.50)	5.22	(1.28)	(8.40)	5.30	(3.10)	(9.10)	5.20	(3.90)
April	3.70	5.70	9.40	3.30	5.80	9.10	2.30	5.70	8.00
May	11.10	3.10	14.20	11.00	3.00	14.00	10.30	2.90	13.20
June	16.80	3.30	20.10	16.30	3.20	19.50	15.80	3.10	18.90
July	19.40	3.04	22.44	19.20	3.10	22.30	18.50	3.00	21.50
August	18.10	2.84	20.94	17.90	2.50	20.40	17.10	2.30	19.40
September	12.00	4.54	16.54	11.80	4.20	16.00	11.30	4.00	15.30
October	5.80	4.41	10.21	5.60	4.30	9.90	5.50	4.30	9.80
November	(4.40)	6.13	1.73	(5.00)	6.20	1.20	(5.20)	6.20	1.00
December	(12.30)	5.30	(7.00)	(14.10)	5.20	(8.90)	(14.30)	5.20	(9.10)

Month	Elm Creek Normals C	Elm Creek 2*CO2-1*CO2 GISS	Elm Creek 2*CO2 C	Arborg Normals C	Arborg 2*CO2-1*CO2 GISS	Arborg 2*CO2 C	Swan River Normals C	Swan River 1*CO2-2*CO2 GISS	Swan River 2*CO2 C
January	(18.80)	5.70	(13.10)	(21.60)	5.40	(16.20)	(20.40)	6.00	(14.40)
February	(15.10)	6.00	(9.10)	(18.50)	6.00	(12.50)	(16.20)	6.00	(10.20)
March	(8.00)	5.40	(2.60)	(9.90)	5.30	(4.60)	(9.10)	5.10	(4.00)
April	3.30	5.70	9.00	1.70	5.50	7.20	2.00	5.60	7.60
May	11.30	3.20	14.50	9.90	2.60	12.50	10.30	3.20	13.50
June	17.20	3.50	20.70	15.50	3.20	18.70	15.60	3.00	18.60
July	19.50	3.10	22.60	18.30	2.90	21.20	18.40	3.10	21.50
August	18.40	2.90	21.30	16.70	2.40	19.10	16.80	2.40	19.20
September	12.70	4.20	16.90	10.90	4.00	14.90	10.60	4.20	14.80
October	6.50	4.30	10.80	4.90	4.20	9.10	4.80	4.50	9.30
November	(4.30)	6.20	1.90	(5.60)	6.10	0.50	(6.00)	6.40	0.40
December	(13.50)	5.20	(8.30)	(16.60)	5.20	(11.40)	(16.10)	5.50	(10.60)

(a) 1951-1980 Temperature Normals. Atmospheric Environment Service, Canada.
(b) Linear Interpolation from GISS GCM results, provided by Atmospheric Environment Service, Canada.
( ) Denotes a negative Value.

Table 5.2

Thirty Year Monthly Precipitation Normals and 2*CO2 Scenario Precipitation Predictions for Selected Stations in Manitoba

Months	Deloraine(a) Normals mm	Deloraine 2*CO2-1*CO2 GISS (b)	Deloraine 2*CO2 mm	Brandon CDA Normals mm	Brandon CDA 2*CO2-1*CO2 GISS	Brandon CDA 2*CO2 mm	Dauphin Normals mm	Dauphin 2*CO2-1*CO2 GISS	Dauphin 2*CO2 mm
January	20.90	108.00	22.57	21.30	106.00	22.58	24.50	105.00	25.73
February	17.40	124.00	21.58	20.00	122.00	24.40	17.50	125.00	21.88
March	22.50	132.00	29.70	23.50	131.00	30.79	24.50	130.00	31.85
April	32.40	104.00	33.70	36.80	104.00	38.27	31.90	103.00	32.86
May	56.00	105.00	58.80	49.70	101.00	50.20	47.40	100.00	47.40
June	85.60	106.00	90.74	81.20	107.00	86.88	86.30	108.00	93.20
July	67.50	120.00	81.00	69.40	123.00	85.36	64.10	128.00	82.05
August	72.10	122.00	87.96	69.50	122.00	84.79	62.20	122.00	75.88
September	48.70	72.00	35.06	49.70	71.00	35.29	59.00	67.00	39.53
October	27.40	117.00	32.06	23.40	119.00	27.85	28.90	126.00	36.41
November	20.60	138.00	28.43	19.90	138.00	27.46	25.20	142.00	35.78
December	19.10	108.00	20.63	20.20	107.00	21.61	24.30	106.00	25.76

Months	Elm Creek Normals mm	Elm Creek 2*CO2-1*CO2 GISS	Elm Creek 2*CO2 mm	Arborg Normals mm	Arborg 2*CO2-1*CO2 GISS	Arborg 2*CO2 mm	Swan River Normals mm	Swan River 2*CO2-1*CO2 GISS	Swan River 2*CO2 mm
January	26.10	109.00	28.45	23.60	101.00	23.84	29.50	111.00	32.75
February	28.50	122.00	34.77	18.30	125.00	22.88	20.60	129.00	26.57
March	31.80	137.00	43.57	25.80	123.00	31.73	28.90	137.00	39.59
April	40.40	108.00	43.63	36.80	108.00	39.74	22.80	106.00	24.17
May	55.80	103.00	57.47	52.80	97.00	51.22	42.10	106.00	44.63
June	70.10	111.00	77.81	74.20	114.00	84.59	76.10	112.00	85.23
July	76.00	118.00	89.68	61.40	120.00	73.68	69.70	128.00	89.22
August	73.50	124.00	91.14	75.60	126.00	95.26	65.90	120.00	79.08
September	47.60	91.00	43.32	50.60	72.00	36.43	53.70	73.00	39.20
October	38.30	120.00	45.96	35.10	126.00	44.23	26.30	127.00	33.40
November	32.70	133.00	43.49	28.40	136.00	38.62	23.70	139.00	32.94
December	26.60	112.00	29.79	21.70	113.00	24.52	28.80	109.00	31.39

(a) 1951-1980 Precipitation Normals. Atmospheric Environment Service, Canada.
(b) Linear Interpolation from GISS GCN results, provided by Atmospheric Environment Service.

could be expanded if temperatures increased.

Precipitation is also expected to increase under this GISS model run. Manitoba would experience wetter summers (precipitation increasing between 10% to 25%), and wetter winters (precipitation increasing between 10% to 38%). Although precipitation is predicted to increase, care must be taken when interpreting these figures. Higher precipitation does not necessarily mean that moisture available for crop production will increase, as this is also dependent upon other factors such as soil type and, most importantly, temperature. Whether the moisture conditions become more favourable for crop production is predominantly dependent upon the degree of evaporation and transpiration taking place. Under this GISS scenario, precipitation has increased but so have temperatures. If precipitation increases sufficiently to offset the increase in evapotranspiration brought about by increased temperatures, more moisture will become available for crop production. If precipitation cannot offset increased evapotranspiration then moisture availability is reduced and crops are more likely to suffer from water stress, which can reduce yields.

One other factor to be considered is the increase in winter precipitation. Over the winter months, evaporation can be considered to be negligible; therefore water available at the beginning of the season for crop usage is greater than before, which could help to offset some evaporation of summer precipitation and make more moisture available for plant use[26]. The precipitation figures presented should be treated with some caution as it is widely agreed that GCMs cannot yet simulate precipitation as well as they can

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[26] Work done by Shaykewich would seem to indicate that extra moisture at the beginning of the season as a result of a heavy winter snow fall does not really seem to make a big difference to moisture availability later in the season, unless its a dry year, as there is a lot of seepage through the soil.

temperatures, particularly at a regional resolution. Heat availability is only one factor affecting plant growth. Moisture availability, day length and many other factors must also be taken into account.

The effects of climate change on the yields of existing crops is uncertain and is explored in the following section where the results described above are incorporated in a weather crop yield model and used to estimate changes in the yields of present crops as a result of the new climate scenario. They were also compared against climatic data for several of the U.S. states in order to forecast the extent of crop migration.

5.2 The Yield Model

This study uses a crop growth model to estimate changes in the agroclimatic environment and their corresponding effects on the yields of several prairie crops in response to the climate presented in Tables 5.1 and 5.2. The model estimates potential net biomass and dry matter yields, which are later adjusted by yield reducing agroclimatic constraint indices reflecting factors such as soil workability and moisture stress experienced by the crop. The final figures estimate agroclimatically attainable or expected net biomass and dry matter yields (Stewart 1983). Dr. R. Stewart and R.W. Muma of the Soil and Climate Section of Agriculture Canada kindly agreed to run the model for this study.

The model was run using the weather data presented in Section 5.1, for several different points across Manitoba[27] in an attempt to account for different soil types and

[27] Deloraine, Portage la Prairie, Niverville, Arborg, Dauphin, Swan River and The Pas.

climatic variability within the province. Data relating to alterations in both the agroclimatic environment and yield changes were produced. These results are discussed in the following sections.

5.2.1 The Agroclimatic Environment

The model produces information about growing season length (frost free period), number of degree days, potential evapotranspiration and precipitation effectiveness (shown in table 5.3), for the historical and 2*CO_2 scenario.

The measure of growing season length (GSL) is synonymous with the frost free period, that is the number of days between the last spring and first autumn frost. This figure is unlikely to remain the same each year as there is some variability in the occurrence of these frosts[28]. Dunlop (1981) found that the standard deviation of the last spring frost was about 12 days, while for the first autumn frost and frost free period it was approximately 10 and 15-20 days respectively. The measure growing degree days (GDDs), is generally accepted as a way to relate plant growth to temperature (Edey 1977, 5). It is assumed that crop growth and development is some function of temperature over a certain minimum threshold. GDDs are normally summed over the growing season or over the number of days taken for a crop to progress from planting to maturity. GDDs for each calendar day are calculated using the following formula:

$$GDD = \frac{(Tmax + Tmin)}{2} - Tbase$$

[28] Manitoba Agriculture (1984), "Southern Manitoba's Climate and Agriculture", contains maps indicating the variability of frost occurrence and frost free period.

Table 5.3

Agroclimatic change resulting from a 2*CO2 scenario

Station	GSL 1951-80	2*CO2	%Change	Deg. Days 1951-80	2*CO2	%Change	PET 1951-80	2*CO2	%Change	GSL P/PET 1951-80	2*CO2	%Change
Deloraine	123.00	164.00	33.33	1459.00	2199.00	50.72	519.00	775.40	49.40	0.55	0.47	-14.63
Portage A	130.00	170.00	30.77	1556.00	2263.00	45.44	537.30	781.10	45.38	0.54	0.48	-11.69
Niverville	123.00	164.00	33.33	1443.00	2175.00	50.73	493.50	747.10	51.39	0.55	0.49	-11.91
Arborg	113.00	150.00	32.74	1246.00	1869.00	50.00	397.90	603.00	51.55	0.62	0.57	-8.12
Dauphin	116.00	163.00	40.52	1301.00	2009.00	54.42	430.50	685.40	59.21	0.57	0.51	-11.67
Swan R.	113.00	162.00	43.36	1256.00	1977.00	57.40	417.70	658.10	57.55	0.58	0.53	-9.64
The Pas	116.00	157.00	35.34	1216.00	1864.00	53.29	401.20	617.20	53.84	0.58	0.57	-2.08

Where,

GDD = growing degree days
Tmax = maximum temperature recorded during that day
Tmin = minimum temperature recorded during that day
Tbase = threshold temperature below which no growth occurs.

The base temperature represents a point below which growth cannot occur and differs for most crops[29]. However, for general calculations, the base temperature is usually assumed to be 5°C. Although GDDs are normally calculated on a daily basis, these were calculated from monthly mean temperature figures and standard deviations of monthly mean temperatures, using a method developed by Thom (1954a, b. Cited in Williams et al 1987). For most crops, the minimum accumulations of GDDs needed for a plant to reach maturity have been calculated. These figures help indicate whether an area is suited to grow these crops: for example, if an area accumulates 1750 GDDs over the growing season but the crop requires 2000 GDDs to reach maturity that crop is not really suited for growth in that area. The measures of GSL and GDD are related because in general, a longer growing season and higher temperatures increase the number of GDDs received by an area (Williams et al 1988, 27).

Potential evapotranspiration is, "the evaporation from an extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water" (Rosenberg, Blad and Verma 1983, 211). Potential evapotranspiration (PE), is the maximum water loss that can occur. The concept is made up of two parts, evaporation from the soil and transpiration from the plant canopy. PE is often used as an index of aridity and is useful in predicting the water needs in dryland and irrigation agriculture (Rosenberg,

[29] A number of base temperatures for different crops are included in Edey, S.N. 1977 p.8.

Blad and Verma 1983, 211). The higher PE, the greater the potential for water loss from the soil and plant canopy and the higher the risk of moisture stress resulting if precipitation is insufficient to meet moisture needs. Precipitation effectiveness (PEf) relates actual precipitation to PE (over the growing season length in this case). The smaller the figure, the less moisture available for plant growth and the greater likelihood of reductions in yield due to moisture stress.

Results obtained from the F.A.O. model show that the growing season length extends 40 days and more under this GISS scenario, meaning that even the most northerly areas considered will have a longer growing season than experienced anywhere at present. Degree days also increase significantly, suggesting that heat is not such a limiting factor to plant development and growth as it may have been in the past. These increases in GSL and GDDs confirm the expectations in section 5.1.

Table 5.3 indicates that PE values increase between 45% (Portage la Prairie) and 59% (Dauphin), the greatest increase occurring in the more northerly areas such as Dauphin, Swan River and The Pas. Although these areas experience the largest change in PE values between the present and 2*CO_2 scenarios, PE is not as high as that expected in more southerly areas of the province, meaning that any crops grown in these areas are less likely to be subject to moisture deficiencies if winter precipitation is equal to or greater than the southern areas. This is substantiated by the figures for PEf, which illustrate that the more northerly part of the province tends to have more moisture available for crop growth. No account is taken of water stored in th soil prior to the begging of the growing season, its inclusion could lead to differing results from those presented. Care should be taken when comparing PEf over GSL for the current (thirty year normal) with the 2*CO_2 scenarios as their GSLs are different, the

GSL in the 2*CO_2 scenario being longer.

5.2.2 Yield Predictions of F.A.O. Model

The F.A.O. model estimates yields using present climatic data and then uses the GISS 2*CO_2 results to calculate yields under a climate change scenario. Table 5.4 shows the percentage changes in crop yield, from present levels, predicted under the adjusted GISS 2*CO_2 climate scenario.

Drastic reductions in yields from present levels are predicted by the F.A.O. model for almost all crops. Of particular importance are the reductions in yields of wheat, canola, oats and barley, which are some of the most important crops currently grown on the prairies in terms of hectares planted and revenue received (the model was not yet adapted to predict yield changes for flax). The model predicts that these crops will experience decreases in yields in the order of between 20% to 30%, which would likely have a very detrimental effect on the present farming system. For example: if prices did not rise sufficiently to offset the yield reductions, farm revenues would decline substantially and even greater numbers of farmers than at present could be subject to financial difficulties. In addition export revenues could be reduced if the same quantity of grain was not available for sale as in the past, having negative effects on the Canadian economy as a whole. Yields of a few crops are predicted to increase: for example across the stations studied, yields of corn silage, corn and potatoes increased and corn was expected to grow in areas it did not previously. The introduction of corn into these new areas is significant, suggesting that areas of land previously devoted to wheat, barley or canola could be used to cultivate corn instead, partially offsetting any revenues that may be lost and opening possibilities for new

Table 5.4

Percentage Change in Crop Yields under 2*CO2 senario

Crop	Deloraine	Portage	Niverville	Arborg	Dauphin	Swan River	The Pas
Barley	-24.10	-19.50	-19.50	-32.40		-22.50	-19.00
Oats	-31.20	-28.70	-28.20	-37.50		-32.00	-30.30
Canola	-30.50	-29.00	-28.40	-39.80		-33.20	-32.50
Sunflower	-31.40	-30.70	-29.40	-36.40		-33.20	
Corn Sil.	-5.00	-8.60	-6.90	18.60		7.40	
Corn Grn.	-5.00	-8.60	-6.90				
Soybean	-25.90	-29.40	-28.60	-9.70		-16.90	
Potato	-16.60	-20.50	-17.30	9.30		1.00	
Wheat	-31.50	-30.80	-36.00	-31.90	-30.80	-30.10	-26.80

marketing strategies.

The figures calculated for potential evapotranspiration (PE) and precipitation effectiveness (PEf) over the growing season could account for the drastic reduction in yields expressed in table 5.4. On a world wide scale, the critical factor determining plant survival, development and productivity is water availability. Crop yield is directly related to the availability of soil moisture during the growing season therefore, it seems likely that the drastic yield reductions predicted are a result of moisture stress (Roseberg, Blad and Verma 1983, 213). Transpiration is very important to the plant as it regulates temperature; a reduction in transpiration has been shown to cause an increase of 2°C to 3°C in plant temperature which can increase plant stress (Rosenberg, Blad and Verma 1983, 215).

The F.A.O. model results suggest that under a 2*CO_2 climate, yields will undergo dramatic reductions, predominantly as a result of increasing moisture stress. These reductions were so large that additional models were run in order to give an indication as to their validity. Dr. C. Shaykewich of the Dept. Soil Science, University of Manitoba, kindly ran models predicting days to maturity, water use and soil moisture stress for a crop of wheat at Altona, Brandon, Dauphin, Deloraine, Morden, Portage la Prairie and Swan River. A very brief outline of the procedures used is presented in appendix 3. These models were run using daily weather data between 1954-1982, and in most cases from 1945-1982. Three different scenario's were considered:

i) historical planting dates and climate (scenario 1),

ii) historical planting dates and a flat 3°C increase in temperature (scenario 2),

iii) planting advanced two weeks (that is, plant fourteen days early), and a flat 3°C increase in temperature (scenario 3).

The 3°C increase in temperature over the growing season is very similar to the increase in temperature predicted by the GISS model runs. Table 5.1 indicates an increase in temperatures in the region of 3°C between May and August inclusive. When considering the results discussed in the following paragraphs it should be remembered that precipitation was not increased as in the GISS scenario used by the F.A.O. model. Therefore, these results relate to a slightly drier scenario. The results of the model runs are presented graphically in appendix 3.

In all areas, wheat matures earlier than historically. When temperatures are increased by 3°C, maturity is advanced between 10 to 20 days; when the crop is planted two weeks earlier wheat still matures marginally faster than historically. These results suggest that the growing season will indeed increase under a situation of climatic warming (as crops can be planted at least two weeks earlier and still mature).

The graphs showing water use indicate that if temperatures are increased by 3°C then the quantity of moisture needed to bring a crop of wheat to maturity is less than under historical conditions. The same can be said if the planting date is advanced 14 days; however under this scenario, although water requirements are less than historical they are greater than when the planting date is not advanced and temperature is increased. These differences could be related to the number of days it takes for crops to reach maturity, and the temperatures at each stage of plant growth under the different scenarios. The faster a crop reaches maturity, the less water it requires at a given temperature as it will be transpiring for fewer days. For example: under scenario 1, the crop uses most water as it is transpiring for the greatest number of days. Daily transpiration may not be as great as in the other scenarios where the temperatures are increased, but in this case the cumulative effect of less transpiration for a greater number of days results in greater water use. Under scenario 2, the crop will require more water each day than in the first scenario but reaches maturity so quickly that the total water demand is less. In scenario 3, the crop requires less water than in scenario 2 during its initial growth stages because temperatures are not as high during the initial 14 days, during the later stages of growth more water will be required per day but for a lesser period of time than in scenario 1 resulting in a water use requirement mid way between scenario 1 and scenario 2.

The soil water status is an indication of the moisture stress experienced by a crop. Water stress is affected by, a) the quantity of water required to grow a crop (water use), b) the amount of moisture supplied by precipitation, and c) the amount of water in the soil at the start of the growing season (Shaykewich and Dunlop 1987, 170). The amount of water used by a crop at various times in the growing season is determined by PE and the ratio of potential water use by the crop to PE, that is the consumptive use factor (CU) (Shaykewich and Dunlop 1987, 170); the consumptive use factor is the ratio of actual evapotranspiration to potential evapotranspiration. The higher the negative numbers, the greater stress a plant is experiencing as the water deficit is greatest. The three scenarios considered indicate similar degrees of moisture stress for wheat. This is probably due to a combination of a number of factors such as the number of days required for wheat to reach maturity, the temperatures experienced during the period in which the crop is developing and the leaf area[30] during these periods. Under the flat temperature increase of 3°C (scenario 2), a crop of wheat reaches maturity very quickly. Therefore, it transpires for fewer days and may need

[30] Transpiration is directly proportional to leaf area until complete ground cover is achieved. Thereafter transpiration does not change with changes in leaf area.

less water to reach maturity because of this. In addition, the leaf area through which transpiration can occur will not be as great as that in scenario 1 for the same period of time and transpiration is reduced in this way. Therefore, although the temperatures are greater throughout the crop's progress to maturity, the crop experiences moisture stress similar to that observed historically as the crop requires water over a shorter period and can obtain it before it is evaporated from the soil.

When the planting date is advanced by fourteen days in addition to an increase in temperatures by 3°C (scenario 3), the crop requires more water to reach maturity. Planting earlier than in scenario 1, results in exposure to lower temperatures and less evaporation in the first few weeks when the crop is developing. If temperatures are lower, the plant will need less water to transpire and less water is evaporated from the soil. Once temperatures increase, the crop will transpire more freely but is closer to maturity at these increased temperatures and will transpire freely for a lesser amount of time than in scenario 2 (or a similar amount of time as in scenario 1), which seems to lead to similar degrees of water stress. These results are presented in appendix 3.

The results of these additional models run by Shaykewich tend to suggest moisture stress may not be as great as that implied by results from the F.A.O. model and therefore yields might not decrease quite as dramatically as indicated. Each of the models used different methods to estimate PET. Stewart and Muma used the Penman (1963) method whereas Shaykewich used the Baier and Robertson (1965) method. These have slightly different input variables, for example Baier and Robertson estimate PET with solar radiation as an input variable whereas this is not included in the Penman method; which could account in some part for the differences in their final results. However, in future sections, these F.A.O. yield results are considered to relate to a "dry" scenario, the results being pessimistic rather than allowing for farmers to adjust practices to take advantage of the new growing season.

5.3 Crop Migration using the method of Analogous Regions

Cluster analysis was used to match the adjusted 2*CO_2 temperature and precipitation values calculated for Manitoba with U.S. thirty year climate normals from North Dakota, South Dakota, Minnesota, Montana and Iowa[31].

Monthly temperature normals and monthly precipitation normals were clustered separately due their different units of measurement. Results of clustering temperature alone suggested a south to north movement. The Pas coincided with southern Manitoba, northern North Dakota and northern Minnesota. Swan Lake and Dauphin coincided with central North Dakota and Minnesota. Brandon, Deloraine, Niverville, Portage la Prairie and Elm Creek coincided with northern South Dakota and southern Minnesota.

Clustering using 2*CO_2 precipitation for Manitoba and present precipitation in the selected states did not give such good clusters, as all the Manitoba points were clustered in one area in the north of Minnesota. This suggests some north westerly movement in precipitation but with the whole province receiving approximately equal amounts. Due to the problems associated with GCM predictions of precipitation, historical precipitation figures associated with areas matched using analogous regions were used in this study. These figures indicate a wetter scenario than GCM predictions. Yield results associated with this scenario are considered to be linked to

[31] These states were chosen on the basis of results by Newman 1980, Rosenzweig 1985 and Fraser 1984, which suggested the likely extents of climate movement.

a "wet" scenario.

The results of the analysis indicate a north westerly movement of climate. These results are similar to those predicted by Newman for the situation of a warmer and wetter climate (which is indeed the case for GISS). The results differ slightly from those of the other studies reviewed which tended to favour movement north easterly. However it would seem safe to accept these results, as differences could be due to the new GISS climate scenario used in addition to the different technique.

It seems that the climate will move approximately 650km NW. If we assume that the climatic warming is on average between 3°C and 4°C this means that for every 1°C change, climate will shift between 162km to 216km. Once again, this is roughly consistent with Newman who estimated a shift of 175km for each 1°C change in temperature.

On the basis of these results, areas of the U.S. were divided into four regions in order that yields from these areas could be transferred to the four Manitoba "fields" used in the LP model. When model areas were matched with analogous regions under a 2*CO2 scenario, Field 1 was matched with crop areas NE1, NCE2, SC7 and EC8 in South Dakota (Fig. 5.1). Field 2 was matched with east central North Dakota (Fig. 5.2). Field 3 was matched with crop areas 2, 3, 5 and 6 in Minnesota (Fig 5.3), and Field 4 was matched with the Red River Valley area in North Dakota and crop area 4 in Minnesota (Figs. 5.2 and 5.3). In the final model run, areas in the north of Manitoba were included in the model as Field 5. Yields for this area were obtained from historical yields in Field 3. When areas are matched with more than one crop district, an average of the yields in each district is used.

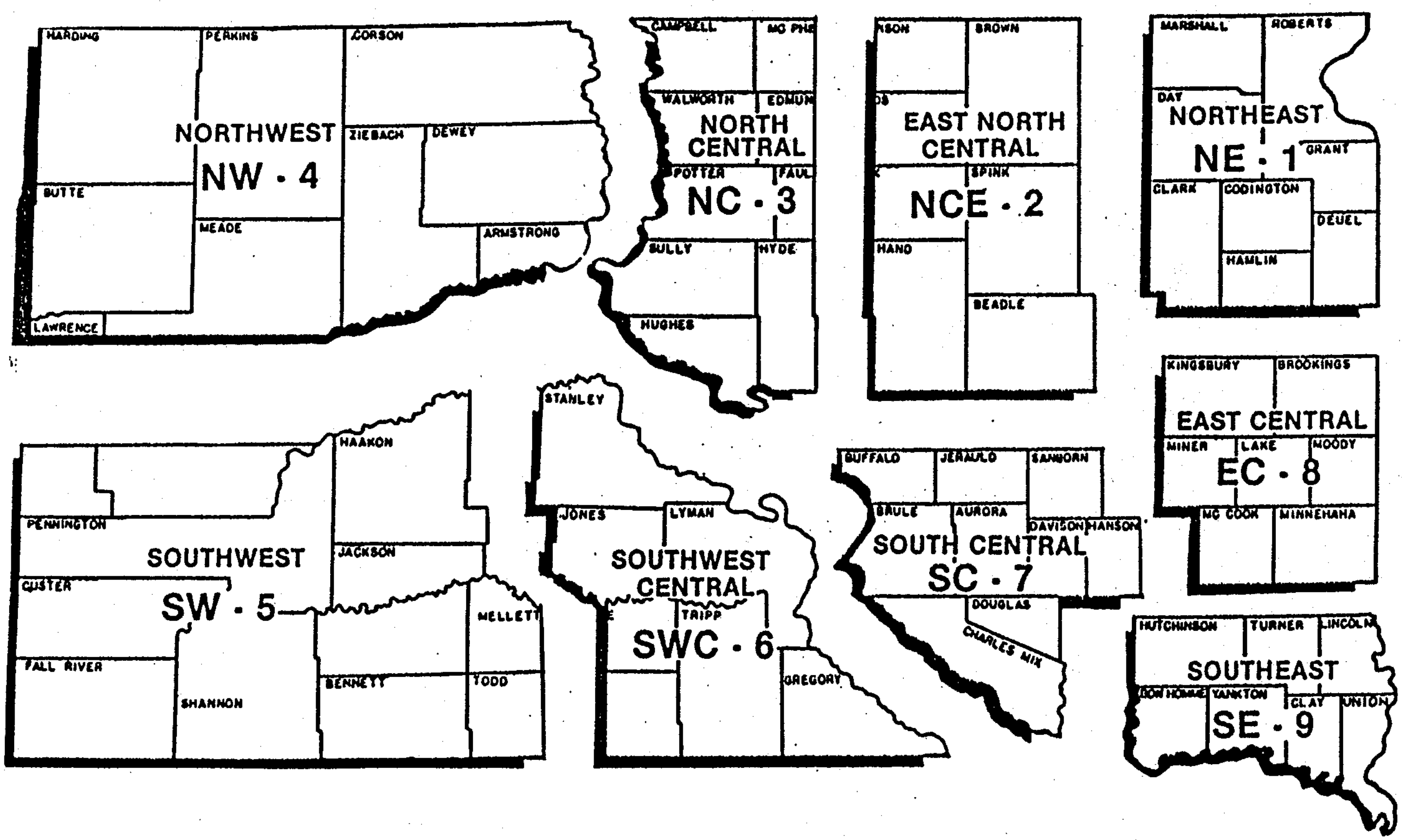

Figure 5.1 Cropping Regions - South Dakota

Source: South Dakota State University (1989).

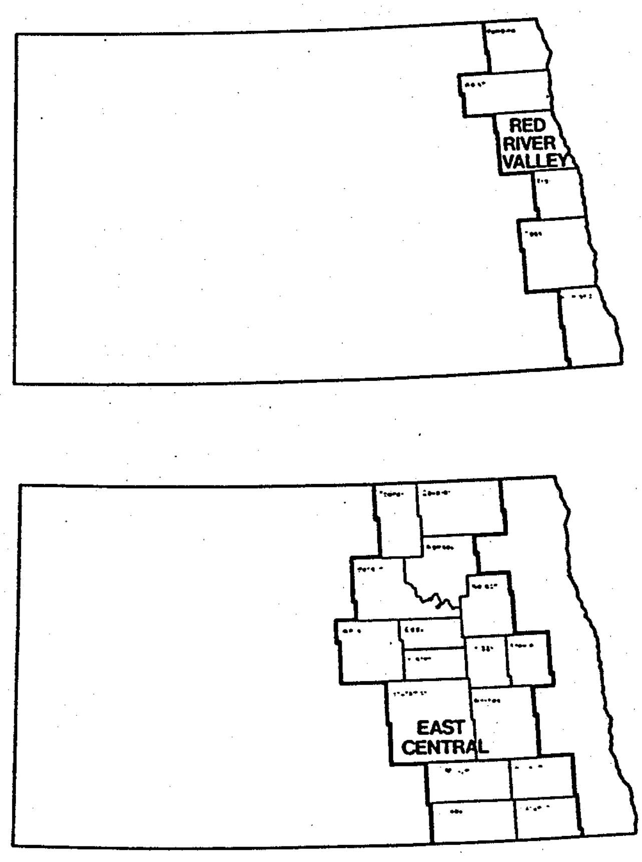

Figure 5.2 Cropping Regions - North Dakota

Source: North Dakota State University (1987)

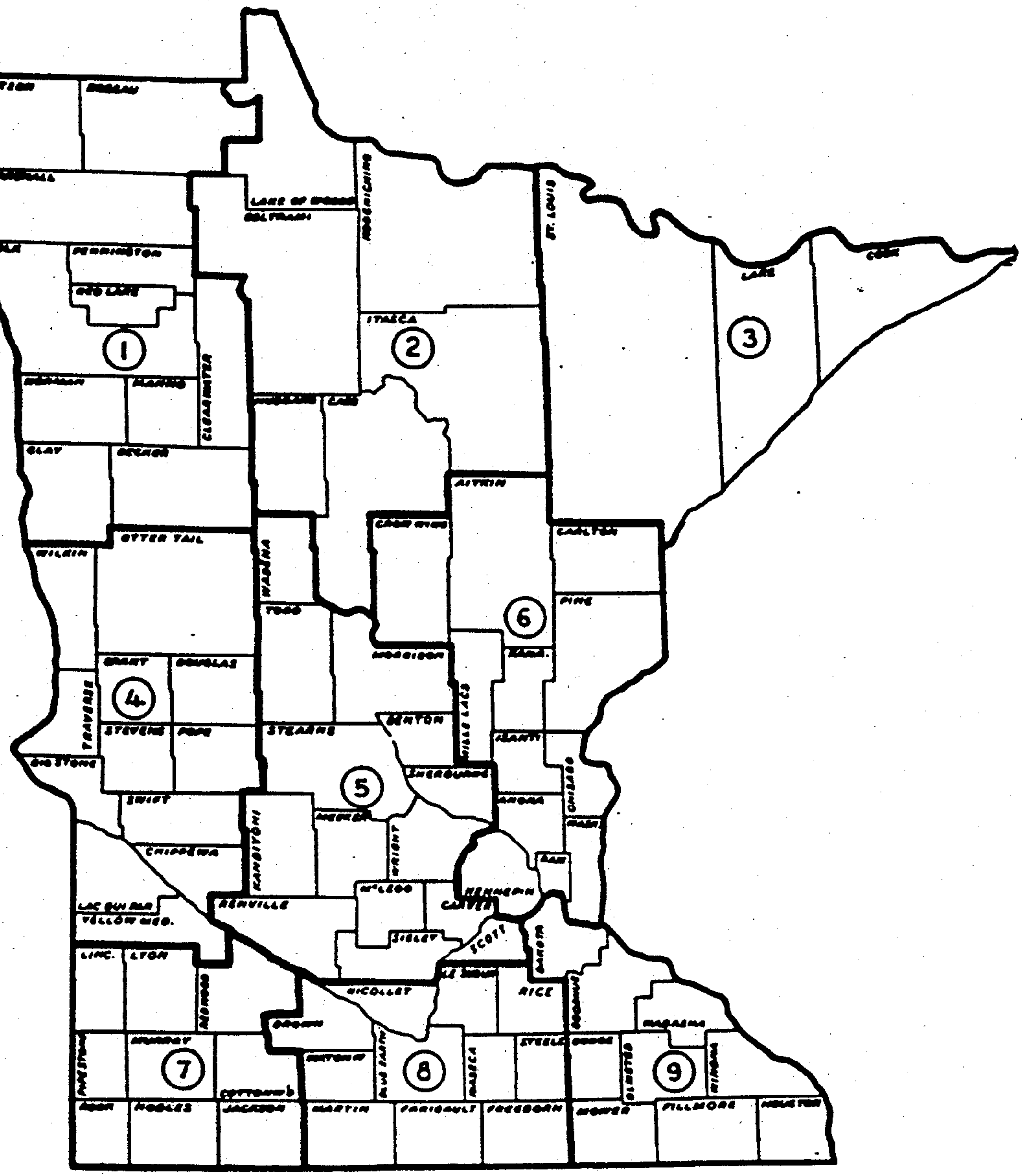

Figure 5.3 Cropping Regions - Minnesota

Source: Minnesota Department of Agriculture (1987)

5.4 Description of Data for LP Model

5.4.1 Variable Costs and Prices

Variable costs and prices remain constant throughout each of the model runs so that the effects of yield and crop changes are more easily recognised and because of the long run nature of the scenario which make it difficult to assess changes that will occur in agricultural policies, market conditions and prices. An effort was made to ensure that data for each crop came from the same source in order that comparisons might be easier; however in some cases this was not possible, as indicated in the following sections.

5.4.1.1 Variable Costs

Variable costs for the majority of crops were calculated from items presented in the Manitoba Agriculture publication, Farm Planning Guide 1989 Crop Estimates. However, the guide did not include cost data for barley, potatoes, soybeans, corn silage or sorghum. Manitoba Agriculture personnel recommended that costs relating to barley were similar to those for oats but should be reduced due to lower fertiliser and seed costs. Barley costs were adjusted to reflect those of oats according to their recommendations. Variable Costs associated with potato production were adapted from a potato budget produced by the Vegetable growers association of Manitoba in 1982. This was adjusted to 1988 prices using an index of farmer input costs. The costs associated with producing corn silage were assumed to be the same as those incurred producing corn grain[32]. Costs of soybean production were not readily available in Manitoba; therefore production costs associated with growing soybeans in the northern U.S States were adapted and used. The same approach was used to obtain costs associated with producing sorghum. The budgets used are presented in appendix 3.

5.4.1.2 Prices

Prices for wheat; corn; corn silage; potatoes; flax; sunflowers; barley; oats and canola are a five year average of historical prices (1983-1987 inclusive) obtained from the Manitoba Agriculture Yearbook 1987. The price of soybeans was obtained from CSP Foods (Altona). A price for sorghum was taken from South Dakota and converted to Canadian dollars using the average exchange rates for the year from the IMF, International Financial Statistics, June 1989. Prices are presented in appendix four.

5.4.2 Yields

Each of the three LP model runs used different yield data in order to simulate the effects of a changed climate on agriculture in Manitoba. The origins of each of the yield estimates are presented in the following sections.

5.4.2.1 Historical yields

Yields relating to the production of most crops were obtained from several issues of the Manitoba Agricultural Yearbook and averaged over ten years for each of the model areas. However for corn grain yields were not available for ten years; for

[32] Examination of budgets for corn grain and corn silage in the northern U.S States indicated that costs of production for both crops were very similar in most cases.

sunflowers, corn silage and potatoes yields were available for ten years but were not available on the basis of individual districts; therefore average yields across the crop district areas (mainly those south central areas) were used. See appendix four.

5.4.2.2 FAO Model Yields under a 2*CO_2 Scenario

Results from the FAO model run by Stewart and Muma, were used to adjust historical yield averages to reflect yields possible under a 2*CO_2 scenario. These yield results were used in a second model run aimed at examining the economic implications of a slightly drier climate on the agriculture sector in Manitoba. See appendix four.

5.4.2.3 Yields Predicted using the Method of Analogous Regions

For the third model run, yield data was taken from areas of the states suggested by the results of cluster analysis. Yields from North Dakota were obtained from the Co-operative Extension Service, North Dakota State University (North Dakota State University 1987). Yields for areas matching with South Dakota were obtained from the Co-operative Extension Service, South Dakota State University (South Dakota State University 1989). Yields for Minnesota were taken from statistics published by the Minnesota Dept. of Agriculture (Minnesota Dept. Agriculture 1987, 1988). See appendix four.

In the following chapter, the results from the LP model runs are presented and discussed.

CHAPTER SIX

ANALYSIS OF FINAL MODEL AND CONCLUSIONS

6.1 Analysis of Linear Programming Economic Models

In the following sections results of three linear programming models, run to assess the economic impacts of a 2*CO_2 greenhouse scenario on the agricultural sector in Manitoba, are presented and discussed. The full results and model formulation are presented in appendix one. Figures presented in the tables and text are taken to two decimal places.

6.1.1 Scenario One

The maximum gross margin[33] predicted for scenario one (the historical model) using the information provided concerning yields, prices and costs is $769,551,114.9. This figure was achieved by combining crops in the following way. In field 1 (South western Manitoba), 273,890ha were planted with barley, 245,500ha planted with canola and 462,610ha with wheat. In field 2 (North western Manitoba), 282,000ha were planted with canola, 564,000ha with wheat and 282,000ha with flax. In field 3 (the Interlake and South eastern Manitoba), 223,250ha were planted with canola, 446,500ha with wheat and 223,250ha with corn silage. In field 4 (South central Manitoba), 354,250ha of canola, 495,950ha wheat, 354,250ha potatoes and 212,550ha of

[33] Gross Margin is defined as, price times yield minus variable costs.

corn/canola were grown (Table 6.1). All of the activities appearing in the basic solution have a reduced gradient of zero. The reduced gradient is the partial derivative of the objective function minus the partial derivative of the constraints with respect to a particular enterprise. Therefore the Kuhn-Tucker conditions are satisfied (as a positive level of production is associated with marginal revenue being equal to marginal cost). The other activities have a reduced gradient that is either negative (in most cases), or zero. A negative reduced gradient means that if a unit of that particular activity were forced into the solution, the value of the objective function would be reduced by its amount. Therefore, the smaller the negative number, the closer that activity is to being included in the final solution. It is useful to consider enterprises with small reduced gradients in addition to those appearing in the final solution because of the simplistic and approximate nature of the model formation. Those activities with very small reduced gradients (above -$50) are corn silage and flax in field 1; barley in field 2; barley and oats in field 3 and barley, sunflowers, soybeans and flax in field 4. When these activities are considered together with those included in the final solution, the model gives a guide to the major crops presently grown in the province. It is considered valid to use as a benchmark for comparison of the present system with the future scenarios as its constraints were validated by consultation with plant scientists and others conversant with farming practices. In addition the purpose of the model is to indicate the type of crops which could be grown rather than their absolute quantities. The model succeeds in predicting these when compared to historical production and is therefore valid for use in this study.

Table 6.2 indicates previous actual farming practices in Manitoba. It is evident that wheat, barley, canola and flax are the most dominant crops in the province in terms

Table 6.1

Solution Quantities and Reduced Gradients for all Three Scenarios

Scenario	One	Two	Three
	$769,551,114.6	$1,175,963,639.4	$2,234,305,878.8

Field 1. South Western Manitoba.

Scenario Solution Crops	One Quantity '000 ha	Reduced Gradient	Two Quantity '000 ha	Reduced Gradient	Three Quantity '000 ha	Reduced Gradient
Bar1	273.89	0.00	273.89	0.00	273.89	0.00
Can1	245.50	0.00	0.00	(7.49)		
Wht1	462.61	0.00	236.16	0.00	217.11	0.00
Oat1	0.00	(68.10)	0.00	(89.16)	0.00	(24.15)
Crns1	0.00	(16.80)	0.00	(31.71)		
Sun1	0.00	(90.49)	0.00	(39.85)	245.50	0.00
Soy1	0.00	(90.49)	0.00	(29.27)	245.50	0.00
Flax1	0.00	(1.33)	226.44	0.00		
Pot1	0.00	(90.49)	245.50	0.00		
Crncan1			0.00	(89.16)		
Sorg1					0.00	(7.72)

Field 2. North Western Manitoba.

Scenario Solution Crops	One Quantity '000 ha	Reduced Gradient	Two Quantity '000 ha	Reduced Gradient	Three Quantity '000 ha	Reduced Gradient
Bar2	0.00	0.00	0.00	(279.58)	0.00	(69.65)
Can2	282.00	0.00	0.00	(289.93)		
Wht2	564.00	0.00	0.00	(267.71)	0.00	(61.18)
Oat2	0.00	(57.07)	0.00	(372.65)	0.00	(167.15)
Crns2	0.00	(85.34)	0.00	(274.91)	1,128.00	0.00
Sun2	0.00	(85.34)	0.00	(329.45)	0.00	(20.33)
Soy2	0.00	(85.34)	0.00	(296.14)		
Flax2	282.00	0.00	0.00	(247.30)	0.00	(163.91)
Pot2	0.00	(85.34)	282.00	0.00		
Crncan2			564.00	0.00		
Crnsoy2			282.00	0.00	0.00	(35.15)

Field 3. The Interlake and South Eastern Manitoba.

Scenario Solution Crops	One Quantity '000 ha	Reduced Gradient	Two Quantity '000 ha	Reduced Gradient	Three Quantity '000 ha	Reduced Gradient
Bar3	0.00	(37.89)	0.00	(40.18)	0.00	(245.54)
Can3	223.25	0.00	0.00	(69.29)		
Wht3	446.50	0.00	0.00	(4.58)	0.00	(191.58)
Oat3	0.00	(41.97)	0.00	(92.70)	0.00	(319.43)
Crns3	223.25	0.00	669.75	0.00	0.00	(106.16)
Sun3	0.00	(73.69)	0.00	(48.48)	0.00	(194.69)
Soy3	0.00	(73.69)	0.00	(20.35)	0.00	(77.85)
Flax3	0.00	(73.69)	0.00	(25.86)	0.00	(286.96)
Pot3	0.00	(73.69)	223.25	0.00	223.25	0.00
Crncan3			0.00	(92.70)		
Crnsoy3					669.75	0.00

Field 4. South Central Manitoba.

Scenario Solution Crops	One Quantity '000 ha	Reduced Gradient	Two Quantity '000 ha	Reduced Gradient	Three Quantity '000 ha	Reduced Gradient
Bar4	0.00	(2.50)	0.00	(58.78)	0.00	(150.19)
Can4	354.25	0.00	0.00	(71.33)		
Wht4	495.95	0.00	0.00	(69.74)	0.00	(101.91)
Oat4	0.00	(73.86)	0.00	(184.35)	0.00	(235.76)
Crns4	0.00	(50.90)	0.00	(138.61)	0.00	(45.95)
Sun4	0.00	0.00	0.00	(132.66)	0.00	(89.61)
Soy4	0.00	(48.08)	0.00	(130.93)	0.00	(94.00)
Flax4	0.00	(15.10)	0.00	(43.64)	0.00	(217.33)
Pot4	354.25	0.00	0.00	(27.30)	354.25	0.00
Crncan4	212.55	0.00	708.50	0.00		
Crnsoy4			708.50	0.00	1,062.75	0.00

Field 5. Northern Manitoba.

Scenario Solution Crops	One Quantity '000 ha	Reduced Gradient	Two Quantity '000 ha	Reduced Gradient	Three Quantity '000 ha	Reduced Gradient
Bar5					0.00	(4.30)
Can5					325.00	0.00
Wht5					650.00	0.00
Oat5					0.00	(66.10)
Flax5					0.00	0.00
Pot5					325.00	0.00

Table 6.2

Comparison of Linear Programming Results from Scenario One with Actual Cropping Practices in Manitoba

	Field1		Field2		Field3		Field4	
Crop	L.P.	Actual	L.P.	Actual	L.P.	Actual	L.P.	Actual
Barley	273.89	174.45	(a)	238.35	(a)	148.35	(a)	226.87
Canola	245.50	65.72	282.00	100.45	223.25	41.81	354.25	111.23
Wheat	462.61	424.23	564.00	462.85	446.50	(b)	495.95	482.77
Oats		52.88		62.61	(a)	39.89		44.73
Corn/S	(a)	2.00		1.26	223.25	4.46		8.39
Sunflower		20.94		1.12		(b)	(a)	35.96
Soybean		0.14		0.15		0.18	(a)	0.73
Flax	(a)	73.21	282.00	53.12		56.21	(a)	168.49
Potato		4.84		0.09		0.86	354.25	11.84
Crncan		6.64		0.72		6.19	212.55	37.78

Source: Statistics Canada. 1986 Census of Agriculture.
(a) insufficient data in 1986 census.
(b) crops close to inclusion in the LP model solution for scenario one.

of hectarage devoted to their production. This pattern is largely reflected by the L.P. model results as wheat, barley, canola and flax appear as dominant crops in the L.P. solution or are close to inclusion in the final solution. It is evident from table 6.2 that the model does not predict the hectarage of these crops with any degree of accuracy. This is a result of the models simplistic nature and could also be associated with the particular crop rotations chosen, of which there are alternative options in real life.

The model contains land constraints for each of the four growing areas; these were binding and consequently had positive dual values. The dual value relating to each constraint indicates the degree of change in the objective function value from the addition of another unit of the resource constrained. To consider the value in another way, in relation to the land constraints, it would be the maximum amount of money that a farmer should be prepared to pay in order to rent another unit of land. The dual values indicate that for this particular problem formulation, an extra hectare of land in field 1 would increase the value of the objective function by $90.47; whereas an extra hectare of land in field 4 would increase the value of the objective function by $124.59 and so on (Table 6.3). The dual values for each land area in scenario one indicate that field 4 is the most profitable area of land (having a dual value of $124.59). This is fairly consistent with reality as the Red River Valley, one of the most fertile areas in Manitoba, lies within this area. Field 1, south western Manitoba, is indicated as the next most profitable area with a dual value of $90.49. Field 2, north western Manitoba, has a dual value of $85.34; very similar to that of field 1. Field 3, south western Manitoba and the interlake, is calculated to be the least profitable area with a dual of $73.69. The poor soil quality, particularly in the eastern areas, and unpredictable weather patterns may account in some part for the low dual value.

Table 6.3

Land and Feed Constraints for each of the Three Linear Programming Scenarios

Scenario	One		Two		Three	
	Level	Dual	Level	Dual	Level	Dual
Field1	982.00	90.49	982.00	89.16	982.00	102.58
Field2	1128.00	85.34	1128.00	372.65	1128.00	259.03
Field3	893.00	73.69	893.00	92.70	893.00	329.87
Field4	1417.00	124.59	1417.00	184.35	1417.00	344.68
Field5					1300.00	96.09
WheatF	1969.06	0.00	236.16	-81.95	867.11	0.00
BarleyF	273.89	-16.77	273.89	-72.89	273.80	-47.99

The dual values associated with the feed constraints WHEATF and BARLEYF, suggest that barley would not be included in the optimal solution in such great quantities if it were not constrained to do so in order to meet the feed requirement. The addition of an extra unit of barley could decrease the value of the objective function by $16.77. The constraint for wheat is not binding and consequently has a dual value of zero (Table 6.3). This suggests that wheat would appear in the basic solution even without this constraint. Although the model only considered wheat and barley for feed, several other crops are used to feed livestock in practice; for example, oats and corn silage. These can be substituted into feed rations to varying degrees dependent upon their nutritional content and price. If the model allowed these feedstuffs to be substituted into the animal enterprises rather than sold, the quantities and mix of crops grown in the final solutions would differ slightly. The constraints for wheat and barley production are mainly representative of current feed use but are more inflexible in the model than in the real world.

The crop rotation constraints in scenario one have positive dual values or dual values of zero (Table 6.4). A positive dual value indicates that the constraint is binding and that by relaxing the quantities that could be planted, an increase in the value of the objective function would be achieved. Those constraints with a dual value of zero are not binding and therefore no extra value can be obtained from relaxing the constraint as spare units are already available (Table 6.4). Constraints that are binding in scenario one are canola hectarage in field 1; wheat, flax and canola in field 2; wheat and canola in field 3 and canola, potatoes and corn/canola in field 4. To a large extent, these reflect the major crops in the province at the present time, perhaps with the exception of potatoes and corn which are grown in fairly limited areas. In the real

Table 6.4

Rotational Constraints for Fields 1, 2, 3, 4 and 5

Scenario Crop	One Level	Dual	Two Level	Dual	Three Level	Dual
Field 1 South Western Manitoba						
Rbar1	273.89	0.00	273.89	0.00	273.89	0.00
Rwht1	462.61	0.00	236.16	0.00	217.11	0.00
Roat1	0.00	0.00	0.00	0.00	0.00	0.00
Rflax1	0.00	0.00	226.44	0.00	0.00	0.00
Rcan1	245.50	96.21	0.00	0.00	0.00	0.00
Rpot1	0.00	0.00	245.50	153.99	0.00	0.00
Rsoy1	0.00	0.00	0.00	0.00	245.50	132.12
Rsun1	0.00	0.00	0.00	0.00	245.50	82.74
Rspec1	245.50	0.00	471.94	491.00	491.00	0.00
Rcmcan1			0.00	0.00	0.00	0.00
Field 2 North Western Manitoba						
Rbar2	0.00	0.00	0.00	0.00	0.00	0.00
Rwht2	564.00	18.98	0.00	0.00	0.00	0.00
Roat2	0.00	0.00	0.00	0.00	0.00	0.00
Flax2	282.00	40.01	0.00	0.00	0.00	0.00
Rcan2	282.00	114.99	0.00	0.00	0.00	0.00
Rpot2	0.00	0.00	282.00	259.10	0.00	0.00
Rsoy2	0.00	0.00	0.00	0.00	0.00	0.00
Rsun2	0.00	0.00	0.00	0.00	0.00	0.00
Rspec2	564.00	0.00	282.00	0.00	0.00	0.00
Rcmcan2			564.00	164.35	0.00	0.00
Field 3 The Interlake and South Eastern Manitoba						
Rbar3	0.00	0.00	0.00	0.00	0.00	0.00
Rwht3	446.50	25.03	0.00	0.00	0.00	0.00
Roat3	0.00	0.00	0.00	0.00	0.00	0.00
Rflax3	0.00	0.00	0.00	0.00	0.00	0.00
Rcan3	223.25	43.43	0.00	0.00	0.00	0.00
Rpot3	0.00	0.00	223.25	428.65	223.25	943.00
Rsoy3	0.00	0.00	0.00	0.00	0.00	0.00
Rsun3	0.00	0.00	0.00	0.00	0.00	0.00
Rspec3	223.25	0.00	223.25	0.00	223.25	0.00
Rcmcan3			0.00	0.00	0.00	0.00
Field 4 South Central Manitoba						
Rbar4	0.00	0.00	0.00	0.00	0.00	0.00
Rwht4	495.95	0.00	0.00	0.00	0.00	0.00
Roat4	0.00	0.00	0.00	0.00	0.00	0.00
Rflax4	0.00	0.00	0.00	0.00	0.00	0.00
Rcan4	354.25	67.77	0.00	0.00	0.00	0.00
Rpot4	354.25	453.86	0.00	0.00	354.25	1294.59
Rsoy4	0.00	0.00	0.00	0.00	0.00	0.00
Rsun4	0.00	0.00	0.00	0.00	0.00	0.00
Rspec4	708.50	31.21	0.00	0.00	354.25	0.00
Rcmcan4	212.55	192.12	708.50	90.48	0.00	0.00
Field 5 Northern Manitoba						
Rbar5					0.00	0.00
Rwht5					650.00	57.58
Roat5					0.00	0.00
Rflax5					0.00	0.00
Rcan5					325.00	62.63
Rpot5					325.00	513.57
Rsoy5					0.00	0.00
Rsun5					0.00	0.00
Rspec5					650.00	0.00
Rcmcan5					0.00	0.00

world there is a degree of scope to alter these rotational constraints. However, ultimately there are always disease and pest constraints (among others) that limit the selection of crops that can be grown on areas of land in any given year.

In summary, scenario one does appear to give at least a general indication of the crops grown in Manitoba at present and the model is considered valid as it abstracts reality adequately for its intended use as an indicator of the general nature of crop changes under a 2*CO_2 scenario. It is against this benchmark that the following two scenarios relating to climate change will be compared. During the comparisons, more emphasis will be placed on directions of change and the relative importance of crops in different areas than on purely monetary change indicated by the gross margins.

6.1.2 Scenario Two

The maximum gross margin obtainable from scenario two (one where the climate is warmer and drier) using the cost and price information from scenario one and yields predicted by the F.A.O. yield model Agriculture Canada, is $1,175,963,639.4, $406,412,524 greater than base line. This figure is achieved by combining cropping activities in the following way. In field 1, 273,890ha barley, 236,161ha wheat, 226,449ha flax and 245,500ha potatoes. In field 2, 282,000ha potatoes, 564,000ha corn/canola and 282,000ha corn/soybean. In field 3, 669,750ha corn silage and 223,250ha potatoes. In field 4, 708,500ha corn/canola and 708,500ha of corn/soybeans were suggested (Table 6.1). Those activities approaching inclusion in the final solution (reduced gradient of -$50 or above), are canola, corn silage, sunflowers and soybeans in field 1; barley in field 2; wheat, sunflowers, soybeans and flax in field 3 and in field 4 flax and potatoes. These "near misses" combined with the crops included in the optimal solution suggest a migration of cropping areas northward and a small shift away from the importance of presently grown crops to facilitate the inclusion of crops such as soybeans, sunflowers, corn (grain and silage) and potatoes. For example, in scenario one, crops such as corn, sunflowers, soybeans and potatoes were only included (or close to inclusion) in field 4; whereas in scenario two these are grown further north and over a much wider area. In scenario two, less wheat is recommended for production and barley is not close to inclusion in many areas as it was previously. Flax is still included in the basic solution as well as the "near misses", although the area in which it is produced has changed from field 2 to field 1 and it is close to inclusion in fields 3 and 4 as compared to fields 1 and 4 in scenario one. Production of canola is greatly reduced in scenario two as compared with scenario one. In scenario two it is produced solely in rotation with corn and in fields 2 and 4, only coming close to inclusion in field 1. This probably occurs because a corn/canola rotation has a higher gross margin than a simple canola crop. In addition, potatoes have a higher gross margin than canola in areas 1 and 3 and are grown in preference. Although wheat and barley have lower gross margins they are grown in these areas to ensure that the feed requirements are achieved.

These results suggest that although the prevalent "traditional crops" of wheat, barley, canola and flax are still produced under scenario two they are produced in lesser quantities and in different areas than previously. The newer production patterns favour the inclusion of crops such as potatoes, corn (silage in areas 1 and 3; canola and soybean rotations in areas 2 and 4), soybeans (areas 1, 2, 3 and 4) and sunflowers (areas 1 and 3).

The land constraints were binding once again, however the dual values were changed in relation to the first model run and to each other. In this scenario, field 2 becomes the most profitable area of land (having a dual of $372.65), followed by field 4 (dual value $184.35), then field 3 (dual value $92.70) and finally field 1 (dual value $89.16). These figures suggest a change in the relative profitabilities of each of the fields (Table 6.3). These changes in the value of each area of land are directly related to the yield changes predicted in each area. Areas 2 and 4 are the most profitable because of their capacity to produce corn and therefore the set corn rotations devised for the model. Field 2 may have increased in terms of relative profitability because it is likely that moisture stress would not be such a great factor further north therefore allowing higher yields. Field 1 (south western Manitoba), tends to be well drained at the present time (and a little droughty). A warmer climate would increase moisture stress in this area contributing to lower yields. The feed requirements of the livestock sector are also binding. However, unlike the first model run, the addition of extra units of both wheat and barley result in a decrease in the objective function value (see table 6.1). This suggests that resources devoted to production of these crops could be more profitably used elsewhere. The validity of this statement would depend on the profits that could be made from the livestock fed on this feed in comparison to those fed on imported feed or alternative feedstuffs.

The binding rotational constraints are also different from those in the first scenario. In field 1, the constraint relating to the production of potatoes is binding; an extra hectare of land for potatoes would increase the objective function value by $153.99; in scenario one canola was most binding. The same constraint is also binding for fields 2 and 3 whereas in scenario one, wheat and canola were binding for both areas and flax binding for field 2 (Table 6.4). This suggests that in each of the three areas, potatoes are now the most profitable crop, ousting the traditional crops. In field 4, the rotation constraints for corn/canola are the most limiting, similar to the case in scenario one. The change in these limiting rotational constraints reflect a switch in the most profitable crops as a result of yield changes predicted by the F.A.O. model. For all areas, except field 4, potatoes have become the crop from which most revenue can be made per unit. In field 4, corn/canola still remains the most profitable.

6.1.3 Scenario Three

The maximum gross margin that can be obtained under scenario three (depicting a warmer and wetter climate) given the prices and costs used in scenario one and yield figures from areas in the States selected using cluster analysis, is $2,234,305,878, $1,464,754,763 greater than baseline. This is significantly greater than that achieved in the previous scenarios. However, it should be borne in mind that scenario three includes an expanded land base of 1,300,000ha upon which crops can be grown, which would contribute substantially to the increase in revenue noted. To obtain an approximate measure of revenue without this expanded land base, crops appearing in field 5 in the optimal solution (Table 6.1) can be multiplied by their prices and subtracted from the objective function value (see below). This calculation would aid comparisons with the previous scenarios,

```
325 CAN  *  158.7289  =   51586.8925
650 WHT  *  153.6865  =   99896.2250
325 POT  *  609.6760  =  198144.7000
                         349627.8175
or    $349,627,817.5.
```

This leaves the objective function value at $1,884,678,061, an increase of $1,115,126,946 over base. This method will work well for all crops where production decisions in each area are independent. The only exceptions are barley and wheat, the production of which is interrelated throughout all five areas. The problems associated with the separation of barley do not arise as barley is not recommended for production in field 5. This could be for a number of reasons. Firstly, gross margins associated with barley in this area tend to be lower than in other areas; secondly, crops such as wheat and canola are more profitable per hectare then barley in field 5. Changes in the objective function value that would arise from forcing total wheat production into fields 1 to 4 cannot be determined very easily as resources in areas 1 to 4 would have to be freed to enable the minimum amount of wheat to be grown. However 217,000ha of wheat are already produced in field 1 therefore only 19,161ha have to be grown to satisfy the minimum wheat requirement of 236,161ha. The wheat crop is not as profitable as many crops it would replace and therefore the objective function value would drop further than the estimate given above. This could be verified by a further model run in which field 5 was excluded. However this is not necessary as there is no doubt that even with the forced inclusion of total wheat production in areas 1 to 4, the objective function value would still remain higher than in the previous scenarios.

In order to achieve the objective function value, activities are combined in the following manner. In field 1, 273,890ha barley, 217,110ha wheat, 245,500ha sunflowers and 245,000ha soybeans. Field 2, 1,128,000ha is devoted entirely to corn silage[34]. In field 3, 223,250ha potatoes and 669,750ha corn/soybeans are grown. In field 4, 354,250ha potatoes and 1,062,750ha corn/soybeans are grown. In field 5,

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[34] This is not very realistic as an area of land so large would not be devoted to the production of only a single crop. Rather this indicates that corn silage is the most profitable crop to produce in the region given the model constraints.

325,000ha canola, 650,000ha wheat and 325,000ha potatoes are grown (Table 6.1). Those activities close to being entered in the final solution (those with a reduced gradient of -$50 of above) are sorghum and oats in field 1; sunflowers and corn/soybeans in field 2; corn silage in field 4 and barley and flax in field 5. Once again it must be stressed that it is important to consider these "near misses" due to the approximate nature of the model. Production patterns recommended for field 5 in scenario three are very similar to those observed in southern Manitoba in scenario one, suggesting that the production of crops such as wheat, flax, barley and canola will tend to move further northward under a 2*CO_2 scenario. Production of wheat in the presently cultivated areas of Manitoba (fields 1 to 4) is predicted to decline to only 11% of that produced in scenario one. Barley is included in scenario three at its minimum level (similar to scenario one) but does not get included in the list of "near misses" in any of the original land areas, suggesting that its production possibilities have declined in relation to scenario one. The same can be said for canola; however, this is because the analogous regions in the states from which yields were taken for fields 1 to 4 do not produce canola at present. Canola is a new crop to the States only recently having received GRAS (Generally Regarded as Safe for Consumption) status. It is expected that production will increase in the future. Flax production in areas 1 to 4 is also shown to decline under the warmer and wetter climate depicted by scenario three. Those crops appearing most favourable for production are once again, sunflowers, soybeans, corn (grain and silage) and potatoes. The corn/soybean rotation seems popular in fields 2, 3, and 4 and soybeans alone in field 1. Corn silage is favoured in areas 2 and 4. Potatoes in areas 3 and 4, sunflowers in areas 1 and 2 and rather interestingly sorghum and oats in field 1. The addition of sorghum to the list of near misses is quite interesting as this is one crop not grown at all in the province at present. This suggests that under a situation of climatic warming it is likely that new crops would be introduced.

There is not a great deal of difference between crops recommended in scenario two and three except that in scenario three canola (and therefore its rotation with corn) is not present (as canola was not a crop grown in the areas analogous to fields 1 to 4). The major difference in the revenues achieved in scenario two and three is therefore likely to be due to the different yields achieved under each scenario. Crops in scenario three (warmer and wetter) tend to have higher yields than in scenario two; probably because they do not suffer so much from moisture stress and are likely to be longer maturing higher yielding varieties than are grown at present.

The land constraints are binding as in the other scenarios. Dual values are ranked as follows from high to low, field 4 (dual $344.68), field 3 (dual $329.89), field 2 (dual $259.03), field 1 (dual $102.58), field 5 (dual $96.09, see table 6.1). When compared with scenario one, each area of land has increased in value as a result of the higher yielding more profitable crops it became possible to produce. Similar to scenario 2, the most profitable areas seem to be those where it is possible to introduce or expand production of corn (and the associated rotational crops) and potatoes. The production of wheat is not forced into the solution by the feed requirement constraint and therefore has a dual value of zero. On the other hand when barley is forced into the solution, each extra hectare decreases the value of the objective function by $47.99 (Table 6.3). This occurs because of the relative unprofitability of a crop of barley in relation to the returns that can be obtained from planting another crop. However, similar to the proviso for scenario two, it should be considered that in the gross margins for barley and wheat, there is no distinction made between the portion of those crops going for feed and those used for other purposes. Therefore no account is taken of the revenues from the associated livestock enterprises (be they greater or smaller). Rotation constraints most binding are soybean and sunflower for field 1; potatoes for field 3 and 4; wheat, canola and potatoes in field 5 (Table 6.4). These are quite different from those which were binding in scenario one, once again reflecting the relative changes in the importance of different crops, as a result of their changed yields, for revenue creation.

The results of scenario 3 (similar to scenario two) suggest a movement away from the more traditional crops in favour of new ones. In addition a regional shift in cropping areas and an expansion of the production of some selected existing crops was implied.

6.2 Impact of Risk

In the previous discussions it was stated that no formal account has been taken of the impacts of risk on the farmers decision making process. It is likely that if risk were accounted for the model solutions in sections 6.1.1 to 6.1.3 might differ slightly. For example oilseeds and potatoes are known to be more sensitive to moisture deficiencies than many of the other crops, therefore if moisture availability was a concern, fewer hectares would be planted to these crops and more hectares would be planted to alternative "less risk" crops such as barley or wheat, resulting in a different solution. Possible changes in the model solutions as a result of accommodating risk, such as the example above, should be considered when reviewing the model results.

6.3 Conclusions

The purpose of this study was to assess the economic impacts of a 2*CO_2 greenhouse scenario on the agricultural sector within Manitoba. In order to achieve this goal, three linear programming models were run. The first representing the present climatic conditions; the second representing a climate that is warmer and drier and the third representing a climate warmer and wetter. It was necessary to examine the economic effects of climatic warming using more than one scenario because the impacts of an increase in greenhouse gasses on the global climate are not yet well understood. In particular there is a lack of confidence in the precipitation patterns predicted using GCMs.

In sections 6.1.1 to 6.1.3, results of the three linear programming models were presented, discussed and compared. Several conclusions emerged as a result of these analyses. The results of both scenario two and scenario three suggest that the existing pattern of agriculture across the region is likely to be changed as a result of climatic warming. Agriculture could expand further northward into areas presently uncultivated for reasons such as a short growing season or too few growing degree days. Crops such as sunflowers, soybeans, corn and potatoes presently grown only in small quantities are likely to be grown over much wider areas and again their production could shift further north.

The technique of cluster analysis, used to estimate yields in scenario three, enabled the performance of different varieties of existing crops to be studied. The longer growing season would allow later maturing higher yielding varieties to be introduced. The adoption of later maturing varieties would probably mean that planting dates presently common in the province would be altered and brought forward to use the lengthened growing season to its full extent. Only one totally new crop sorghum, and one new to commercial production in Manitoba, soybeans, entered into the model runs. The main reason for this is the difficulty in assessing the relationship between climate change and crop yields. Other studies for example Williams et al (1987), considered the potential of crops such as winter wheat for wider adoption under a 2*CO_2 climate on the prairies. This crop might possibly be grown in Manitoba, but was not considered in this study due to the difficulty predicting its yield response in a warmer winter, because of problems with rust and winter kill.

In summary, five major points have emerged from the analysis:

i) the regional pattern of agriculture in Manitoba is likely to be changed and as a result, the relative profitability of areas in the province will also change;

ii) longer maturing higher yielding varieties of crops could be introduced;

iii) there is potential to introduce totally new crops into the province (including winter wheat);

iv) seeding dates could be advanced to facilitate the introduction of new crops;

v) areas further north may become suited for agricultural practices.

The results of the linear programming model scenarios indicate that the economic effects of climatic warming on agriculture in Manitoba are fairly positive.

6.4 Caveats

When considering the above conclusions, the reader must bear in mind several factors. These results were achieved using assumptions concerning current economic and technological conditions which could very likely be different in the future. However, it is likely that any technological changes would have positive effects upon the results; the effects of economic changes are more uncertain and would depend upon the nature of those changes. No account is taken of the effects that global warming will have on production patterns throughout the world; the implications of these changes, affecting the supply of agricultural commodities, would have an impact on world prices. Of particular importance is the effect on relative prices. As the relationships between prices change, the relative profitability of crops will alter and so will production patterns. The way in which supply and price behave is therefore very important for the overall effects of climate change on agriculture in Manitoba. In addition, transportation costs and the manner in which they could alter the relative profitability of crops were not considered. Transport costs can be quite considerable for some crops, this should be remembered when considering the outcome predicted.

Factors such as the incidence of pests, the occurrence of new pests or the introduction of new weeds and diseases have not been considered at all during the analysis. In addition, the direct effects of increased CO_2 on the photosynthetic rate and plant water use were not accounted for. It is obvious that these would have significant effects on yields and could affect the results obtained from the model runs and therefore the final conclusions. Climatic variability was also ignored; incidents such as drought, severe hailstorms, high winds and heavy rains were not considered. The effect of climate change on the severity and frequency of these events is at present uncertain.

Two different climate scenarios were considered because the potential impacts of the greenhouse effect are not yet well modelled, in particular the effects of an increase in the greenhouse gases on precipitation. During the discussion of scenario two, no exact definition of "how much drier" than at present the climate represented. No exact definition can be given, but it is likely that this scenario depicts yields that occur in a climate only slightly drier. The extent of dryness will have a major bearing on the validity of model predictions. A greater degree of moisture stress would cause yields of all crops considered to decline (although they will not all decline at the same rate). Yields of oilseeds and potatoes are particularly susceptible to reductions as a result of moisture stress (Smitt 1987, 7). These are crops that feature quite prominently in the linear programming results; therefore the possibility of increased moisture stress should be considered.

Use of the method of analogous regions to predict suitable crops for the new 2*CO_2 climate should be treated with caution. Government policies can play a part in determining the crops grown in an area and can influence production patterns. Distortions of this nature are carried from the analogous region to the original area and may cause the researcher to overlook more suitable crops for those that are more popularly produced. In addition, the affect of daylength on crop maturity must also be considered. Crops with a C_3 photosynthetic pathway, such as wheat, respond positively to a longer daylength, maturing faster. Therefore, the migration northward of this group could be underestimated. Conversely, crops with a C_4 photosynthetic pathway, such as corn, require longer to mature as daylength increases, therefore the migration northward of this group of crops could be overestimated.

The likelihood of production moving further north should also be examined closely. Although it is likely that agricultural production would be possible, transport costs incurred shipping produce to market would be large and there would be additional costs involved in improving the land and providing services for new settlements. These costs could prove to be an impediment to the migration of farming further north. Land pressure is not great in Southern Manitoba at present; the obvious isolation further north could be a factor deterring a swift northerly migration as a result of climate change, but those with farms already further north might use more of this land and expand their operations.

6.5 Recommendations for Further Research

Throughout the study, data limitations have posed a problem. There is a lot of uncertainty in any kind of research involving the representation of future events. It is obviously important to have good models for research into the effects of climate change. Much work is already underway to improve confidence in the climate predictions of the major GCMs. However, once a future climate scenario has been predicted, these changes need to be translated into impacts on agricultural practices throughout the world. This particular study considered only the effects of a climate change due to a doubling of CO_2 on crop yields. No particular emphasis was placed on soil type or other factors affecting yield. The relationships between crop yields and climatic/weather factors are not well modelled and are very difficult to come by. In addition, estimates of these relationships are not available for all crops and are often sight specific. Crop weather relationships are obviously very complex; however, improved modelling of these relationships would greatly enhance the economic analyses based on yield change figures.

In order to expand the body of knowledge available concerning the effects of climatic change the relationship between livestock production and climatic factors could also be studied. This would enable a broader picture of the effects of climatic change on the crop/livestock enterprise that are interlinked in production decisions in addition to giving a more complete picture of changes affecting agriculture.

Once the response of crops and livestock to climate change have been better estimated it will be worthwhile for economists to build better and more detailed economic models. It would also be of benefit to increase research into weather variability; pest/disease and weed changes which would enable the riskiness associated with production of different enterprises to be incorporated into models.

Finally, more research is also required into methods which can be used to halt the build up of CO_2 and other greenhouse gasses; for example, alternative energy sources such as wave, wind and solar power which will reduce the reliance upon fossil fuels for power, or methods to reduce global methane emissions to name a few. If this research is successful, the likelihood of even larger climatic changes, perhaps accompanied by other unknown phenomena, could be reduced.

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APPENDICIES

APPENDIX ONE

Specification and Results of the Three Linear Programming Models.

SCENARIO ONE

A HISTORICAL MODEL

SETS

H CONSTRAINTS1

FIELD1
FIELD2
FIELD3
FIELD4
WHEATF
BARLEYF
RBAR1
RWHT1
ROAT1
RFLAX1
RCAN1
RPOT1
RSOY1
RSUN1
RSPEC1
RBAR2
RWHT2
ROAT2
RFLAX2
RCAN2
RPOT2
RSOY2
RSUN2
RSPEC2
RBAR3
RWHT3
ROAT3
RFLAX3
RCAN3
RPOT3
RSOY3
RSUN3
RSPEC3
RBAR4
RWHT4
ROAT4
RFLAX4
RCAN4
RPOT4
RSOY4
RSUN4
RCRNGCAN4
RSPEC4

J ACTIVITIES

BAR1H
BAR2H
BAR3H
BAR4H
CAN1H
CAN2H
CAN3H
CAN4H
WHT1H
WHT2H
WHT3H

WHT4H
OAT1H
OAT2H
OAT3H
OAT4H
CRNS1H
CRNS2H
CRNS3H
CRNS4H
SUN1H
SUN2H
SUN3H
SUN4H
SOY1H
SOY2H
SOY3H
SOY4H
FLAX1H
FLAX2H
FLAX3H
FLAX4H
POT1H
POT2H
POT3H
POT4H
CRNCAN4H

PARAMETERS

A(H) RHS FOR LESS THAN CONSTRAINTS

FIELD1	982
FIELD2	1128
FIELD3	893
FIELD4	1417

LR1(H) LT ROTATION CONSTRAINTS FIELD1

RBAR1	491
RWHT1	491
ROAT1	491
RFLAX1	245.5
RCAN1	245.5
RPOT1	245.5
RSOY1	245.5
RSUN1	245.5
RSPEC1	491

LR2(H) LT ROTATION CONSTRAINTS FIELD2

RBAR2	564
RWHT2	564
ROAT2	564
RFLAX2	282
RCAN2	282
RPOT2	282
RSOY2	282
RSUN2	282
RSPEC2	564

LR3(H) LT ROTATION CONSTRAINTS FIELD3

RBAR3	446.5
RWHT3	446.5
ROAT3	446.5
RFLAX3	223.25
RCAN3	223.25
RPOT3	223.25
RSOY3	223.25
RSUN3	223.25
RSPEC3	446.5

LR4(H) LT ROTATION CONSTRAINTS FIELD4

RBAR4	708.5
RWHT4	708.5
ROAT4	708.5
RFLAX4	354.25
RCAN4	354.25
RPOT4	354.25
RSOY4	354.25
RSUN4	354.25
RCNCAN4	212.55
RSPEC4	708.5

B(H) RHS FOR GREATER THAN CONSTRAINTS

WHEATF	236.1607
BARLEYF	273.89

C(J) OBJECTIVE FUNCTION COEFFICIENTS

BAR1H	73.7235
BAR2H	68.57043
BAR3H	19.03263
BAR4H	105.3157
CAN1H	186.7054
CAN2H	200.3324
CAN3H	117.1255
CAN4H	223.5862
WHT1H	90.49424
WHT2H	104.3211
WHT3H	98.73096
WHT4H	124.5951
SUN1H	0
SUN2H	0
SUN3H	0
SUN4H	155.8089
CRNS1H	73.69352
CRNS2H	0
CRNS3H	73.69352
CRNS4H	73.69532
OAT1H	22.38772
OAT2H	28.26897
OAT3H	31.72244
OAT4H	50.73064
SOY1H	0
SOY2H	0
SOY3H	0
SOY4H	107.72
FLAX1H	89.16099

FLAX2H	125.3524
FLAX3H	0
FLAX4H	140.7048
POT1H	0
POT2H	0
POT3H	0
POT4H	609.676
CRNCAN4H	316.722

TABLE D(H,J) COEFFICIENTS FOR LESS THAN CONSTRAINTS

	BAR1H	BAR2H	BAR3H	BAR4H	CAN1H
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	CAN2H	CAN3H	CAN4H	WHT1H
FIELD1				1.0
FIELD2	1.0			
FIELD3		1.0		
FIELD4			1.0	

+	WHT2H	WHT3H	WHT4H	OAT1H	OAT2H
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	OAT3H	OAT4H
FIELD3	1.0	
FIELD4		1.0

+	CRNS1H	CRNS2H	CRNS3H	CRNS4H
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	SUN1H	SUN2H	SUN3H	SUN4H	SOY1H
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	SOY2H	SOY3H	SOY4H	FLAX1H	FLAX2H
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	FLAX3H	FLAX4H
FIELD3	1.0	
FIELD4		1.0

+	CRNCAN4H	POT1H	POT2H	POT3H	POT4H
FIELD1		1.0			
FIELD2			1.0		
FIELD3				1.0	
FIELD4	1.0				1.0

TABLE E(H,J) COEFFICIENTS FOR GREATER THAN CONSTRAINTS

	BAR1H	BAR2H	BAR3H	BAR4H	WHT1H
WHEATF					1.0
BARLEYF	1.0	1.0	1.0	1.0	

+	WHT2H	WHT3H	WHT4H
WHEATF	1.0	1.0	1.0

TABLE F(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD1

	BAR1H	WHT1H	OAT1H	FLAX1H	CAN1H
RBAR1	1.0				
RWHT1		1.0			
ROAT1			1.0		
RFLAX1				1.0	
RCAN1					1.0
RSPEC1				1.0	1.0

+

	POT1H	SOY1H	SUN1H
RPOT1	1.0		
RSPEC1	1.0	1.0	1.0
RSUN1			1.0
RSOY1		1.0	

TABLE K(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD2

	BAR2H	WHT2H	OAT2H	FLAX2H	CAN2H	POT2H
RBAR2	1.0					
RWHT2		1.0				
ROAT2			1.0			
RFLAX2				1.0		
RCAN2					1.0	
RPOT2						1.0
RSPEC2				1.0	1.0	1.0

+	SOY2H	SUN2H
RSPEC2	1.0	1.0
RSOY2	1.0	
RSUN2		1.0

TABLE L(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD3

	BAR3H	WHT3H	OAT3H	FLAX3H	CAN3H	POT3H
RBAR3	1.0					
RWHT3		1.0				
ROAT3			1.0			
RFLAX3				1.0		
RCAN3					1.0	
RPOT3						1.0
RSPEC3				1.0	1.0	1.0

+	SOY3H	SUN3H
RSPEC3	1.0	1.0
RSOY3	1.0	
RSUN3		1.0

TABLE M(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD4

	BAR4H	WHT4H	OAT4H	FLAX4H	CAN4H	POT4H
RBAR4	1.0					
RWHT4		1.0				
ROAT4			1.0			
RFLAX4				1.0		
RCAN4					1.0	
RPOT4						1.0
RSPEC4				1.0	1.0	1.0

+	SOY4H	SUN4H	CRNCAN4H
RSPEC4	1.0	1.0	
RSOY4	1.0		
RSUN4		1.0	
RCRNGCAN4			1.0

```
VARIABLES
    X(J)    CROP QUANTITIES IN HECTARES
    Z        OBJECTIVE FUNCTION VALUE
  POSITIVE VARIABLE X


EQUATIONS
   OBJECT        DEFINES OBJECTIVE FUNCTION
   CON1(H)       RESOURCE REQUIREMENTS LESS THAN
   CON2(H)       RESOURCE REQUIREMENTS GREATER THAN
   CON3(H)       LT ROTATION CONSTRAINTS FIELD1
   CON4(H)       LT ROTATION CONSTRAINTS FIELD2
   CON5(H)       LT ROTATION CONSTRAINTS FIELD3
   CON6(H)       LT ROTATION CONSTRAINTS FIELD4;

OBJECT..  Z =E= SUM(J, C(J)*X(J));
CON1(H).. SUM (J, D(H,J)*X(J)) =L= A(H);
CON2(H).. SUM (J, E(H,J)*X(J)) =G= B(H);
CON3(H).. SUM (J, F(H,J)*X(J)) =L= LR1(H);
CON4(H).. SUM (J, K(H,J)*X(J)) =L= LR2(H);
CON5(H).. SUM (J, L(H,J)*X(J)) =L= LR3(H);
CON6(H).. SUM (J, M(H,J)*X(J)) =L= LR4(H);


MODEL HIST1 /ALL/
OPTION LIMROW = 80
SOLVE HIST1 USING LP MAXIMIZING Z
```

```
---- OBJECT       =E=  DEFINES OBJECTIVE FUNCTION

OBJECT.. - 73.7235*X(BAR1H) - 68.5704*X(BAR2H) - 19.0326*X(BAR3H)- 105.3157*X(BAR4H) - 186.7054*X(CAN1H) -
         200.3324*X(CAN2H) - 117.1255*X(CAN3H) - 223.5862*X(CAN4H) - 90.4942*X(WHT1H) - 104.3211*X(WHT2H)
         - 98.731*X(WHT3H) - 124.5951*X(WHT4H)- 22.3877*X(OAT1H) - 28.269*X(OAT2H) - 31.7224*X(OAT3H)-
         50.7306*X(OAT4H) - 73.6935*X(CRNS1H)- 73.6935*X(CRNS3H) - 73.6953*X(CRNS4H) - 155.8089*X(SUN4H) -
         107.72*X(SOY4H) - 89.161*X(FLAX1H) - 125.3524*X(FLAX2H) -  140.7048*X(FLAX4H) - 609.676*X(POT4H) -
         316.722*X(CRNCAN4H) + Z =E= 0


---- CON1 =L=  RESOURCE REQUIREMENTS LESS THAN

CON1(FIELD1)..     X(BAR1H) + X(CAN1H) + X(WHT1H) + X(OAT1H) + X(CRNS1H) + X(SUN1H) + X(SOY1H) +
                   X(FLAX1H) + X(POT1H) =L= 982

CON1(FIELD2)..     X(BAR2H) + X(CAN2H) + X(WHT2H) + X(OAT2H) + X(CRNS2H) + X(SUN2H) + X(SOY2H) +
                   X(FLAX2H) + X(POT2H) =L= 1128

CON1(FIELD3)..     X(BAR3H) + X(CAN3H) + X(WHT3H) + X(OAT3H) + X(CRNS3H) + X(SUN3H) + X(SOY3H) +
                   X(FLAX3H) + X(POT3H) =L= 893
```

CON1(FIELD4).. X(BAR4H) + X(CAN4H) + X(WHT4H) + X(OAT4H) + X(CRNS4H) + X(SUN4H) + X(SOY4H) + X(FLAX4H) + X(POT4H) + X(CRNCAN4H) =L= 1417

---- CON2 =G= RESOURCE REQUIREMENTS GREATER THAN

CON2(WHEATF).. X(WHT1H) + X(WHT2H) + X(WHT3H) + X(WHT4H) =G= 236.1607

CON2(BARLEYF).. X(BAR1H) + X(BAR2H) + X(BAR3H) + X(BAR4H) =G= 273.89

---- CON3 =L= LT ROTATION CONSTRAINTS FIELD1

CON3(RBAR1).. X(BAR1H) =L= 491

CON3(RWHT1).. X(WHT1H) =L= 491

CON3(ROAT1).. X(OAT1H) =L= 491

CON3(RFLAX1).. X(FLAX1H) =L= 245.5

CON3(RCAN1).. X(CAN1H) =L= 245.5

CON3(RPOT1).. X(POT1H) =L= 245.5

CON3(RSOY1).. X(SOY1H) =L= 245.5

CON3(RSUN1).. X(SUN1H) =L= 245.5

CON3(RSPEC1).. X(CAN1H) + X(SUN1H) + X(SOY1H) + X(FLAX1H) + X(POT1H) =L= 491

---- CON4 =L= LT ROTATION CONSTRAINTS FIELD2

CON4(RBAR2).. X(BAR2H) =L= 564

CON4(RWHT2).. X(WHT2H) =L= 564

CON4(ROAT2).. X(OAT2H) =L= 564

CON4(RFLAX2).. X(FLAX2H) =L= 282

CON4(RCAN2).. X(CAN2H) =L= 282

CON4(RPOT2).. X(POT2H) =L= 282

CON4(RSOY2).. X(SOY2H) =L= 282

CON4(RSUN2).. X(SUN2H) =L= 282

CON4(RSPEC2).. X(CAN2H) + X(SUN2H) + X(SOY2H) + X(FLAX2H) + X(POT2H) =L= 564

---- CON5 =L= LT ROTATION CONSTRAINTS FIELD3

CON5(RBAR3).. X(BAR3H) =L= 446.5

CON5(RWHT3).. X(WHT3H) =L= 446.5

CON5(ROAT3).. X(OAT3H) =L= 446.5

CON5(RFLAX3).. X(FLAX3H) =L= 223.25

CON5(RCAN3).. X(CAN3H) =L= 223.25

CON5(RPOT3).. X(POT3H) =L= 223.25

CON5(RSOY3).. X(SOY3H) =L= 223.25

CON5(RSUN3).. X(SUN3H) =L= 223.25

CON5(RSPEC3).. X(CAN3H) + X(SUN3H) + X(SOY3H) + X(FLAX3H) + X(POT3H) =L= 446.5

---- CON6 =L= LT ROTATION CONSTRAINTS FIELD4

CON6(RBAR4).. X(BAR4H) =L= 708.5

CON6(RWHT4).. X(WHT4H) =L= 708.5

CON6(ROAT4).. X(OAT4H) =L= 708.5

CON6(RFLAX4).. X(FLAX4H) =L= 354.25

CON6(RCAN4).. X(CAN4H) =L= 354.25

CON6(RPOT4).. X(POT4H) =L= 354.25

CON6(RSOY4).. X(SOY4H) =L= 354.25

CON6(RSUN4).. X(SUN4H) =L= 354.25

CON6(RCRNGCAN4).. X(CRNCAN4H) =L= 212.55

CON6(RSPEC4).. X(CAN4H) + X(SUN4H) + X(SOY4H) + X(FLAX4H) + X(POT4H) =L= 708.5

S O L V E   S U M M A R Y

```
MODEL   HIST1            OBJECTIVE  Z
TYPE    LP               DIRECTION  MAXIMIZE
SOLVER  BDMLP            FROM LINE  343

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL
**** OBJECTIVE VALUE        769551.1146

RESOURCE USAGE, LIMIT       0.067      1000.000
ITERATION COUNT, LIMIT     38          1000

BDM - LP  VERSION 1.01

A. Brooke, A. Drud, and A. Meeraus,
Analytic Support Unit,
Development Research Department,
World Bank,
Washington, D.C. 20433, U.S.A.

WORK SPACE NEEDED (ESTIMATE)  --    6261 WORDS.
WORK SPACE AVAILABLE          --   45426 WORDS.

EXIT -- OPTIMAL SOLUTION FOUND.
```

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU OBJECT	.	.	.	1.000

OBJECT DEFINES OBJECTIVE FUNCTION

---- EQU CON1 RESOURCE REQUIREMENTS LESS THAN

	LOWER	LEVEL	UPPER	MARGINAL
FIELD1	-INF	982.000	982.000	90.494
FIELD2	-INF	1128.000	1128.000	85.341
FIELD3	-INF	893.000	893.000	73.694
FIELD4	-INF	1417.000	1417.000	124.595

---- EQU CON2 RESOURCE REQUIREMENTS GREATER THAN

	LOWER	LEVEL	UPPER	MARGINAL
WHEATF	236.161	1969.060	+INF	.
BARLEYF	273.890	273.890	+INF	-16.771

---- EQU CON3 LT ROTATION CONSTRAINTS FIELD1

	LOWER	LEVEL	UPPER	MARGINAL
RBAR1	-INF	273.890	491.000	.
RWHT1	-INF	462.610	491.000	.
ROAT1	-INF	.	491.000	.
RFLAX1	-INF	.	245.500	.
RCAN1	-INF	245.500	245.500	96.211
RPOT1	-INF	.	245.500	.
RSOY1	-INF	.	245.500	.
RSUN1	-INF	.	245.500	.
RSPEC1	-INF	245.500	491.000	.

---- EQU CON4 LT ROTATION CONSTRAINTS FIELD2

	LOWER	LEVEL	UPPER	MARGINAL
RBAR2	-INF	.	564.000	.
RWHT2	-INF	564.000	564.000	18.980
ROAT2	-INF	.	564.000	.
RFLAX2	-INF	282.000	282.000	40.011
RCAN2	-INF	282.000	282.000	114.991
RPOT2	-INF	.	282.000	.
RSOY2	-INF	.	282.000	.
RSUN2	-INF	.	282.000	.
RSPEC2	-INF	564.000	564.000	.

---- EQU CON5 LT ROTATION CONSTRAINTS FIELD3

	LOWER	LEVEL	UPPER	MARGINAL
RBAR3	-INF	.	446.500	.
RWHT3	-INF	446.500	446.500	25.037
ROAT3	-INF	.	446.500	.
RFLAX3	-INF	.	223.250	.
RCAN3	-INF	223.250	223.250	43.432
RPOT3	-INF	.	223.250	.
RSOY3	-INF	.	223.250	.
RSUN3	-INF	.	223.250	.
RSPEC3	-INF	223.250	446.500	.

---- EQU CON6 LT ROTATION CONSTRAINTS FIELD4

	LOWER	LEVEL	UPPER	MARGINAL
RBAR4	-INF	.	708.500	.
RWHT4	-INF	495.950	708.500	.
ROAT4	-INF	.	708.500	.
RFLAX4	-INF	.	354.250	.
RCAN4	-INF	354.250	354.250	67.777
RPOT4	-INF	354.250	354.250	453.867
RSOY4	-INF	.	354.250	.
RSUN4	-INF	.	354.250	.
RCRNGCAN4	-INF	212.550	212.550	192.127
RSPEC4	-INF	708.500	708.500	31.214

---- VAR X CROP QUANTITIES IN HECTARES

	LOWER	LEVEL	UPPER	MARGINAL
BAR1H	.	273.890	+INF	.
BAR2H	.	.	+INF	.
BAR3H	.	.	+INF	-37.890
BAR4H	.	.	+INF	-2.509
CAN1H	.	245.500	+INF	.
CAN2H	.	282.000	+INF	.
CAN3H	.	223.250	+INF	.
CAN4H	.	354.250	+INF	.
WHT1H	.	462.610	+INF	.
WHT2H	.	564.000	+INF	.
WHT3H	.	446.500	+INF	.
WHT4H	.	495.950	+INF	.
OAT1H	.	.	+INF	-68.107
OAT2H	.	.	+INF	-57.072
OAT3H	.	.	+INF	-41.971
OAT4H	.	.	+INF	-73.864
CRNS1H	.	.	+INF	-16.801
CRNS2H	.	.	+INF	-85.341
CRNS3H	.	223.250	+INF	.
CRNS4H	.	.	+INF	-50.900
SUN1H	.	.	+INF	-90.494
SUN2H	.	.	+INF	-85.341
SUN3H	.	.	+INF	-73.694
SUN4H	.	.	+INF	.
SOY1H	.	.	+INF	-90.494
SOY2H	.	.	+INF	-85.341
SOY3H	.	.	+INF	-73.694
SOY4H	.	.	+INF	-48.089
FLAX1H	.	.	+INF	-1.333
FLAX2H	.	282.000	+INF	.
FLAX3H	.	.	+INF	-73.694
FLAX4H	.	.	+INF	-15.104
POT1H	.	.	+INF	-90.494
POT2H	.	.	+INF	-85.341
POT3H	.	.	+INF	-73.694
POT4H	.	354.250	+INF	.
CRNCAN4H	.	212.550	+INF	.

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Z	-INF	7.6955E+5	+INF	.

Z OBJECTIVE FUNCTION VALUE

**** REPORT SUMMARY : 0 NONOPT
0 INFEASIBLE
0 UNBOUNDED

SCENARIO TWO
CLIMATIC CHNAGE: WARMER AND DRIER

SETS

H CONSTRAINTS1

FIELD1
FIELD2
FIELD3
FIELD4
WHEATF
BARLEYF
RBAR1
RWHT1
ROAT1
RFLAX1
RCAN1
RPOT1
RSOY1
RSUN1
RCRNCAN1
RSPEC1
RBAR2
RWHT2
ROAT2
RFLAX2
RCAN2
RPOT2
RSOY2
RSUN2
RCRNCAN2
RSPEC2
RBAR3
RWHT3
ROAT3
RFLAX3
RCAN3
RPOT3
RSOY3
RSUN3
RCRNCAN3
RSPEC3
RBAR4
RWHT4
ROAT4
RFLAX4
RCAN4
RPOT4
RSOY4
RSUN4
RCRNCAN4
RSPEC4

J ACTIVITIES

BAR1AC
BAR2AC
BAR3AC
BAR4AC
CAN1AC
CAN2AC
CAN3AC
CAN4AC
WHT1AC
WHT2AC
WHT3AC
WHT4AC
OAT1AC
OAT2AC
OAT3AC
OAT4AC

CRNS1AC
CRNS2AC
CRNS3AC
CRNS4AC
SUN1AC
SUN2AC
SUN3AC
SUN4AC
SOY1AC
SOY2AC
SOY3AC
SOY4AC
FLAX1AC
FLAX2AC
FLAX3AC
FLAX4AC
POT1AC
POT2AC
POT3AC
POT4AC
CRNCAN1AC
CRNCAN2AC
CRNCAN3AC
CRNCAN4AC
CRNSOY2AC
CRNSOY4AC

PARAMETERS

A(H) RHS FOR LESS THAN CONSTRAINTS

FIELD1	982
FIELD2	1128
FIELD3	893
FIELD4	1417

LR1(H) LT ROTATION CONSTRAINTS FIELD1

RBAR1	491
RWHT1	491
ROAT1	491
RFLAX1	245.5
RCAN1	245.5
RPOT1	245.5
RSOY1	245.5
RSUN1	245.5
RSPEC1	491
RCRNCAN1	491

LR2(H) LT ROTATION CONSTRAINTS FIELD2

RBAR2	564
RWHT2	564
ROAT2	564
RFLAX2	282
RCAN2	282
RPOT2	282
RSOY2	282
RSUN2	282
RSPEC2	564
RCRNCAN2	564

LR3(H) LT ROTATION CONSTRAINTS FIELD3

RBAR3	446.5
RWHT3	446.5
ROAT3	446.5
RFLAX3	223.25
RCAN3	223.25
RPOT3	223.25

RSOY3	223.25
RSUN3	223.25
RSPEC3	446.5
RCRNCAN3	446.5

LR4(H) LT ROTATION CONSTRAINTS FIELD4

RBAR4	708.5
RWHT4	708.5
ROAT4	708.5
RFLAX4	354.25
RCAN4	354.25
RPOT4	354.25
RSOY4	354.25
RSUN4	354.25
RCRNCAN4	708.5
RSPEC4	708.5

B(H) RHS FOR GREATER THAN CONSTRAINTS

WHEATF	236.1607
BARLEYF	273.89

C(J) OBJECTIVE FUNCTION COEFFICIENTS

BAR1AC	16.20319
BAR2AC	20.11494
BAR3AC	0
BAR4AC	52.6139
CAN1AC	81.66783
CAN2AC	82.72531
CAN3AC	23.41684
CAN4AC	113.019
WHT1AC	7.206904
WHT2AC	22.98491
WHT3AC	6.169354
WHT4AC	32.65552
SUN1AC	49.30987
SUN2AC	43.20483
SUN3AC	44.22233
SUN4AC	51.68405
CRNS1AC	57.44284
CRNS2AC	97.74452
CRNS3AC	92.70681
CRNS4AC	45.74236
OAT1AC	0
OAT2AC	0
OAT3AC	0
OAT4AC	0
SOY1AC	59.88486
SOY2AC	76.50842
SOY3AC	72.35253
SOY4AC	53.42015
FLAX1AC	89.16099
FLAX2AC	125.3524
FLAX3AC	66.8453
FLAX4AC	140.7048
POT1AC	243.1603
POT2AC	631.7553
POT3AC	521.359
POT4AC	157.0512
CRNCAN1AC	0
CRNCAN2AC	537.0144
CRNCAN3AC	0
CRNCAN4AC	274.8332
CRNSOY2AC	372.65521
CRNSOY4AC	184.353525

TABLE D(H,J) COEFFICIENTS FOR LESS THAN CONSTRAINTS

	BAR1AC	BAR2AC	BAR3AC	BAR4AC	CAN1AC
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	CAN2AC	CAN3AC	CAN4AC	WHT1AC
FIELD1				1.0
FIELD2	1.0			
FIELD3		1.0		
FIELD4			1.0	

+	WHT2AC	WHT3AC	WHT4AC	OAT1AC	OAT2AC
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	OAT3AC	OAT4AC
FIELD3	1.0	
FIELD4		1.0

+	CRNS1AC	CRNS2AC	CRNS3AC	CRNS4AC
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	SUN1AC	SUN2AC	SUN3AC	SUN4AC	SOY1AC
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	SOY2AC	SOY3AC	SOY4AC	FLAX1AC	FLAX2AC
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	FLAX3AC	FLAX4AC
FIELD3	1.0	
FIELD4		1.0

+	POT1AC	POT2AC	POT3AC	POT4AC
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	CRNCAN1AC	CRNCAN2AC	CRNCAN3AC	CRNCAN4AC
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	CRNSOY2AC	CRNSOY4AC
FIELD2	1.0	
FIELD4		1.0

TABLE E(H,J) COEFFICIENTS FOR GREATER THAN CONSTRAINTS

	BAR1AC	BAR2AC	BAR3AC	BAR4AC	WHT1AC	WHT2AC
WHEATF					1.0	1.0
BARLEYF	1.0	1.0	1.0	1.0		

+	WHT3AC	WHT4AC
WHEATF	1.0	1.0

TABLE F(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD1

	BAR1AC	WHT1AC	OAT1AC	FLAX1AC	CAN1AC	POT1AC
RBAR1	1.0					
RWHT1		1.0				
ROAT1			1.0			
RFLAX1				1.0		
RCAN1					1.0	
RPOT1						1.0
RSPEC1				1.0	1.0	1.0

+	SOY1AC	SUN1AC	CRNCAN1AC
RSPEC1	1.0	1.0	
RSOY1	1.0		
RSUN1		1.0	
RCRNCAN1			1.0

TABLE K(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD2

	BAR2AC	WHT2AC	OAT2AC	FLAX2AC	CAN2AC	POT2AC
RBAR2	1.0					
RWHT2		1.0				
ROAT2			1.0			
RFLAX2				1.0		
RCAN2					1.0	
RPOT2						1.0
RSPEC2				1.0	1.0	1.0

+	SOY2AC	SUN2AC	CRNCAN2AC
RSPEC2	1.0	1.0	
RSOY2	1.0		
RSUN2		1.0	
RCRNCAN2			1.0

TABLE L(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD3

	BAR3AC	WHT3AC	OAT3AC	FLAX3AC	CAN3AC	POT3AC
RBAR3	1.0					
RWHT3		1.0				
ROAT3			1.0			
RFLAX3				1.0		
RCAN3					1.0	
RPOT3						1.0
RSPEC3				1.0	1.0	1.0

+	SOY3AC	SUN3AC	CRNCAN3AC
RSPEC3	1.0	1.0	
RSOY3	1.0		
RSUN3		1.0	
RCRNCAN3			1.0

TABLE M(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD4

	BAR4AC	WHT4AC	OAT4AC	FLAX4AC	CAN4AC	POT4AC
RBAR4	1.0					
RWHT4		1.0				
ROAT4			1.0			
RFLAX4				1.0		
RCAN4					1.0	
RPOT4						1.0
RSPEC4				1.0	1.0	1.0

+	SOY4AC	SUN4AC	CRNCAN4AC
RSPEC4	1.0	1.0	
RSOY4	1.0		
RSUN4		1.0	
RCRNCAN4			1.0

```
VARIABLES
        X(J)    CROP QUANTITIES IN HECTARES
        Z          OBJECTIVE FUNCTION VALUE ;

        POSITIVE VARIABLE X

        EQUATIONS
        OBJECT    DEFINES OBJECTIVE FUNCTION
        CON1(H)   RESOURCE REQUIREMENTS LESS THAN
        CON2(H)   RESOURCE REQUIREMENTS GREATER THAN
        CON3(H)   LT ROTATION CONSTRAINTS FIELD1
        CON4(H)   LT ROTATION CONSTRAINTS FIELD2
        CON5(H)   LT ROTATION CONSTRAINTS FIELD3
        CON6(H)   LT ROTATION CONSTRAINTS FIELD4;

        OBJECT..        Z =E= SUM(J, C(J)*X(J));
                CON1(H)..       SUM (J, D(H,J)*X(J)) =L= A(H);
                CON2(H)..       SUM (J, E(H,J)*X(J)) =G= B(H);
                CON3(H)..       SUM (J, F(H,J)*X(J)) =L= LR1(H);
                CON4(H)..       SUM (J, K(H,J)*X(J)) =L= LR2(H);
                CON5(H)..       SUM (J, L(H,J)*X(J)) =L= LR3(H);
                CON6(H)..       SUM (J, M(H,J)*X(J)) =L= LR4(H);

        MODEL AGCAN2 /ALL/;
        OPTION LIMROW = 80;
        SOLVE AGCAN2 USING LP MAXIMIZING Z;
        COMPILATION TIME    =       0.258 MINUTES
```

---- OBJECT =E= DEFINES OBJECTIVE FUNCTION

```
OBJECT..        - 16.2032*X(BAR1AC) - 20.1149*X(BAR2AC)- 52.6139*X(BAR4AC) - 81.6678*X(CAN1AC) -
                82.7253*X(CAN2AC) - 23.4168*X(CAN3AC) - 113.019*X(CAN4AC) - 7.2069*X(WHT1AC) -
                22.9849*X(WHT2AC) - 6.1694*X(WHT3AC) - 32.6555*X(WHT4AC) - 57.4428*X(CRNS1AC) -
                97.7445*X(CRNS2AC) - 92.7068*X(CRNS3AC) - 45.7424*X(CRNS4AC) - 49.3099*X(SUN1AC) -
                43.2048*X(SUN2AC) - 44.2223*X(SUN3AC) - 51.684*X(SUN4AC) - 59.8849*X(SOY1AC) -
                76.5084*X(SOY2AC) - 72.3525*X(SOY3AC) - 53.4201*X(SOY4AC)- 89.161*X(FLAX1AC) -
                125.3524*X(FLAX2AC) - 66.8453*X(FLAX3AC)- 140.7048*X(FLAX4AC) - 243.1603*X(POT1AC) -
                631.7553*X(POT2AC) - 521.359*X(POT3AC) - 157.0512*X(POT4AC) - 537.0144*X(CRNCAN2AC) -
                274.8332*X(CRNCAN4AC) - 372.6552*X(CRNSOY2AC) - 184.3535*X(CRNSOY4AC)      + Z =E= 0
```

---- CON1 =L= RESOURCE REQUIREMENTS LESS THAN

```
CON1(FIELD1)..  X(BAR1AC) + X(CAN1AC) + X(WHT1AC) + X(OAT1AC) + X(CRNS1AC) + X(SUN1AC) + X(SOY1AC)
                + X(FLAX1AC) + X(POT1AC) + X(CRNCAN1AC) =L= 982

CON1(FIELD2)..  X(BAR2AC) + X(CAN2AC) + X(WHT2AC) + X(OAT2AC) + X(CRNS2AC) + X(SUN2AC) + X(SOY2AC)
                + X(FLAX2AC) + X(POT2AC) + X(CRNCAN2AC) + X(CRNSOY2AC) =L= 1128

CON1(FIELD3)..  X(BAR3AC) + X(CAN3AC) + X(WHT3AC) + X(OAT3AC) + X(CRNS3AC) + X(SUN3AC) + X(SOY3AC)
                + X(FLAX3AC) + X(POT3AC) + X(CRNCAN3AC) =L= 893

CON1(FIELD4)..  X(BAR4AC) + X(CAN4AC) + X(WHT4AC) + X(OAT4AC) + X(CRNS4AC) + X(SUN4AC) + X(SOY4AC)
                + X(FLAX4AC) + X(POT4AC) + X(CRNCAN4AC) + X(CRNSOY4AC) =L= 1417
```

---- CON2 =G= RESOURCE REQUIREMENTS GREATER THAN

CON2(WHEATF).. X(WHT1AC) + X(WHT2AC) + X(WHT3AC) + X(WHT4AC) =G= 236.1607

CON2(BARLEYF).. X(BAR1AC) + X(BAR2AC) + X(BAR3AC) + X(BAR4AC) =G= 273.89

---- CON3 =L= LT ROTATION CONSTRAINTS FIELD1

CON3(RBAR1).. X(BAR1AC) =L= 491

CON3(RWHT1).. X(WHT1AC) =L= 491

CON3(ROAT1).. X(OAT1AC) =L= 491

CON3(RFLAX1).. X(FLAX1AC) =L= 245.5

CON3(RCAN1).. X(CAN1AC) =L= 245.5

CON3(RPOT1).. X(POT1AC) =L= 245.5

CON3(RSOY1).. X(SOY1AC) =L= 245.5

CON3(RSUN1).. X(SUN1AC) =L= 245.5

CON3(RCRNCAN1).. X(CRNCAN1AC) =L= 491

CON3(RSPEC1).. X(CAN1AC) + X(SUN1AC) + X(SOY1AC) + X(FLAX1AC) + X(POT1AC) =L= 491

---- CON4 =L= LT ROTATION CONSTRAINTS FIELD2

CON4(RBAR2).. X(BAR2AC) =L= 564

CON4(RWHT2).. X(WHT2AC) =L= 564

CON4(ROAT2).. X(OAT2AC) =L= 564

CON4(RFLAX2).. X(FLAX2AC) =L= 282

CON4(RCAN2).. X(CAN2AC) =L= 282

CON4(RPOT2).. X(POT2AC) =L= 282

CON4(RSOY2).. X(SOY2AC) =L= 282

CON4(RSUN2).. X(SUN2AC) =L= 282

CON4(RCRNCAN2).. X(CRNCAN2AC) =L= 564

CON4(RSPEC2).. X(CAN2AC) + X(SUN2AC) + X(SOY2AC) + X(FLAX2AC) + X(POT2AC) =L= 564

---- CON5 =L= LT ROTATION CONSTRAINTS FIELD3

CON5(RBAR3).. X(BAR3AC) =L= 446.5

CON5(RWHT3).. X(WHT3AC) =L= 446.5

CON5(ROAT3).. X(OAT3AC) =L= 446.5

CON5(RFLAX3).. X(FLAX3AC) =L= 223.25

CON5(RCAN3).. X(CAN3AC) =L= 223.25

CON5(RPOT3).. X(POT3AC) =L= 223.25

CON5(RSOY3).. X(SOY3AC) =L= 223.25

CON5(RSUN3).. X(SUN3AC) =L= 223.25

CON5(RCRNCAN3).. X(CRNCAN3AC) =L= 446.5

CON5(RSPEC3).. X(CAN3AC) + X(SUN3AC) + X(SOY3AC) + X(FLAX3AC) + X(POT3AC) =L= 446.5

---- CON6 =L= LT ROTATION CONSTRAINTS FIELD4

CON6(RBAR4).. X(BAR4AC) =L= 708.5

CON6(RWHT4).. X(WHT4AC) =L= 708.5

CON6(ROAT4).. X(OAT4AC) =L= 708.5

CON6(RFLAX4).. X(FLAX4AC) =L= 354.25

CON6(RCAN4).. X(CAN4AC) =L= 354.25

CON6(RPOT4).. X(POT4AC) =L= 354.25

CON6(RSOY4).. X(SOY4AC) =L= 354.25

CON6(RSUN4).. X(SUN4AC) =L= 354.25

CON6(RCRNCAN4).. X(CRNCAN4AC) =L= 708.5

CON6(RSPEC4).. X(CAN4AC) + X(SUN4AC) + X(SOY4AC) + X(FLAX4AC) + X(POT4AC) =L= 708.5

S O L V E   S U M M A R Y

MODEL	AGCAN2	OBJECTIVE	Z
TYPE	LP	DIRECTION	MAXIMIZE
SOLVER	BDMLP	FROM LINE	364

**** SOLVER STATUS 1 NORMAL COMPLETION
**** MODEL STATUS 1 OPTIMAL
**** OBJECTIVE VALUE 1175963.6394

RESOURCE USAGE, LIMIT 0.067 1000.000
ITERATION COUNT, LIMIT 37 1000

BDM - LP VERSION 1.01

A. Brooke, A. Drud, and A. Meeraus,
Analytic Support Unit,
Development Research Department,
World Bank,
Washington, D.C. 20433, U.S.A.

WORK SPACE NEEDED (ESTIMATE) -- 6476 WORDS.
WORK SPACE AVAILABLE -- 45426 WORDS.

EXIT -- OPTIMAL SOLUTION FOUND.

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU OBJECT	.	.	.	1.000

OBJECT DEFINES OBJECTIVE FUNCTION

---- EQU CON1 RESOURCE REQUIREMENTS LESS THAN

	LOWER	LEVEL	UPPER	MARGINAL
FIELD1	-INF	982.000	982.000	89.161
FIELD2	-INF	1128.000	1128.000	372.655
FIELD3	-INF	893.000	893.000	92.707
FIELD4	-INF	1417.000	1417.000	184.354

---- EQU CON2 RESOURCE REQUIREMENTS GREATER THAN

	LOWER	LEVEL	UPPER	MARGINAL
WHEATF	236.161	236.161	+INF	-81.954
BARLEYF	273.890	273.890	+INF	-72.958

---- EQU CON3 LT ROTATION CONSTRAINTS FIELD1

	LOWER	LEVEL	UPPER	MARGINAL
RBAR1	-INF	273.890	491.000	.
RWHT1	-INF	236.161	491.000	.
ROAT1	-INF	.	491.000	.
RFLAX1	-INF	226.449	245.500	.
RCAN1	-INF	.	245.500	.
RPOT1	-INF	245.500	245.500	153.999
RSOY1	-INF	.	245.500	.
RSUN1	-INF	.	245.500	.
RCRNCAN1	-INF	.	491.000	.
RSPEC1	-INF	471.949	491.000	.

---- EQU CON4 LT ROTATION CONSTRAINTS FIELD2

	LOWER	LEVEL	UPPER	MARGINAL
RBAR2	-INF	.	564.000	.
RWHT2	-INF	.	564.000	.
ROAT2	-INF	.	564.000	.
RFLAX2	-INF	.	282.000	.
RCAN2	-INF	.	282.000	.
RPOT2	-INF	282.000	282.000	259.100
RSOY2	-INF	.	282.000	.
RSUN2	-INF	.	282.000	.
RCRNCAN2	-INF	564.000	564.000	164.359
RSPEC2	-INF	282.000	564.000	.

---- EQU CON5 LT ROTATION CONSTRAINTS FIELD3

	LOWER	LEVEL	UPPER	MARGINAL
RBAR3	-INF	.	446.500	.
RWHT3	-INF	.	446.500	.
ROAT3	-INF	.	446.500	.
RFLAX3	-INF	.	223.250	.
RCAN3	-INF	.	223.250	.
RPOT3	-INF	223.250	223.250	428.652
RSOY3	-INF	.	223.250	.
RSUN3	-INF	.	223.250	.
RCRNCAN3	-INF	.	446.500	.
RSPEC3	-INF	223.250	446.500	.

---- EQU CON6 LT ROTATION CONSTRAINTS FIELD4

	LOWER	LEVEL	UPPER	MARGINAL
RBAR4	-INF	.	708.500	.
RWHT4	-INF	.	708.500	.
ROAT4	-INF	.	708.500	.
RFLAX4	-INF	.	354.250	.
RCAN4	-INF	.	354.250	.
RPOT4	-INF	.	354.250	.
RSOY4	-INF	.	354.250	.
RSUN4	-INF	.	354.250	.
RCRNCAN4	-INF	708.500	708.500	90.480
RSPEC4	-INF	.	708.500	.

---- VAR X CROP QUANTITIES IN HECTARES

	LOWER	LEVEL	UPPER	MARGINAL
BAR1AC	.	273.890	+INF	.
BAR2AC	.	.	+INF	-279.582
BAR3AC	.	.	+INF	-40.181
BAR4AC	.	.	+INF	-58.782
CAN1AC	.	.	+INF	-7.493
CAN2AC	.	.	+INF	-289.930
CAN3AC	.	.	+INF	-69.290
CAN4AC	.	.	+INF	-71.335
WHT1AC	.	236.161	+INF	.
WHT2AC	.	.	+INF	-267.716
WHT3AC	.	.	+INF	-4.583
WHT4AC	.	.	+INF	-69.744
OAT1AC	.	.	+INF	-89.161

OAT2AC	.	.	+INF	-372.655
OAT3AC	.	.	+INF	-92.707
OAT4AC	.	.	+INF	-184.354
CRNS1AC	.	.	+INF	-31.718
CRNS2AC	.	.	+INF	-274.911
CRNS3AC	.	669.750	+INF	.
CRNS4AC	.	.	+INF	-138.611
SUN1AC	.	.	+INF	-39.851
SUN2AC	.	.	+INF	-329.450
SUN3AC	.	.	+INF	-48.484
SUN4AC	.	.	+INF	-132.669
SOY1AC	.	.	+INF	-29.276
SOY2AC	.	.	+INF	-296.147
SOY3AC	.	.	+INF	-20.354
SOY4AC	.	.	+INF	-130.933
FLAX1AC	.	226.449	+INF	.
FLAX2AC	.	.	+INF	-247.303
FLAX3AC	.	.	+INF	-25.862
FLAX4AC	.	.	+INF	-43.649
POT1AC	.	245.500	+INF	.
POT2AC	.	282.000	+INF	.
POT3AC	.	223.250	+INF	.
POT4AC	.	.	+INF	-27.302
CRNCAN1AC	.	.	+INF	-89.161
CRNCAN2AC	.	564.000	+INF	.
CRNCAN3AC	.	.	+INF	-92.707
CRNCAN4AC	.	708.500	+INF	.
CRNSOY2AC	.	282.000	+INF	.
CRNSOY4AC	.	708.500	+INF	.

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Z	-INF	1.1760E+6	+INF	.

Z OBJECTIVE FUNCTION VALUE

**** REPORT SUMMARY : 0 NONOPT
0 INFEASIBLE
0 UNBOUNDED

SCENARIO THREE
A CLIMATE CHANGE: WARMER AND WETTER

SETS

H	CONSTRAINTS1	
		FIELD1
		FIELD2
		FIELD3
		FIELD4
		FIELD5
		WHEATF
		BARLEYF
		RBAR1
		RWHT1
		ROAT1
		RFLAX1
		RCAN1
		RPOT1
		RSOY1
		RSUN1
		RCRNCAN1
		RSPEC1
		RBAR2
		RWHT2
		ROAT2
		RFLAX2
		RCAN2
		RPOT2
		RSOY2
		RSUN2
		RCRNCAN2
		RSPEC2
		RBAR3
		RWHT3
		ROAT3
		RFLAX3
		RCAN3
		RPOT3
		RSOY3
		RSUN3
		RCRNCAN3
		RSPEC3
		RBAR4
		RWHT4
		ROAT4
		RFLAX4
		RCAN4
		RPOT4
		RSOY4
		RSUN4
		RCRNCAN4
		RSPEC4
		RBAR5
		RWHT5
		ROAT5
		RFLAX5
		RCAN5
		RPOT5
		RSOY5
		RSUN5
		RCRNCAN5
		RSPEC5
J	ACTIVITIES	BAR1US
		BAR2US
		BAR3US
		BAR4US

BAR5MB
CAN1US
CAN2US
CAN3US
CAN4US
CAN5MB
WHT1US
WHT2US
WHT3US
WHT4US
WHT5MB
OAT1US
OAT2US
OAT3US
OAT4US
OAT5MB
CRNS1US
CRNS2US
CRNS3US
CRNS4US
CRNS5MB
SUN1US
SUN2US
SUN3US
SUN4US
SUN5MB
SOY1US
SOY2US
SOY3US
SOY4US
SOY5MB
FLAX1US
FLAX2US
FLAX3US
FLAX4US
FLAX5MB
POT1US
POT2US
POT3US
POT4US
POT5MB
CRNCAN1US
CRNCAN2US
CRNCAN3US
CRNCAN4US
CRNCAN5MB
CRNSOY1US
CRNSOY2US
CRNSOY3US
CRNSOY4US
CRNSOY5MB
SORG1US

PARAMETERS

A(H) RHS FOR LESS THAN CONSTRAINTS

FIELD1	982
FIELD2	1128
FIELD3	893
FIELD4	1417
FIELD5	1300

Area to the north of Field 2 is estimated to increase by 1300000ha's. This has been included as Field 5.

LR1(H) LT ROTATION CONSTRAINTS FIELD1

RBAR1	491
RWHT1	491
ROAT1	491
RFLAX1	245.5
RCAN1	245.5
RPOT1	245.5
RSOY1	245.5
RSUN1	245.5
RSPEC1	491
RCRNCAN1	491

LR2(H) LT ROTATION CONSTRAINTS FIELD2

RBAR2	564
RWHT2	564
ROAT2	564
RFLAX2	282
RCAN2	282
RPOT2	282
RSOY2	282
RSUN2	282
RSPEC2	564
RCRNCAN2	564

LR3(H) LT ROTATION CONSTRAINTS FIELD3

RBAR3	446.5
RWHT3	446.5
ROAT3	446.5
RFLAX3	223.25
RCAN3	223.25
RPOT3	223.25
RSOY3	223.25
RSUN3	223.25
RSPEC3	446.5
RCRNCAN3	446.5

LR4(H) LT ROTATION CONSTRAINTS FIELD4

RBAR4	708.5
RWHT4	708.5
ROAT4	708.5
RFLAX4	354.25
RCAN4	354.25
RPOT4	354.25
RSOY4	354.25
RSUN4	354.25
RCRNCAN4	708.5
RSPEC4	708.5

LR5(H) LT ROTATION CONSTRAINTS FIELD5

RBAR5	650
RWHT5	650
ROAT5	650
RFLAX5	325
RCAN5	325
RPOT5	325
RSOY5	325
RSUN5	325
RCRNCAN5	650
RSPEC5	650

B(H) RHS FOR GREATER THAN CONSTRAINTS

WHEATF	236.1607
BARLEYF	273.89

C(J) OBJECTIVE FUNCTION COEFFICIENTS

BAR1US	54.59166
BAR2US	141.3872
BAR3US	36.33907
BAR4US	146.4928
BAR5MB	43.8
CAN1US	0
CAN2US	0
CAN3US	0
CAN4US	0
CAN5MB	158.72895
WHT1US	102.585
WHT2US	197.848
WHT3US	138.2893
WHT4US	242.7688
WHT5MB	153.68658
SUN1US	185.3324
SUN2US	238.6958
SUN3US	135.1829
SUN4US	255.0686
SUN5MB	0
CRNS1US	0
CRNS2US	259.0325
CRNS3US	223.7094
CRNS4US	298.7264
CRNS5MB	0
OAT1US	78.4325
OAT2US	91.88057
OAT3US	10.44502
OAT4US	90.92426
OAT5MB	29.995705
SOY1US	234.7092
SOY2US	0
SOY3US	252.0254
SOY4US	250.6786
SOY5MB	0
FLAX1US	0
FLAX2US	95.11863
FLAX3US	42.91315
FLAX4US	127.3475
FLAX5MB	96.09885
POT1US	0
POT2US	0
POT3US	1272.923
POT4US	1639.283
POT5MB	609.676
CRNCAN1US	0
CRNCAN2US	0
CRNCAN3US	0
CRNCAN4US	0
CRNCAN5MB	0
CRNSOY1US	0
CRNSOY2US	223.8795
CRNSOY3US	329.8769
CRNSOY4US	344.6847
CRNSOY5MB	0
SORG1US	94.86

TABLE D(H,J) COEFFICIENTS FOR LESS THAN CONSTRAINTS

	BAR1US	BAR2US	BAR3US	BAR4US	CAN1US
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	BAR5MB	CAN5MB	WHT5MB	OAT5MB
FIELD5	1.0	1.0	1.0	1.0

+	CAN2US	CAN3US	CAN4US	WHT1US
FIELD1				1.0
FIELD2	1.0			
FIELD3		1.0		
FIELD4			1.0	

+	WHT2US	WHT3US	WHT4US	OAT1US	OAT2US
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	OAT3US	OAT4US
FIELD3	1.0	
FIELD4		1.0

+	CRNS1US	CRNS2US	CRNS3US	CRNS4US
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	CRNS5MB		SUN5MB	SOY5MB	FLAX5MB
FIELD5	1.0		1.0	1.0	1.0

+	SUN1US	SUN2US	SUN3US	SUN4US	SOY1US
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	SOY2US	SOY3US	SOY4US	FLAX1US	FLAX2US
FIELD1				1.0	
FIELD2	1.0				1.0
FIELD3		1.0			
FIELD4			1.0		

+	FLAX3US	FLAX4US
FIELD3	1.0	
FIELD4		1.0

+	POT1US	POT2US	POT3US	POT4US
FIELD1	1.0			
FIELD2		1.0		
FIELD3			1.0	
FIELD4				1.0

+	POT5MB	CRNCAN5MB		CRNSOY5MB
FIELD5	1.0	1.0		1.0

+	CRNCAN1US	CRNCAN2US	CRNCAN3US	CRNCAN4US	SORG1US
FIELD1	1.0				1.0
FIELD2		1.0			
FIELD3			1.0		
FIELD4				1.0	

+	CRNSOY1US	CRNSOY2US	CRNSOY3US	CRNSOY4US
FIELD2		1.0		
FIELD4				1.0
FIELD1	1.0			
FIELD3			1.0	

TABLE E(H,J) COEFFICIENTS FOR GREATER THAN CONSTRAINTS

	BAR1US	BAR2US	BAR3US	BAR4US	WHT1US	WHT2US
WHEATF					1.0	1.0
BARLEYF	1.0	1.0	1.0	1.0		

+	WHT3US	WHT4US	WHT5MB		BAR5MB
WHEATF	1.0	1.0	1.0		
BARLEYF					1.0

TABLE F(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD1

	BAR1US	WHT1US	OAT1US	FLAX1US	CAN1US	POT1US
RBAR1	1.0					
RWHT1		1.0				
ROAT1			1.0			
RFLAX1				1.0		
RCAN1					1.0	
RPOT1						1.0
RSPEC1				1.0	1.0	1.0

+	SOY1US	SUN1US	CRNCAN1US
RSPEC1	1.0	1.0	
RSOY1	1.0		
RSUN1		1.0	
RCRNCAN1			1.0

TABLE K(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD2

	BAR2US	WHT2US	OAT2US	FLAX2US	CAN2US	POT2US
RBAR2	1.0					
RWHT2		1.0				
ROAT2			1.0			
RFLAX2				1.0		
RCAN2					1.0	
RPOT2						1.0
RSPEC2				1.0	1.0	1.0

+	SOY2US	SUN2US	CRNCAN2US
RSPEC2	1.0	1.0	
RSOY2	1.0		
RSUN2		1.0	
RCRNCAN2			1.0

TABLE L(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD3

	BAR3US	WHT3US	OAT3US	FLAX3US	CAN3US	POT3US
RBAR3	1.0					
RWHT3		1.0				
ROAT3			1.0			
RFLAX3				1.0		
RCAN3					1.0	
RPOT3						1.0
RSPEC3				1.0	1.0	1.0

+	SOY3US	SUN3US	CRNCAN3US
RSPEC3	1.0	1.0	
RSOY3	1.0		
RSUN3		1.0	
RCRNCAN3			1.0

TABLE M(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD4

	BAR4US	WHT4US	OAT4US	FLAX4US	CAN4US	POT4US
RBAR4	1.0					
RWHT4		1.0				
ROAT4			1.0			
RFLAX4				1.0		
RCAN4					1.0	
RPOT4						1.0
RSPEC4				1.0	1.0	1.0

+	SOY4US	SUN4US	CRNCAN4US
RSPEC4	1.0	1.0	
RSOY4	1.0		
RSUN4		1.0	
RCRNCAN4			1.0

```
TABLE P(H,J) COEFFICIENTS FOR LT ROTATIONS FIELD5
          BAR5MB  WHT5MB  OAT5MB  FLAX5MB       CAN5MB       POT5MB
RBAR5     1.0
RWHT5             1.0
ROAT5                     1.0
RFLAX5                            1.0
RCAN5                                           1.0
RPOT5                                                        1.0
RSPEC5                            1.0           1.0          1.0
+         SOY5MB  SUN5MB  CRNCAN5MB
RSPEC5    1.0     1.0
RSOY5     1.0
RSUN5             1.0
RCRNCAN5                  1.0

          VARIABLES
          X(J)    CROP QUANTITIES IN HECTARES
          Z       OBJECTIVE FUNCTION VALUE

          POSITIVE VARIABLE X

          EQUATIONS
          OBJECT   DEFINES OBJECTIVE FUNCTION
          CON1(H)  RESOURCE REQUIREMENTS LESS THAN
          CON2(H)  RESOURCE REQUIREMENTS GREATER THAN
          CON3(H)  LT ROTATION CONSTRAINTS FIELD1
          CON4(H)  LT ROTATION CONSTRAINTS FIELD2
          CON5(H)  LT ROTATION CONSTRAINTS FIELD3
          CON6(H)  LT ROTATION CONSTRAINTS FIELD4
          CON7(H)  LT ROTATION CONSTRAINTS FIELD5;

          OBJECT..      Z =E= SUM(J, C(J)*X(J));
          CON1(H)..     SUM (J, D(H,J)*X(J)) =L= A(H);
          CON2(H)..     SUM (J, E(H,J)*X(J)) =G= B(H);
          CON3(H)..     SUM (J, F(H,J)*X(J)) =L= LR1(H);
          CON4(H)..     SUM (J, K(H,J)*X(J)) =L= LR2(H);
          CON5(H)..     SUM (J, L(H,J)*X(J)) =L= LR3(H);
          CON6(H)..     SUM (J, M(H,J)*X(J)) =L= LR4(H);
          CON7(H)..     SUM (J, P(H,J)*X(J)) =L= LR5(H);


 MODEL USYIELD3 /ALL/;
 OPTION LIMROW = 80;
 SOLVE USYIELD3 USING LP MAXIMIZING Z;
```

COMPILATION TIME = 0.271 MINUTES

---- OBJECT =E= DEFINES OBJECTIVE FUNCTION

```
OBJECT.. - 54.5917*X(BAR1US) - 141.3872*X(BAR2US) - 36.3391*X(BAR3US) - 146.4928*X(BAR4US) - 43.8*X(BAR5MB)
         - 158.7289*X(CAN5MB) - 102.585*X(WHT1US) - 197.848*X(WHT2US) - 138.2893*X(WHT3US) -
         242.7688*X(WHT4US) - 153.6866*X(WHT5MB) - 78.4325*X(OAT1US) - 91.8806*X(OAT2US) -
         10.445*X(OAT3US) - 90.9243*X(OAT4US) - 29.9957*X(OAT5MB) - 259.0325*X(CRNS2US) -
         223.7094*X(CRNS3US) - 298.7264*X(CRNS4US) - 185.3324*X(SUN1US) - 238.6958*X(SUN2US) -
         135.1829*X(SUN3US) - 255.0686*X(SUN4US) - 234.7092*X(SOY1US) - 252.0254*X(SOY3US) -
         250.6786*X(SOY4US) - 95.1186*X(FLAX2US) - 42.9131*X(FLAX3US) - 127.3475*X(FLAX4US) -
         96.0988*X(FLAX5MB) - 1272.923*X(POT3US) - 1639.283*X(POT4US) - 609.676*X(POT5MB) -
         223.8795*X(CRNSOY2US) - 329.8769*X(CRNSOY3US) - 344.6847*X(CRNSOY4US) - 94.86*X(SORG1US) +
         Z =E= 0
```

---- CON1 =L= RESOURCE REQUIREMENTS LESS THAN

```
CON1(FIELD1)..  X(BAR1US) + X(CAN1US) + X(WHT1US) + X(OAT1US) + X(CRNS1US) + X(SUN1US) + X(SOY1US)
                + X(FLAX1US) + X(POT1US) + X(CRNCAN1US) + X(CRNSOY1US) + X(SORG1US) =L= 982
```

CON1(FIELD2).. X(BAR2US) + X(CAN2US) + X(WHT2US) + X(OAT2US) + X(CRNS2US) + X(SUN2US) + X(SOY2US) + X(FLAX2US) + X(POT2US) + X(CRNCAN2US) + X(CRNSOY2US) =L= 1128

CON1(FIELD3).. X(BAR3US) + X(CAN3US) + X(WHT3US) + X(OAT3US) + X(CRNS3US) + X(SUN3US) + X(SOY3US) + X(FLAX3US) + X(POT3US) + X(CRNCAN3US) + X(CRNSOY3US) =L= 893

CON1(FIELD4).. X(BAR4US) + X(CAN4US) + X(WHT4US) + X(OAT4US) + X(CRNS4US) + X(SUN4US) + X(SOY4US) + X(FLAX4US) + X(POT4US) + X(CRNCAN4US) + X(CRNSOY4US) =L= 1417

CON1(FIELD5).. X(BAR5MB) + X(CAN5MB) + X(WHT5MB) + X(OAT5MB) + X(CRNS5MB) + X(SUN5MB) + X(SOY5MB) + X(FLAX5MB) + X(POT5MB) + X(CRNCAN5MB) + X(CRNSOY5MB) =L= 1300

---- CON2 =G= RESOURCE REQUIREMENTS GREATER THAN

CON2(WHEATF).. X(WHT1US) + X(WHT2US) + X(WHT3US) + X(WHT4US) + X(WHT5MB) =G= 236.1607

CON2(BARLEYF).. X(BAR1US) + X(BAR2US) + X(BAR3US) + X(BAR4US) + X(BAR5MB) =G= 273.89

---- CON3 =L= LT ROTATION CONSTRAINTS FIELD1

CON3(RBAR1).. X(BAR1US) =L= 491

CON3(RWHT1).. X(WHT1US) =L= 491

CON3(ROAT1).. X(OAT1US) =L= 491

CON3(RFLAX1).. X(FLAX1US) =L= 245.5

CON3(RCAN1).. X(CAN1US) =L= 245.5

CON3(RPOT1).. X(POT1US) =L= 245.5

CON3(RSOY1).. X(SOY1US) =L= 245.5

CON3(RSUN1).. X(SUN1US) =L= 245.5

CON3(RCRNCAN1).. X(CRNCAN1US) =L= 491

CON3(RSPEC1).. X(CAN1US) + X(SUN1US) + X(SOY1US) + X(FLAX1US) + X(POT1US) =L= 491

---- CON4 =L= LT ROTATION CONSTRAINTS FIELD2

CON4(RBAR2).. X(BAR2US) =L= 564

CON4(RWHT2).. X(WHT2US) =L= 564

CON4(ROAT2).. X(OAT2US) =L= 564

CON4(RFLAX2).. X(FLAX2US) =L= 282

CON4(RCAN2).. X(CAN2US) =L= 282

CON4(RPOT2).. X(POT2US) =L= 282

CON4(RSOY2).. X(SOY2US) =L= 282

CON4(RSUN2).. X(SUN2US) =L= 282

CON4(RCRNCAN2).. X(CRNCAN2US) =L= 564

CON4(RSPEC2).. X(CAN2US) + X(SUN2US) + X(SOY2US) + X(FLAX2US) + X(POT2US) =L= 564

---- CON5 =L= LT ROTATION CONSTRAINTS FIELD3

CON5(RBAR3).. X(BAR3US) =L= 446.5

CON5(RWHT3).. X(WHT3US) =L= 446.5

CON5(ROAT3).. X(OAT3US) =L= 446.5

CON5(RFLAX3).. X(FLAX3US) =L= 223.25

CON5(RCAN3).. X(CAN3US) =L= 223.25

CON5(RPOT3).. X(POT3US) =L= 223.25

CON5(RSOY3).. X(SOY3US) =L= 223.25

CON5(RSUN3).. X(SUN3US) =L= 223.25

CON5(RCRNCAN3).. X(CRNCAN3US) =L= 446.5

CON5(RSPEC3).. X(CAN3US) + X(SUN3US) + X(SOY3US) + X(FLAX3US) + X(POT3US) =L= 446.5

---- CON6 =L= LT ROTATION CONSTRAINTS FIELD4

CON6(RBAR4).. X(BAR4US) =L= 708.5

CON6(RWHT4).. X(WHT4US) =L= 708.5

CON6(ROAT4).. X(OAT4US) =L= 708.5

CON6(RFLAX4).. X(FLAX4US) =L= 354.25

CON6(RCAN4).. X(CAN4US) =L= 354.25

CON6(RPOT4).. X(POT4US) =L= 354.25

CON6(RSOY4).. X(SOY4US) =L= 354.25

CON6(RSUN4).. X(SUN4US) =L= 354.25

CON6(RCRNCAN4).. X(CRNCAN4US) =L= 708.5

CON6(RSPEC4).. X(CAN4US) + X(SUN4US) + X(SOY4US) + X(FLAX4US) + X(POT4US) =L= 708.5

---- CON7 =L= LT ROTATION CONSTRAINTS FIELD5

CON7(RBAR5).. X(BAR5MB) =L= 650

CON7(RWHT5).. X(WHT5MB) =L= 650

CON7(ROAT5).. X(OAT5MB) =L= 650

CON7(RFLAX5).. X(FLAX5MB) =L= 325

CON7(RCAN5).. X(CAN5MB) =L= 325

CON7(RPOT5).. X(POT5MB) =L= 325

CON7(RSOY5).. X(SOY5MB) =L= 325

CON7(RSUN5).. X(SUN5MB) =L= 325

CON7(RCRNCAN5).. X(CRNCAN5MB) =L= 650

CON7(RSPEC5).. X(CAN5MB) + X(SUN5MB) + X(SOY5MB) + X(FLAX5MB) + X(POT5MB) =L= 650

MODEL STATISTICS

BLOCKS OF EQUATIONS	8	SINGLE EQUATIONS	58
BLOCKS OF VARIABLES	2	SINGLE VARIABLES	57
NON ZERO ELEMENTS	174		

GENERATION TIME = 0.832 MINUTES

EXECUTION TIME = 0.876 MINUTES

S O L V E   S U M M A R Y

MODEL USYIELD3	OBJECTIVE Z
TYPE LP	DIRECTION MAXIMIZE
SOLVER BDMLP	FROM LINE 438

**** SOLVER STATUS 1 NORMAL COMPLETION
**** MODEL STATUS 1 OPTIMAL
**** OBJECTIVE VALUE 2234305.8788

RESOURCE USAGE, LIMIT	0.067	1000.000
ITERATION COUNT, LIMIT	36	1000

BDM - LP VERSION 1.01

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World Bank,
Washington, D.C. 20433, U.S.A.

WORK SPACE NEEDED (ESTIMATE) -- 7173 WORDS.
WORK SPACE AVAILABLE -- 45950 WORDS.

EXIT -- OPTIMAL SOLUTION FOUND.

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU OBJECT	.	.	.	1.000

OBJECT DEFINES OBJECTIVE FUNCTION

---- EQU CON1 RESOURCE REQUIREMENTS LESS THAN

	LOWER	LEVEL	UPPER	MARGINAL
FIELD1	-INF	982.000	982.000	102.585
FIELD2	-INF	1128.000	1128.000	259.032
FIELD3	-INF	893.000	893.000	329.877
FIELD4	-INF	1417.000	1417.000	344.685
FIELD5	-INF	1300.000	1300.000	96.099

---- EQU CON2 RESOURCE REQUIREMENTS GREATER THAN

	LOWER	LEVEL	UPPER	MARGINAL
WHEATF	236.161	867.110	+INF	.
BARLEYF	273.890	273.890	+INF	-47.993

---- EQU CON3 LT ROTATION CONSTRAINTS FIELD1

	LOWER	LEVEL	UPPER	MARGINAL
RBAR1	-INF	273.890	491.000	.
RWHT1	-INF	217.110	491.000	.
ROAT1	-INF	.	491.000	.
RFLAX1	-INF	.	245.500	.
RCAN1	-INF	.	245.500	.
RPOT1	-INF	.	245.500	.
RSOY1	-INF	245.500	245.500	132.124
RSUN1	-INF	245.500	245.500	82.747
RCRNCAN1	-INF	.	491.000	.
RSPEC1	-INF	491.000	491.000	.

---- EQU CON4 LT ROTATION CONSTRAINTS FIELD2

	LOWER	LEVEL	UPPER	MARGINAL
RBAR2	-INF	.	564.000	.
RWHT2	-INF	.	564.000	.
ROAT2	-INF	.	564.000	.
RFLAX2	-INF	.	282.000	.
RCAN2	-INF	.	282.000	.
RPOT2	-INF	.	282.000	.
RSOY2	-INF	.	282.000	.
RSUN2	-INF	.	282.000	.
RCRNCAN2	-INF	.	564.000	.
RSPEC2	-INF	.	564.000	.

---- EQU CON5 LT ROTATION CONSTRAINTS FIELD3

	LOWER	LEVEL	UPPER	MARGINAL
RBAR3	-INF	.	446.500	.
RWHT3	-INF	.	446.500	.
ROAT3	-INF	.	446.500	.
RFLAX3	-INF	.	223.250	.
RCAN3	-INF	.	223.250	.
RPOT3	-INF	223.250	223.250	943.046
RSOY3	-INF	.	223.250	.
RSUN3	-INF	.	223.250	.
RCRNCAN3	-INF	.	446.500	.
RSPEC3	-INF	223.250	446.500	.

---- EQU CON6 LT ROTATION CONSTRAINTS FIELD4

	LOWER	LEVEL	UPPER	MARGINAL
RBAR4	-INF	.	708.500	.
RWHT4	-INF	.	708.500	.
ROAT4	-INF	.	708.500	.
RFLAX4	-INF	.	354.250	.
RCAN4	-INF	.	354.250	.
RPOT4	-INF	354.250	354.250	1294.598
RSOY4	-INF	.	354.250	.
RSUN4	-INF	.	354.250	.
RCRNCAN4	-INF	.	708.500	.
RSPEC4	-INF	354.250	708.500	.

---- EQU CON7 LT ROTATION CONSTRAINTS FIELD5

	LOWER	LEVEL	UPPER	MARGINAL
RBAR5	-INF	.	650.000	.
RWHT5	-INF	650.000	650.000	57.588
ROAT5	-INF	.	650.000	.
RFLAX5	-INF	.	325.000	.
RCAN5	-INF	325.000	325.000	62.630
RPOT5	-INF	325.000	325.000	513.577
RSOY5	-INF	.	325.000	.
RSUN5	-INF	.	325.000	.
RCRNCAN5	-INF	.	650.000	.
RSPEC5	-INF	650.000	650.000	.

---- VAR X CROP QUANTITIES IN HECTARES

	LOWER	LEVEL	UPPER	MARGINAL
BAR1US	.	273.890	+INF	.
BAR2US	.	.	+INF	-69.652
BAR3US	.	.	+INF	-245.544

BAR4US	.	.	+INF	-150.199
BAR5MB	.	.	+INF	-4.306
CAN1US	.	.	+INF	-102.585
CAN2US	.	.	+INF	-259.032
CAN3US	.	.	+INF	-329.877
CAN4US	.	.	+INF	-344.685
CAN5MB	.	325.000	+INF	.
WHT1US	.	217.110	+INF	.
WHT2US	.	.	+INF	-61.184
WHT3US	.	.	+INF	-191.588
WHT4US	.	.	+INF	-101.916
WHT5MB	.	650.000	+INF	.
OAT1US	.	.	+INF	-24.152
OAT2US	.	.	+INF	-167.152
OAT3US	.	.	+INF	-319.432
OAT4US	.	.	+INF	-253.760
OAT5MB	.	.	+INF	-66.103
CRNS1US	.	.	+INF	-102.585
CRNS2US	.	1128.000	+INF	.
CRNS3US	.	.	+INF	-106.167
CRNS4US	.	.	+INF	-45.958
CRNS5MB	.	.	+INF	-96.099
SUN1US	.	245.500	+INF	.
SUN2US	.	.	+INF	-20.337
SUN3US	.	.	+INF	-194.694
SUN4US	.	.	+INF	-89.616
SUN5MB	.	.	+INF	-96.099
SOY1US	.	245.500	+INF	.
SOY2US	.	.	+INF	-259.032
SOY3US	.	.	+INF	-77.851
SOY4US	.	.	+INF	-94.006
SOY5MB	.	.	+INF	-96.099
FLAX1US	.	.	+INF	-102.585
FLAX2US	.	.	+INF	-163.914
FLAX3US	.	.	+INF	-286.964
FLAX4US	.	.	+INF	-217.337
FLAX5MB	.	.	+INF	.
POT1US	.	.	+INF	-102.585
POT2US	.	.	+INF	-259.032
POT3US	.	223.250	+INF	.
POT4US	.	354.250	+INF	.
POT5MB	.	325.000	+INF	.
CRNCAN1US	.	.	+INF	-102.585
CRNCAN2US	.	.	+INF	-259.032
CRNCAN3US	.	.	+INF	-329.877
CRNCAN4US	.	.	+INF	-344.685
CRNCAN5MB	.	.	+INF	-96.099
CRNSOY1US	.	.	+INF	-102.585
CRNSOY2US	.	.	+INF	-35.153
CRNSOY3US	.	669.750	+INF	.
CRNSOY4US	.	1062.750	+INF	.
CRNSOY5MB	.	.	+INF	-96.099
SORG1US	.	.	+INF	-7.725

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Z	-INF	2.2343E+6	+INF	.

Z OBJECTIVE FUNCTION VALUE

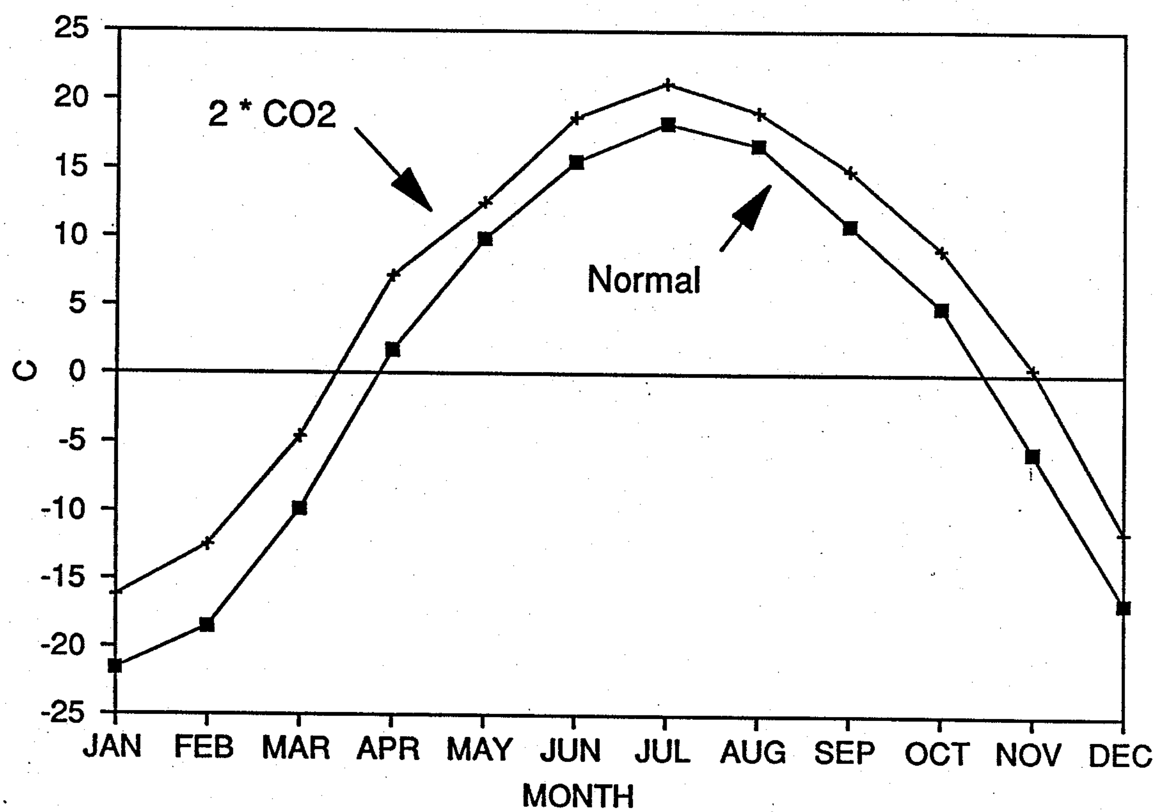
**** REPORT SUMMARY : 0 NONOPT
0 INFEASIBLE
0 UNBOUNDED

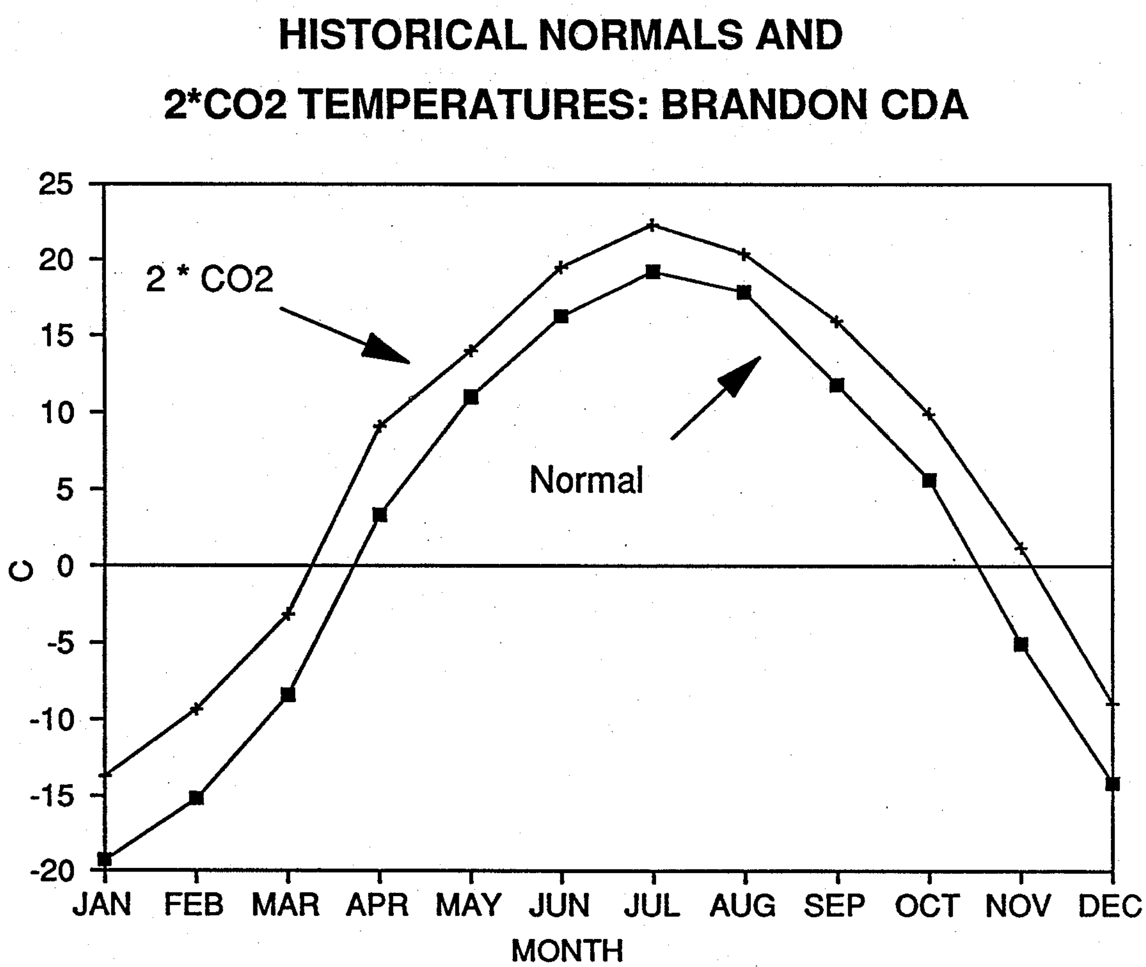
APPENDIX TWO

Graphs Showing Monthly Temperature and Precipitation Normals and the 2*CO_2 Temperature and Precipitation Predictions for Several Weather Stations Within Manitoba.

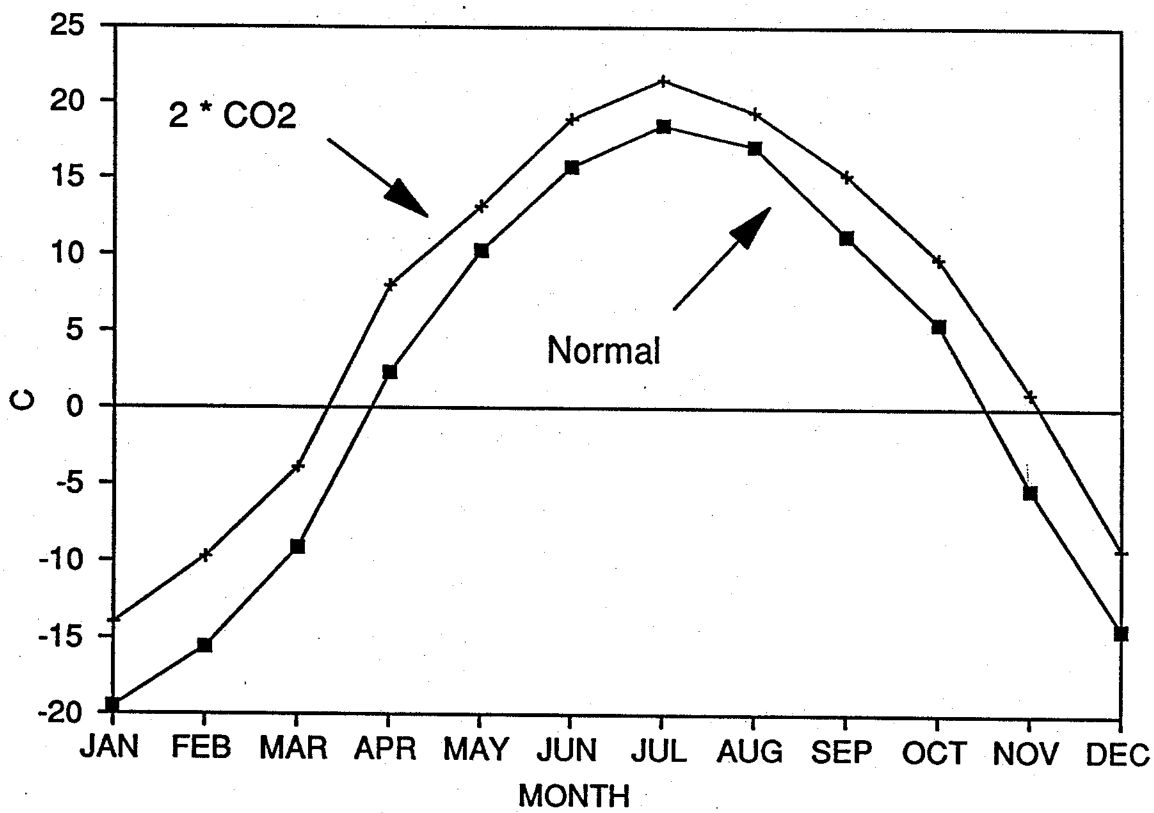
(Monthly normals are adjusted by the differences between the 2*CO_2 and 1*CO_2 GISS GCM model runs to obtain a 2*CO_2 climate for Manitoba)

HISTORICAL NORMALS AND 2*CO2 TEMPERATURES: ARBORG

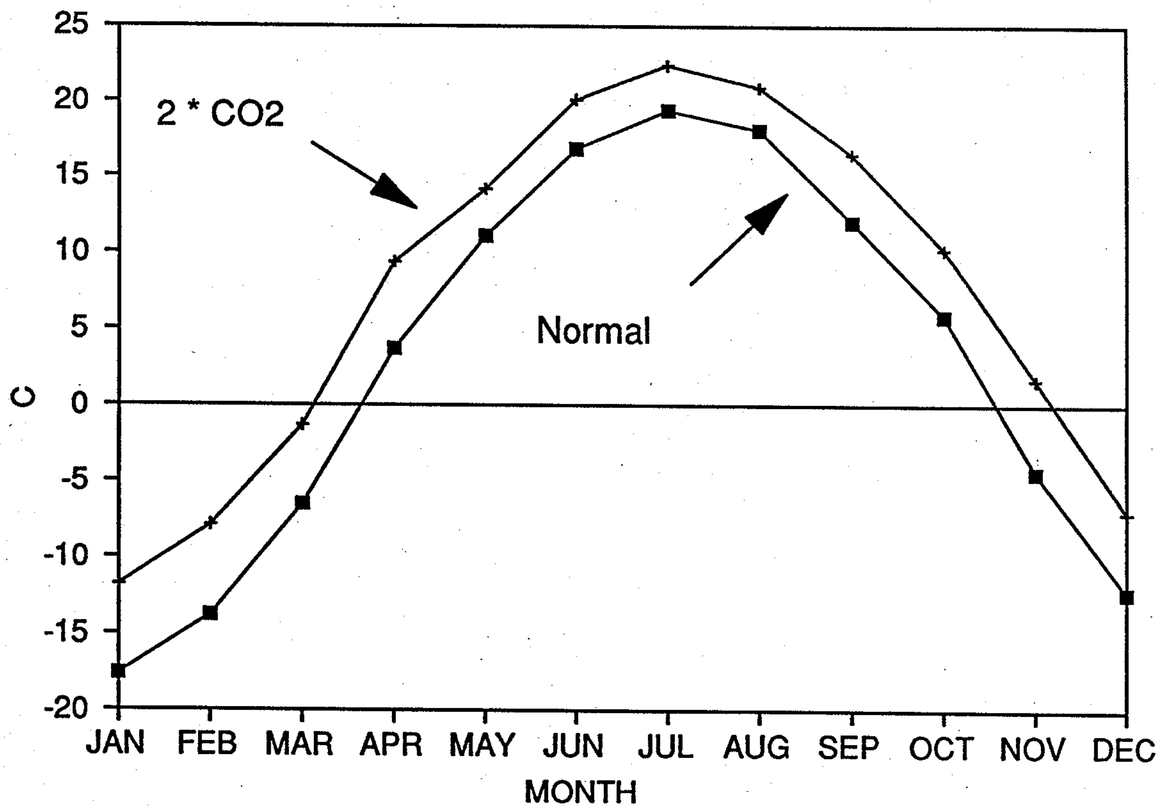



HISTORICAL NORMALS AND
2*CO2 TEMPERATURES: BRANDON CDA
25
20
15
10
5
0
-5
-10
-15
-20
C
2 * CO2
Normal
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

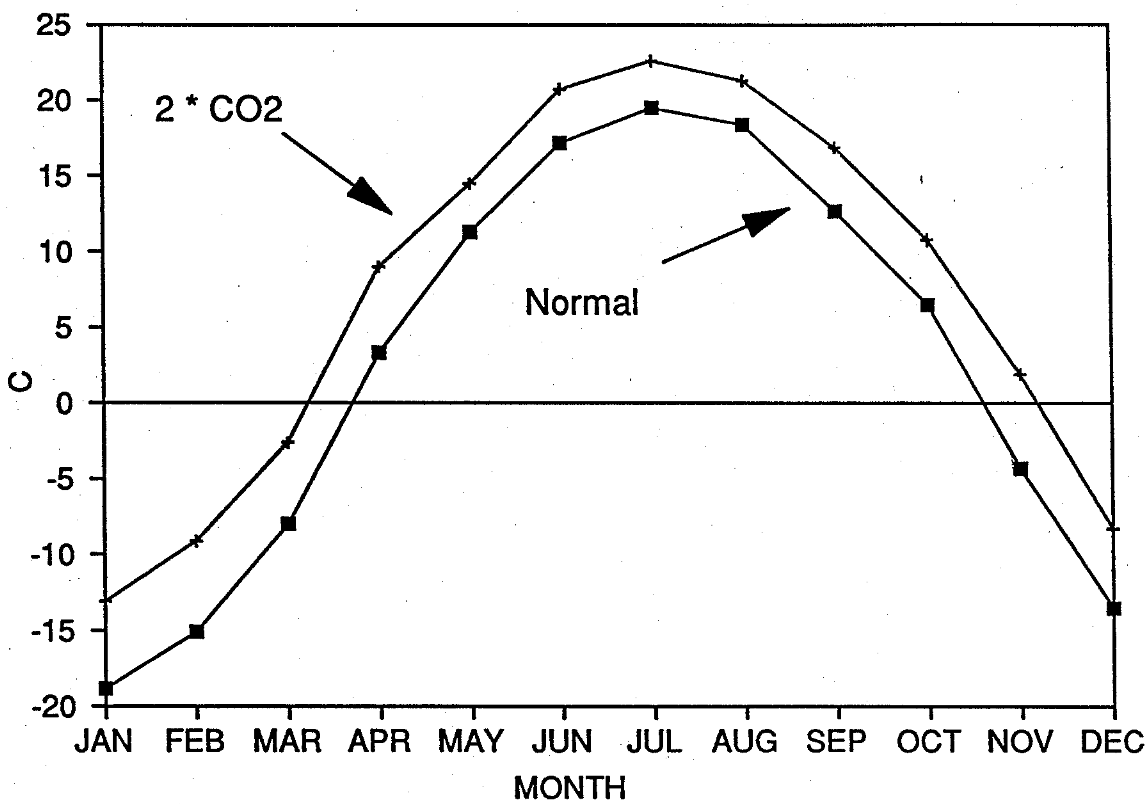
HISTORICAL NORMALS AND 2*CO2 TEMPERATURES: DAUPHIN

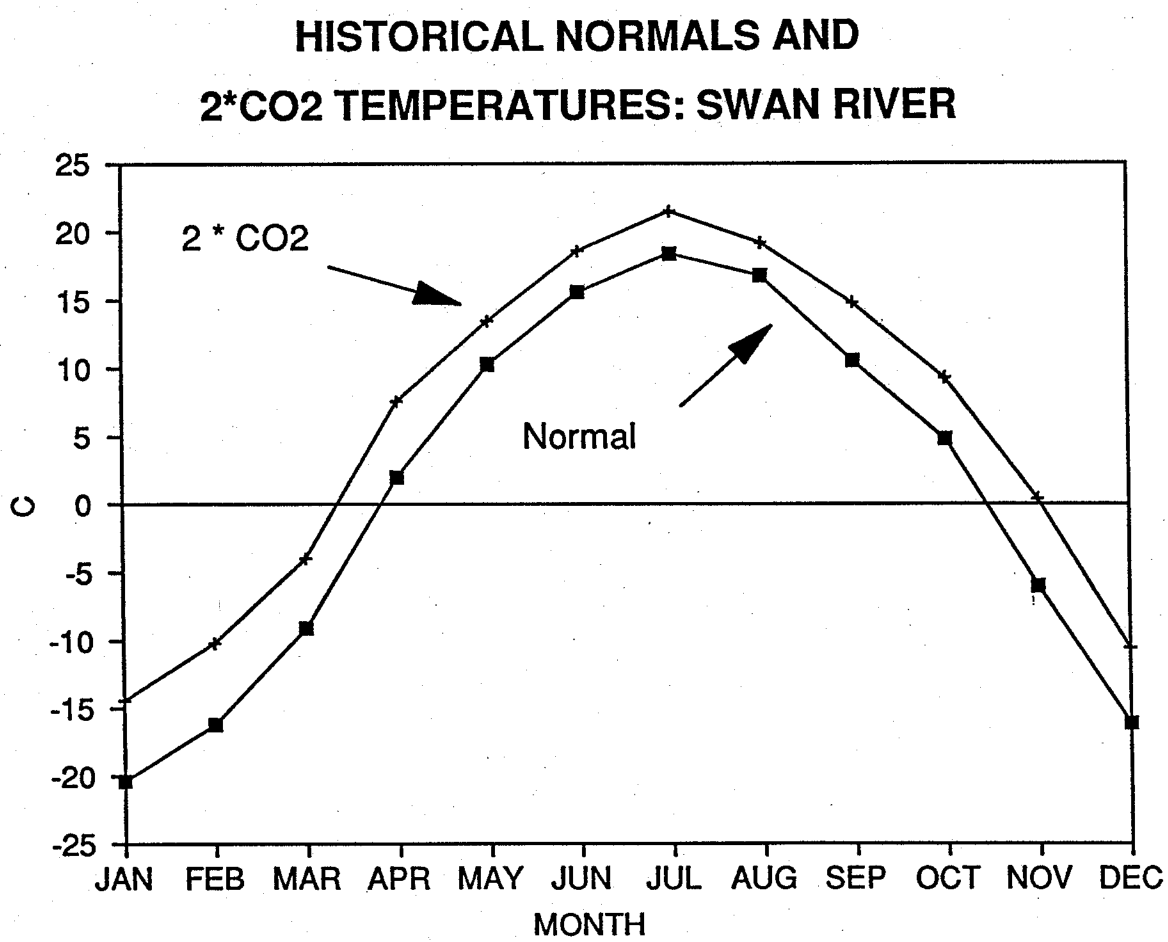


HISTORICAL NORMALS AND 2*CO2 TEMPERATURES: DELORAINE

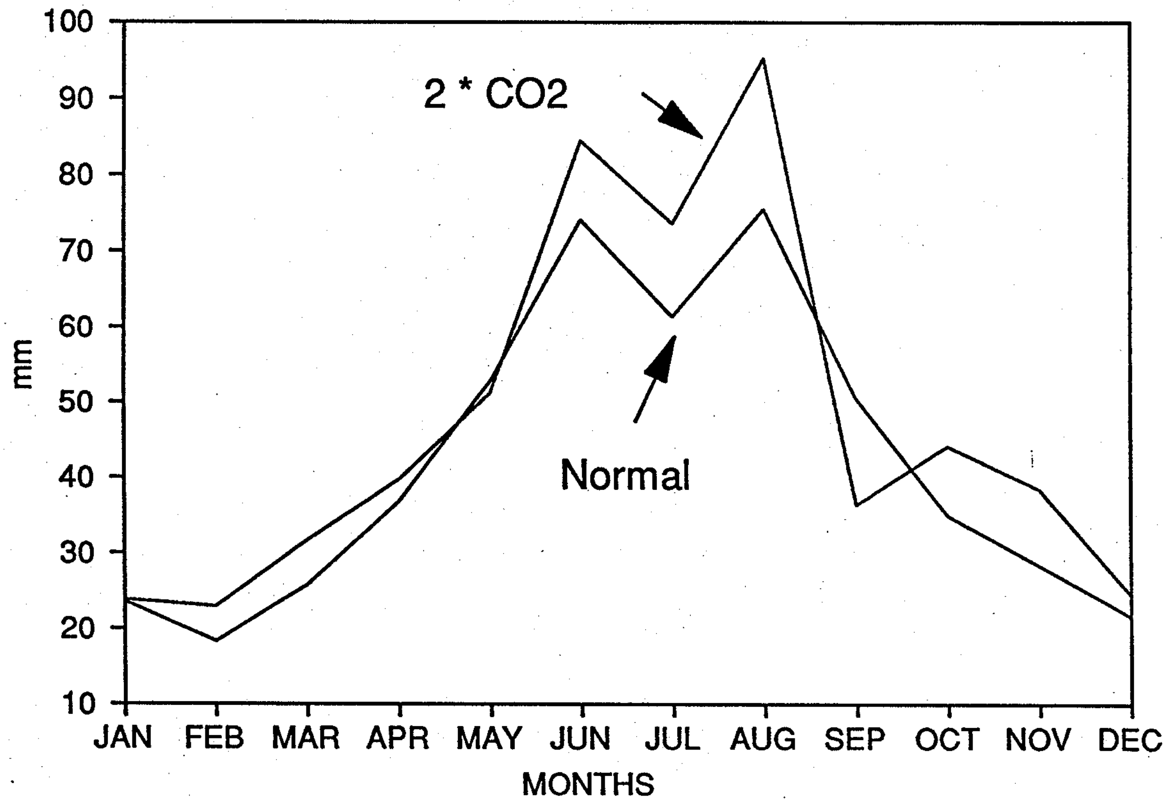


HISTORICAL NORMALS AND 2*CO2 TEMPERATURES: ELM CREEK

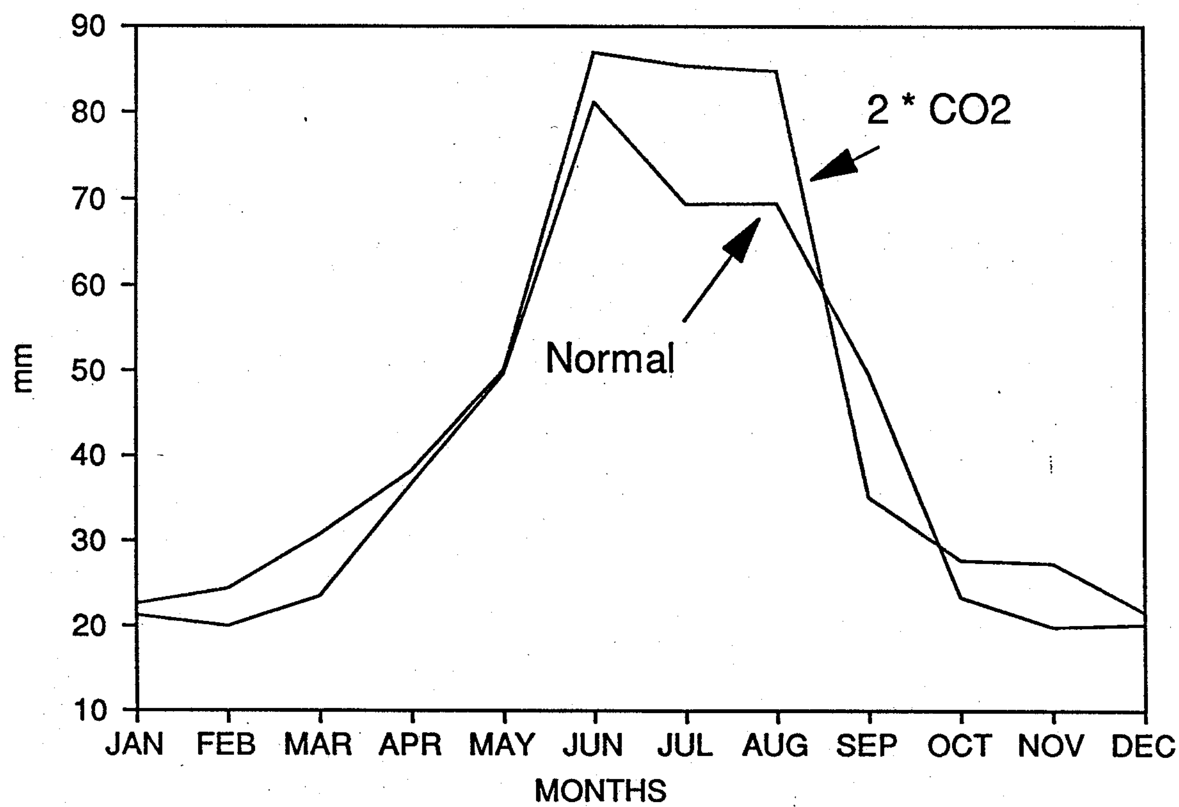



HISTORICAL NORMALS AND
2*CO2 TEMPERATURES: SWAN RIVER
2 * CO2
Normal
C
25
20
15
10
5
0
-5
-10
-15
-20
-25
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

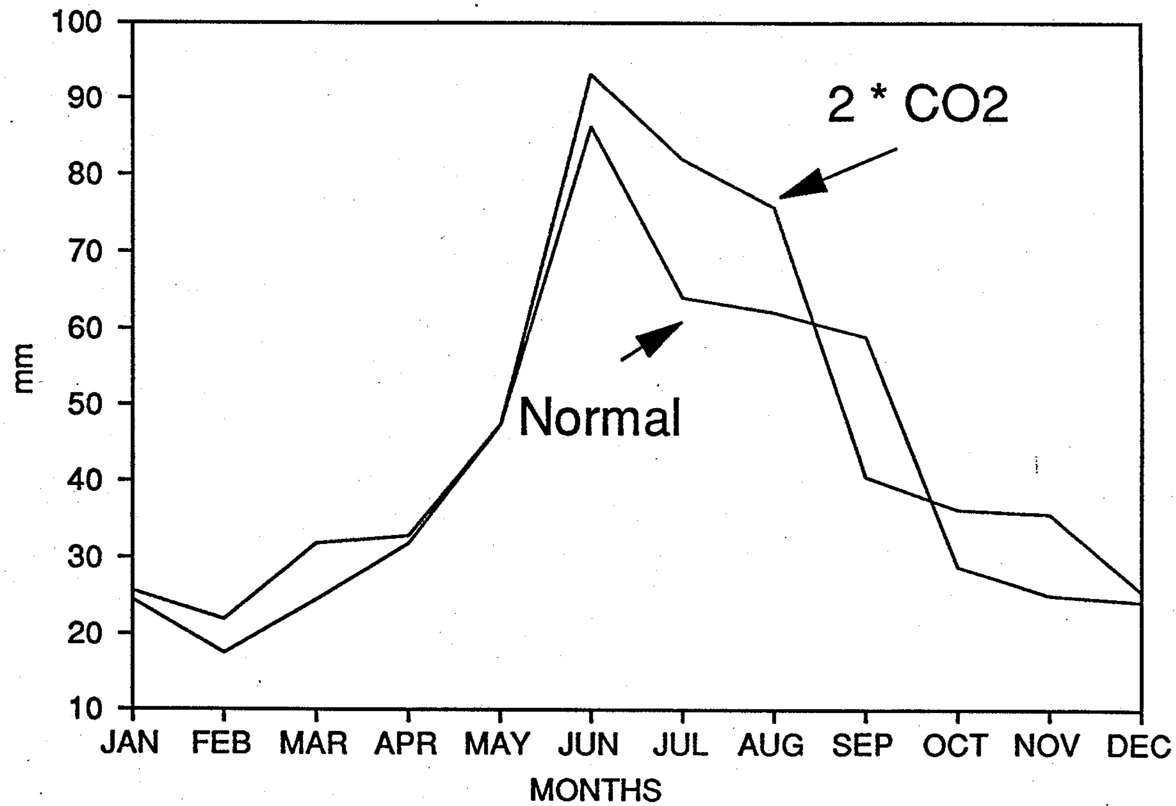
HISTORICAL NORMALS AND 2*CO2 PRECIPITATION: ARBORG

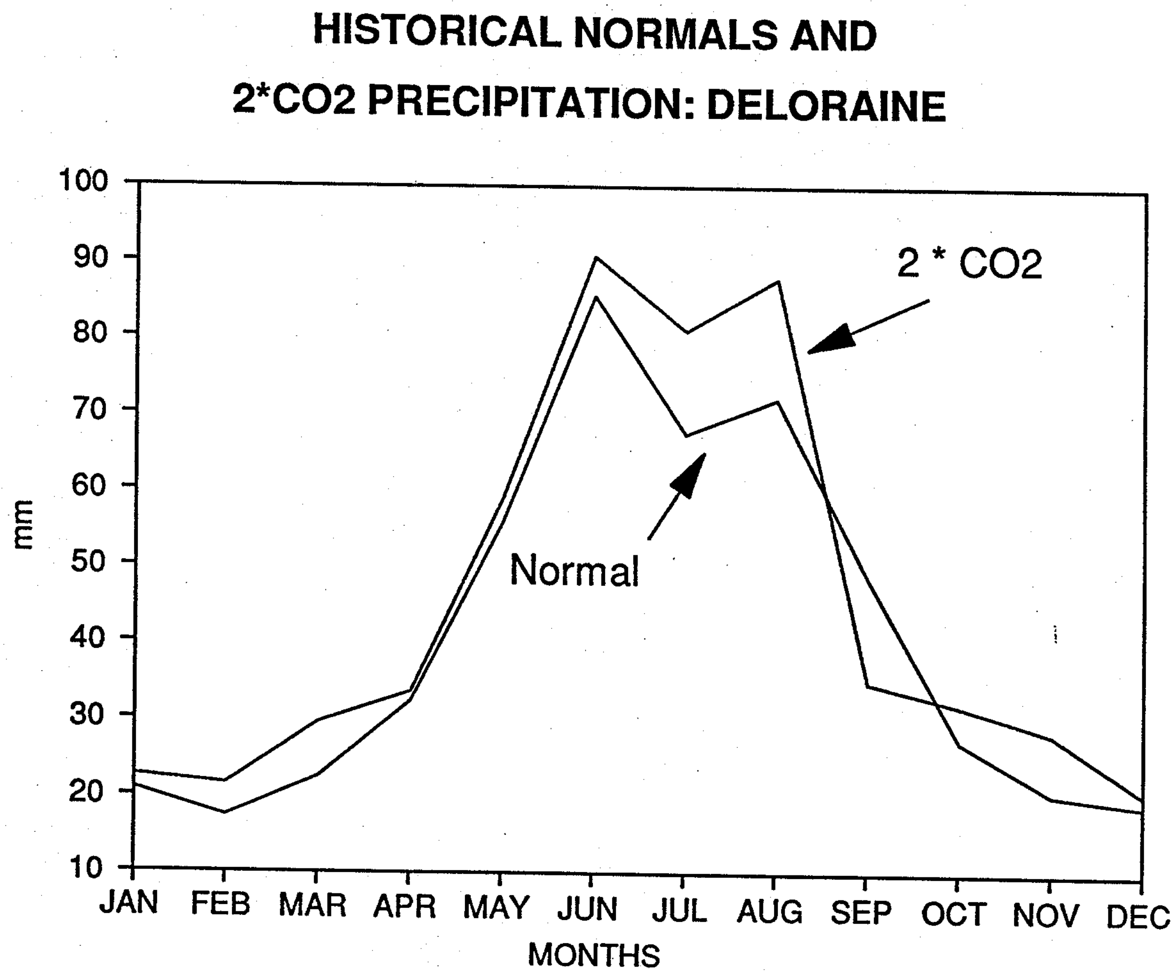


HISTORICAL NORMALS AND
2*CO2 PRECIPITATION: BRANDON CDA

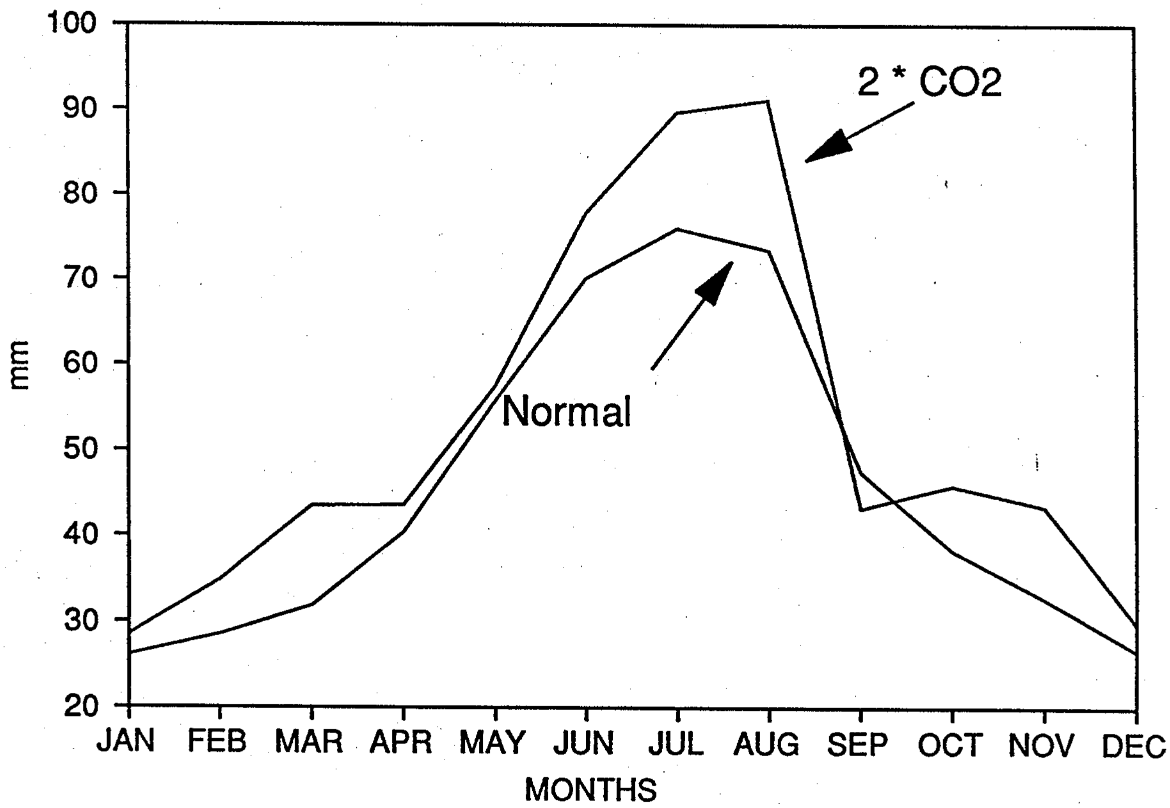


HISTORICAL NORMALS AND 2*CO2 PRECIPITATION: DAUPHIN

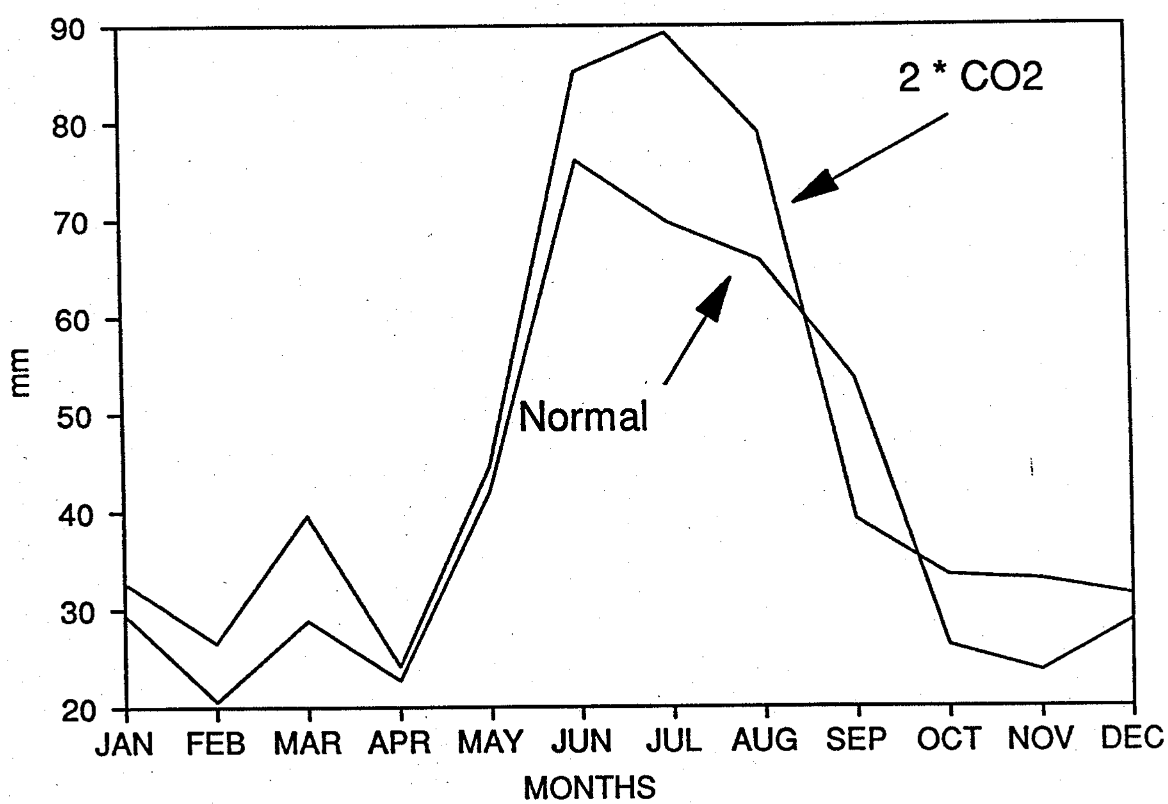



HISTORICAL NORMALS AND
2*CO2 PRECIPITATION: DELORAINE
100
90
80
70
60
50
40
30
20
10
mm
2 * CO2
Normal
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS

HISTORICAL NORMALS AND 2*CO2 PRECIPITATION: ELM CREEK



HISTORICAL NORMALS AND 2*CO2 PRECIPITATION: SWAN RIVER



APPENDIX THREE

Method used to calculate and graphs showing Days to Maturity, Water Use, and Soil Water Status for a Crop of Wheat at selected points in Manitoba under three different scenarios.

1. Historical weather and planting dates.
2. A flat increase of 3°C in temperature and historical planting dates.
3. A flat increase in temperature of 3°C and planting advanced 14 days.

Method Used to Calculate Days to Maturity

Water Use and Soil Water Status

The water use of a crop can be estimated using figures for potential evapotranspiration (PET) and a consumptive use factor, that is the ratio of actual to potential evapotranspiration, summed daily from planting to harvest. Potential evapotranspiration is estimated by a method developed by Baier and Robertson[1] and is then used to obtain a consumptive use factor using a method developed by Hobbs and Krogman (1968). In order to assess the number of days required for the crop to reach maturity a biometeorological time scale[2] is used. This method uses both day and night temperatures as well as photoperiod to estimate crop development and the length of time taken from planting to maturity. A consumptive use factor is assigned to each of the stages of physiological development and water use by the crop estimated. In the calculation of water stress, it is assumed that at the start of the growing season soil water is equal to that on October 31st of the previous year plus half of the average snow fall over the season. Then, actual daily weather station data is used in conjunction with this starting value to assess soil moisture stress using the following formula,

$$\text{Water Status}_{Day2} = \text{Water Status}_{Day1} - (\text{PET} * \text{CU}) + \text{Precipitation}$$

and so on until the water status at the date of maturity is obtained.

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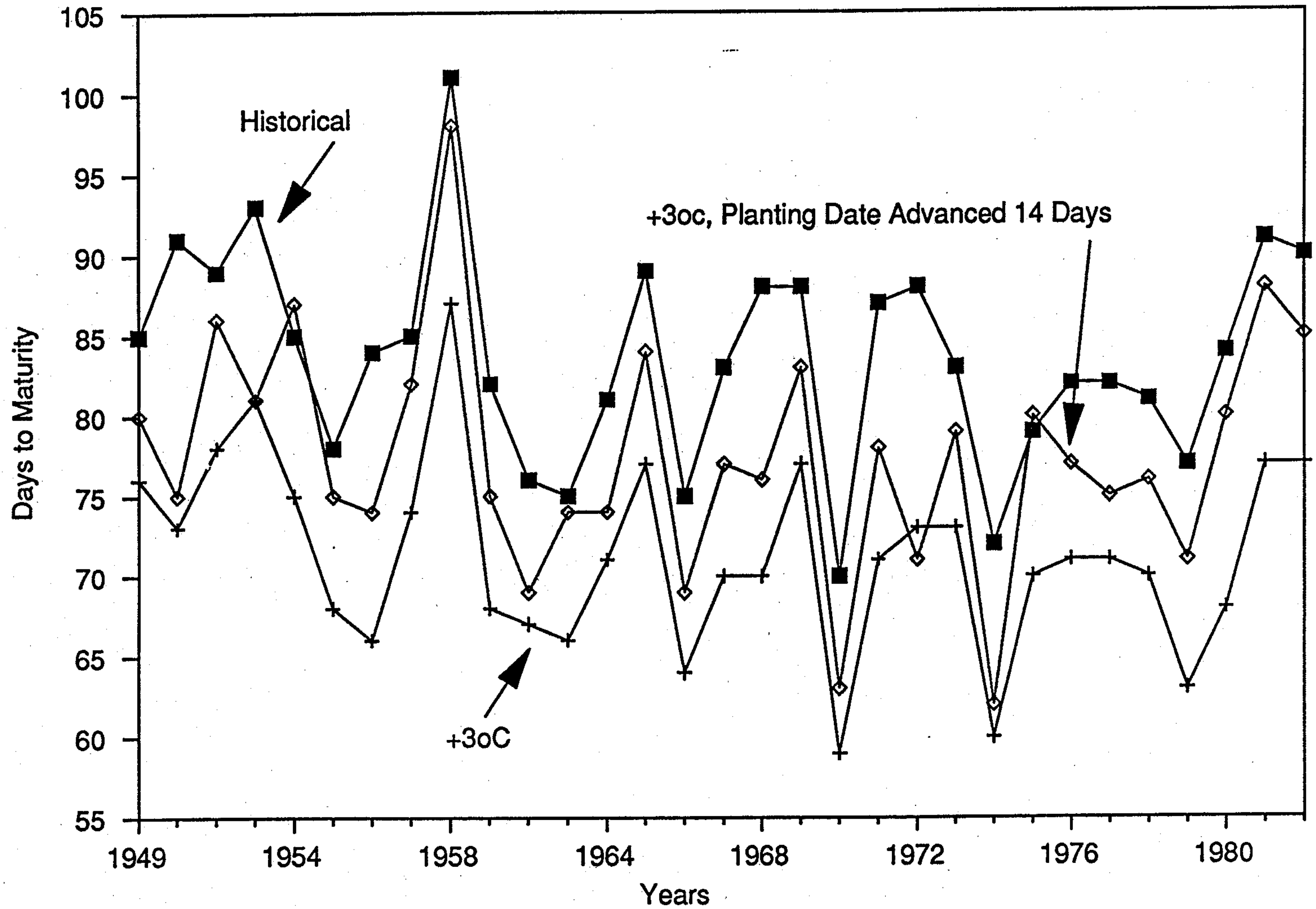
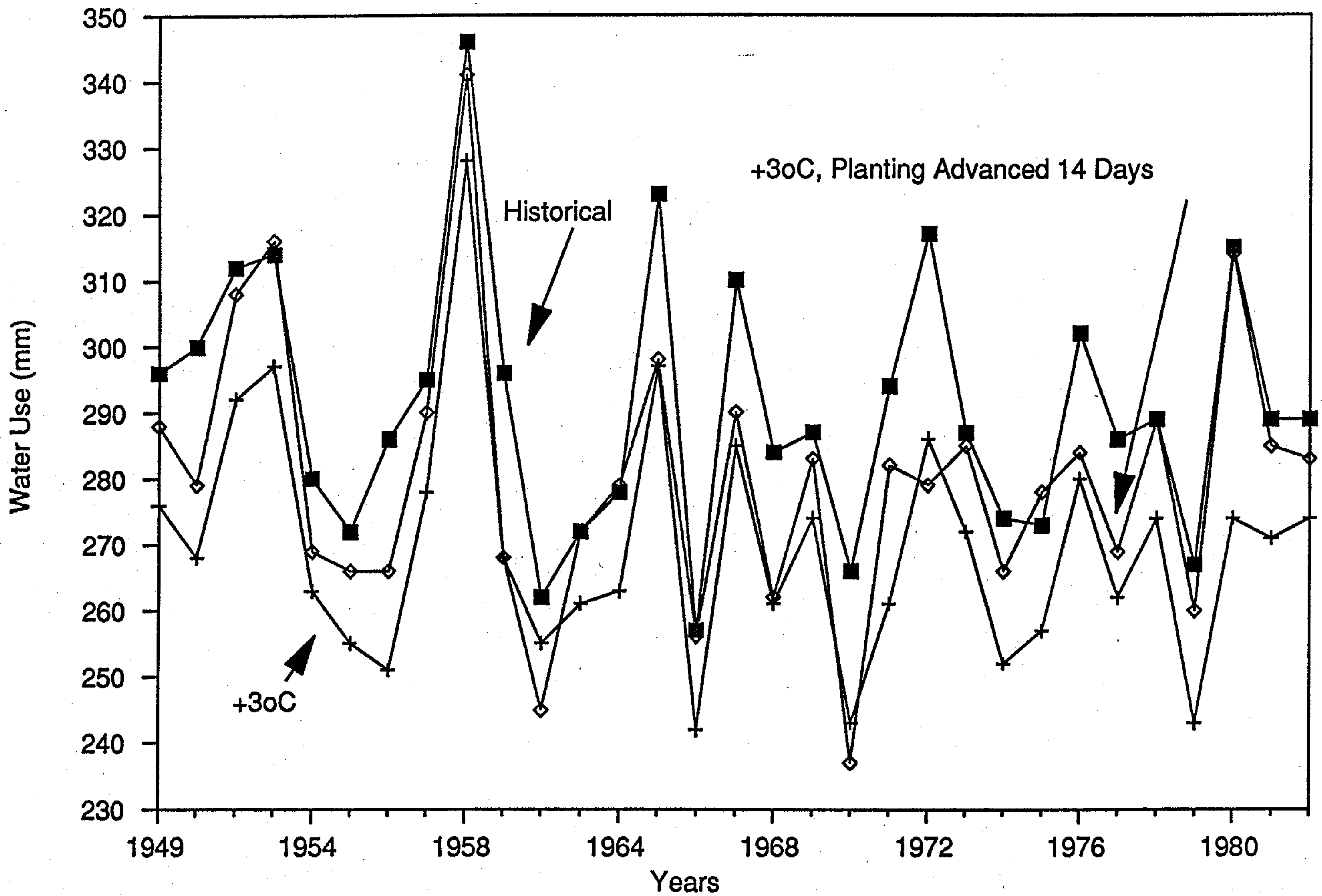
[1] Baier and Robertson. 1965. Estimation of Latent evaporation from simple weather observations. Canadian Journal of Plant Science. 45; 276-284.

[2] Robertson. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. International Journal of Biometeorology. 12: 191-223.

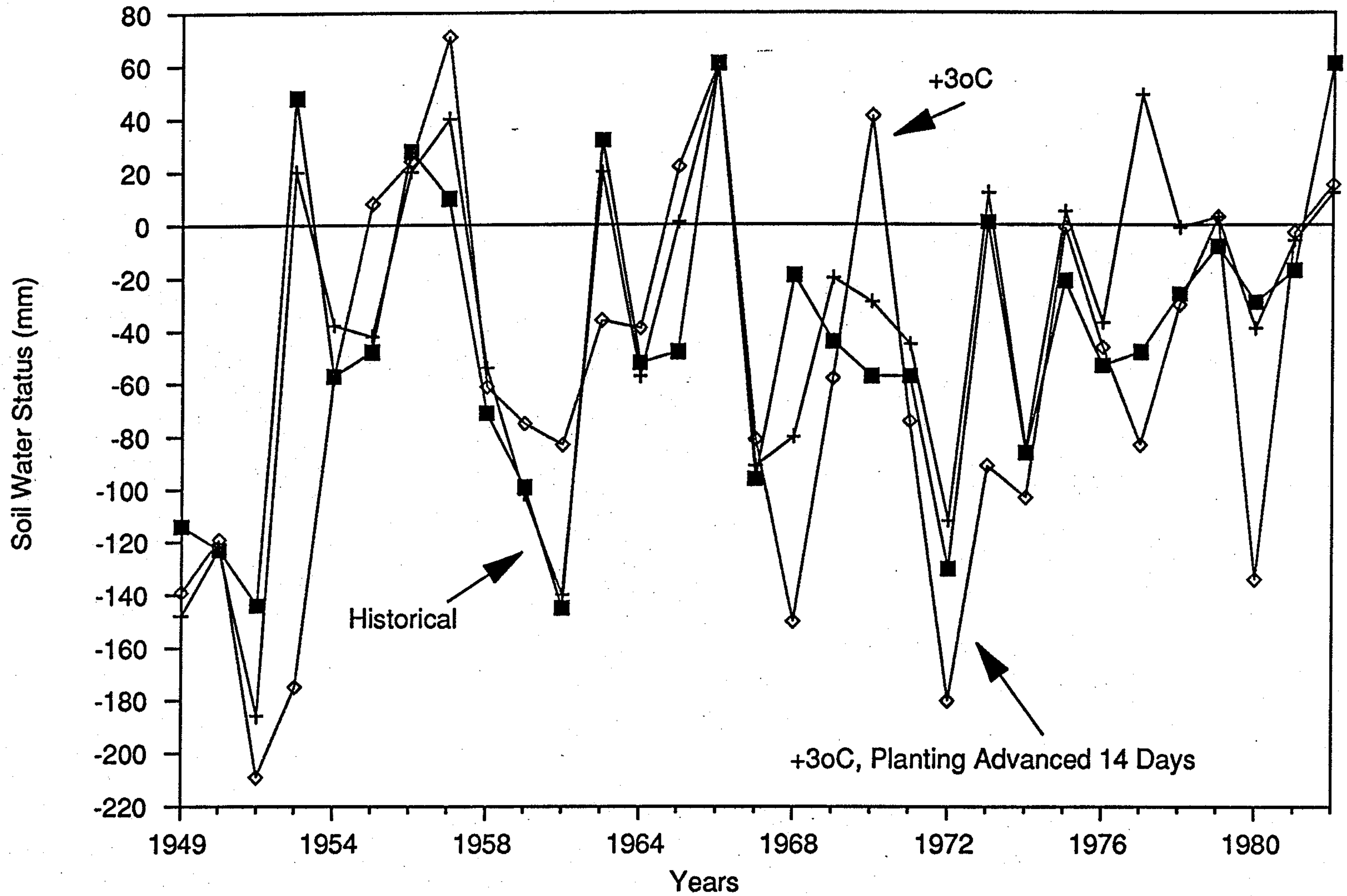
Days to Maturity, Wheat.
Altona

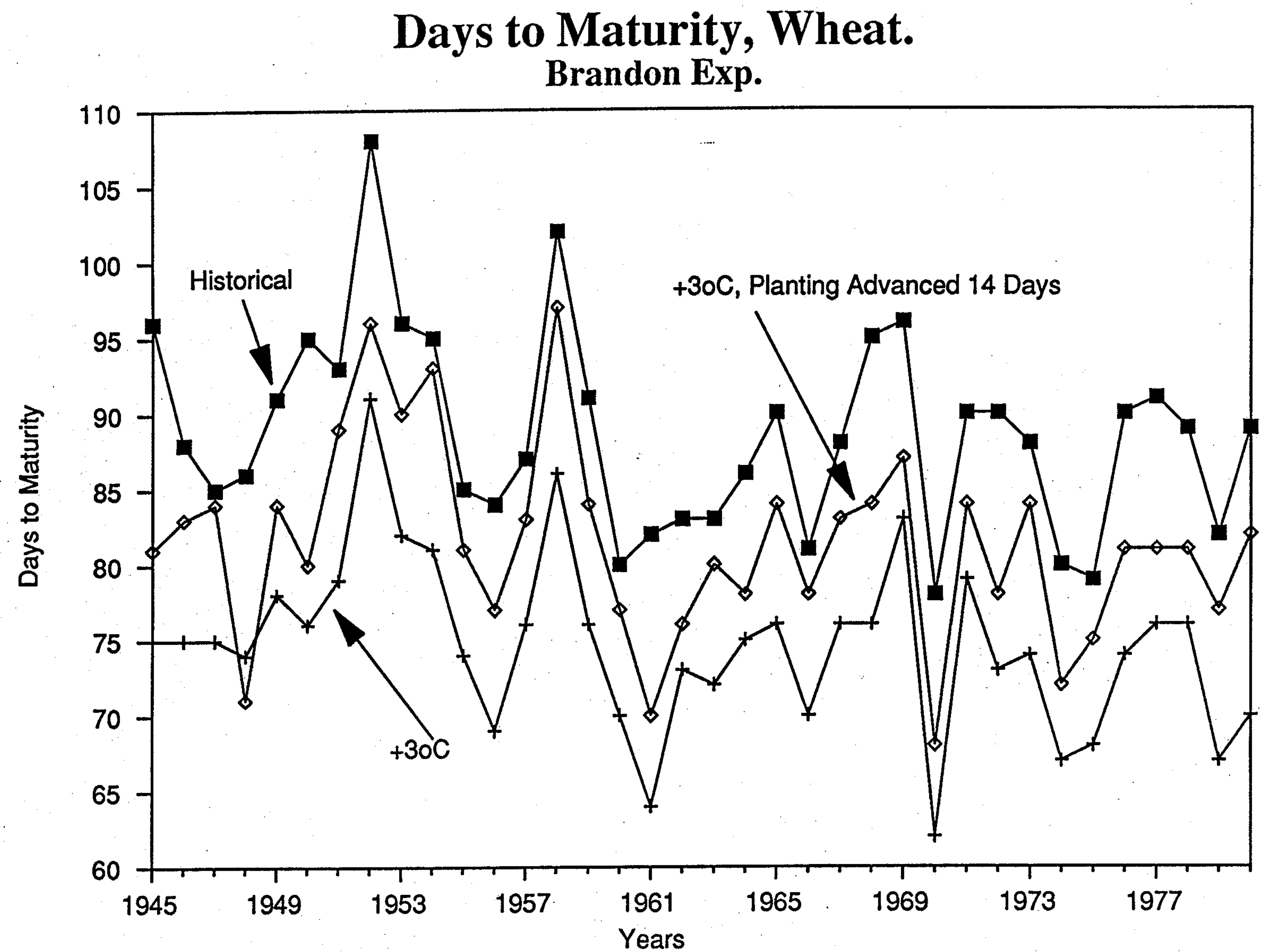


Water Use, Wheat.
Altona.

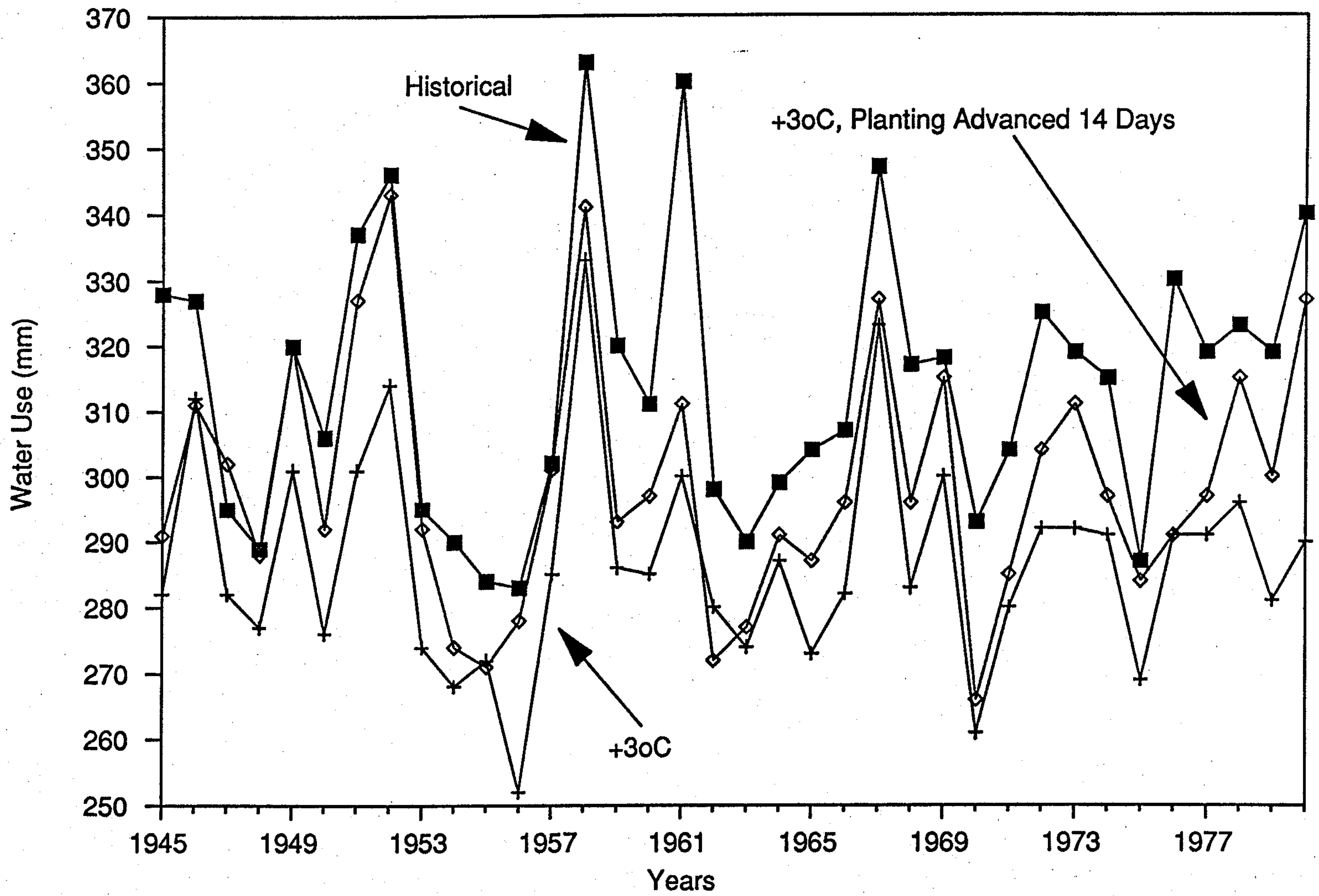


Soil Water Status, Wheat.
Altona.

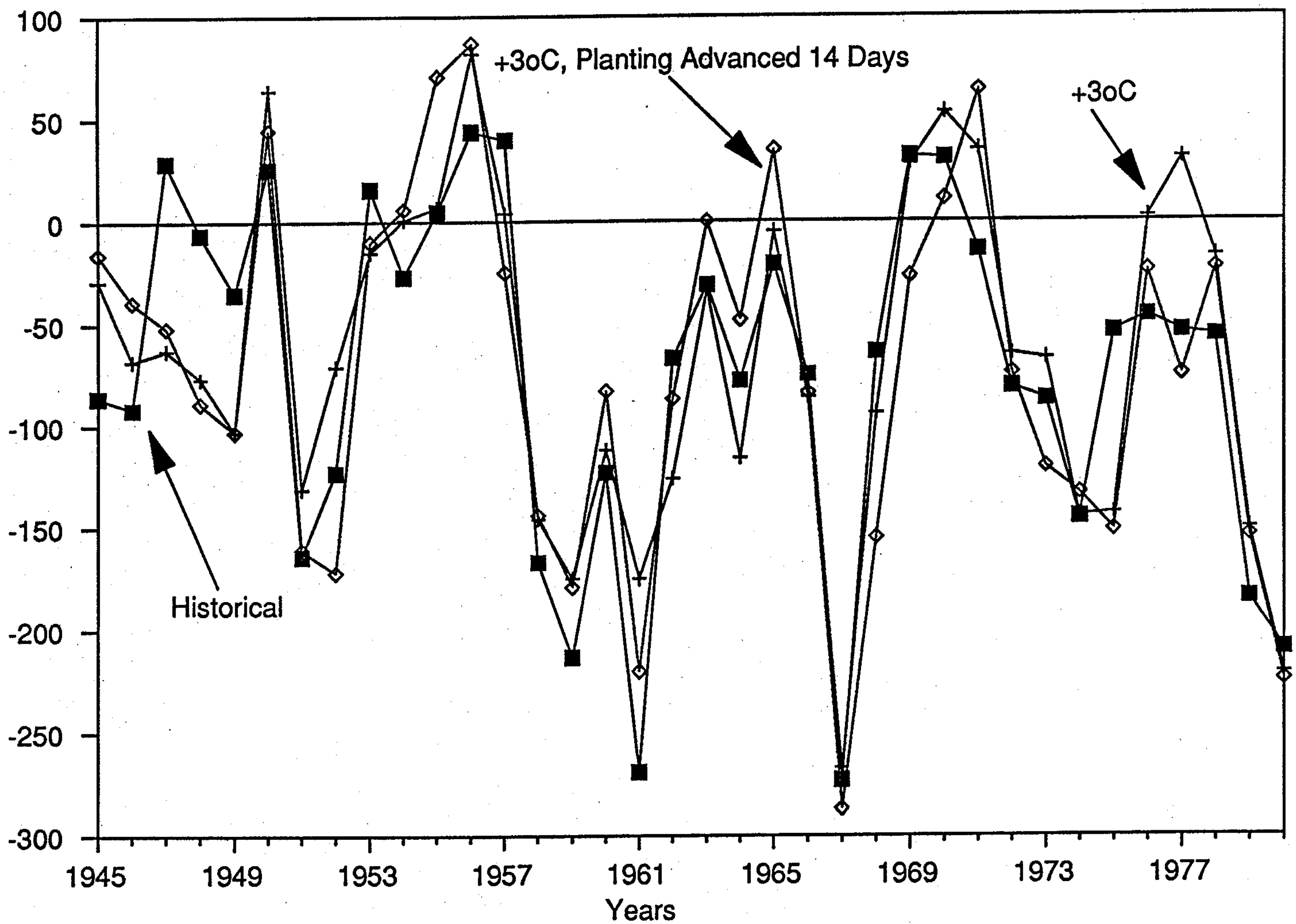



Days to Maturity, Wheat.
Brandon Exp.
Historical
+3oC, Planting Advanced 14 Days
+3oC
Days to Maturity
Years
110
105
100
95
90
85
80
75
70
65
60
1945
1949
1953
1957
1961
1965
1969
1973
1977

Water Use, Wheat.
Brandon Exp.

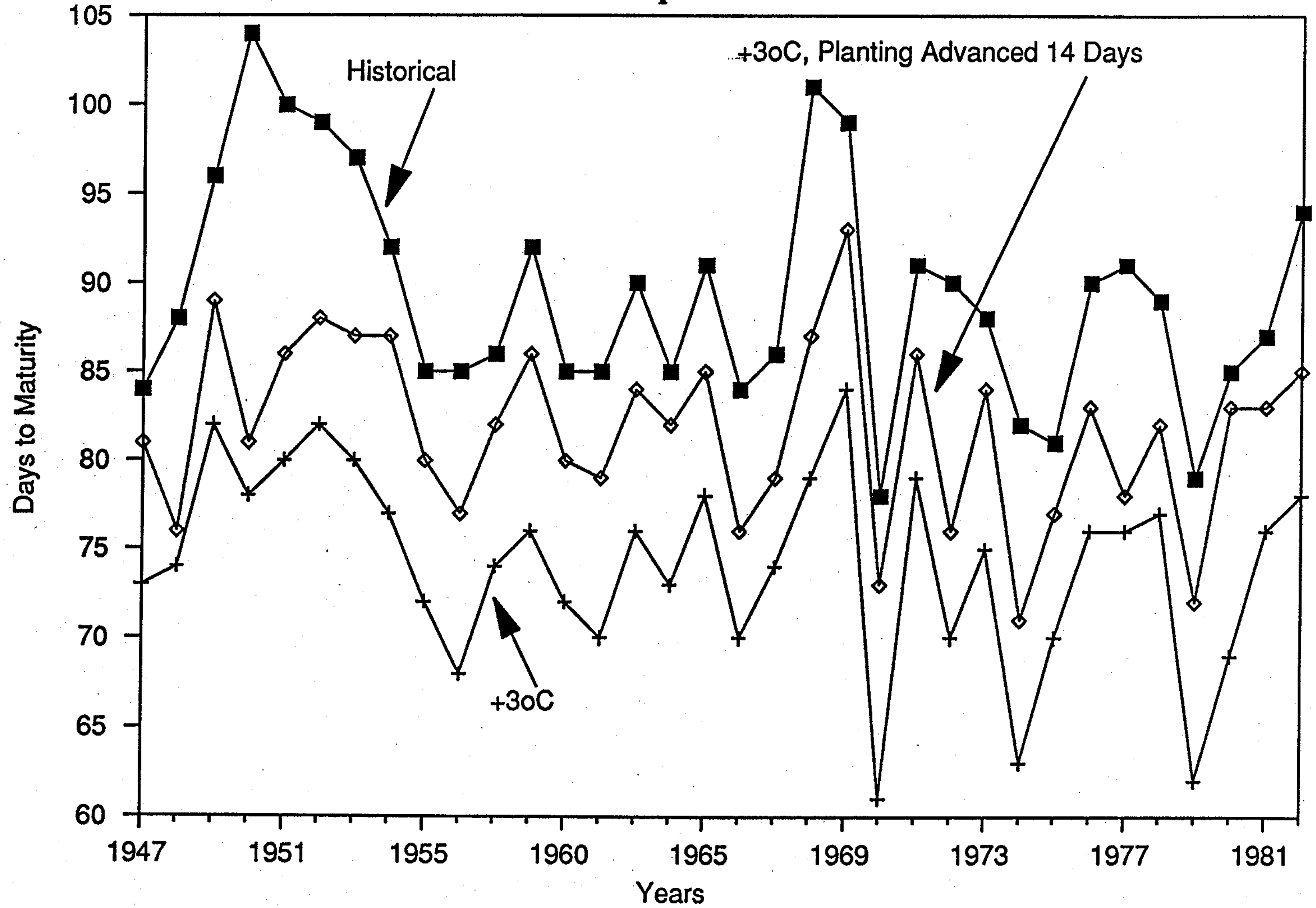


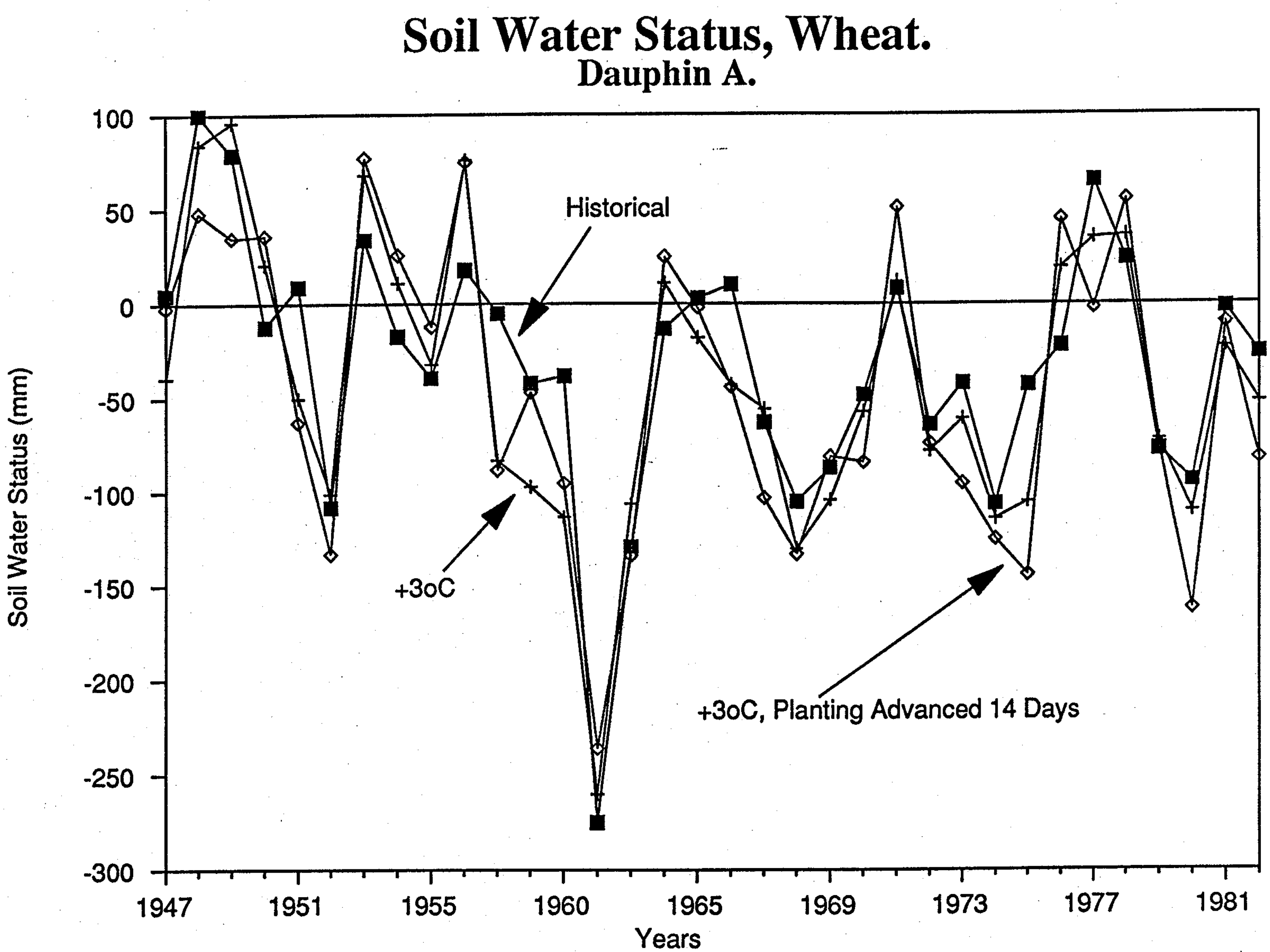
Soil Water Status, Wheat.
Brandon Exp.



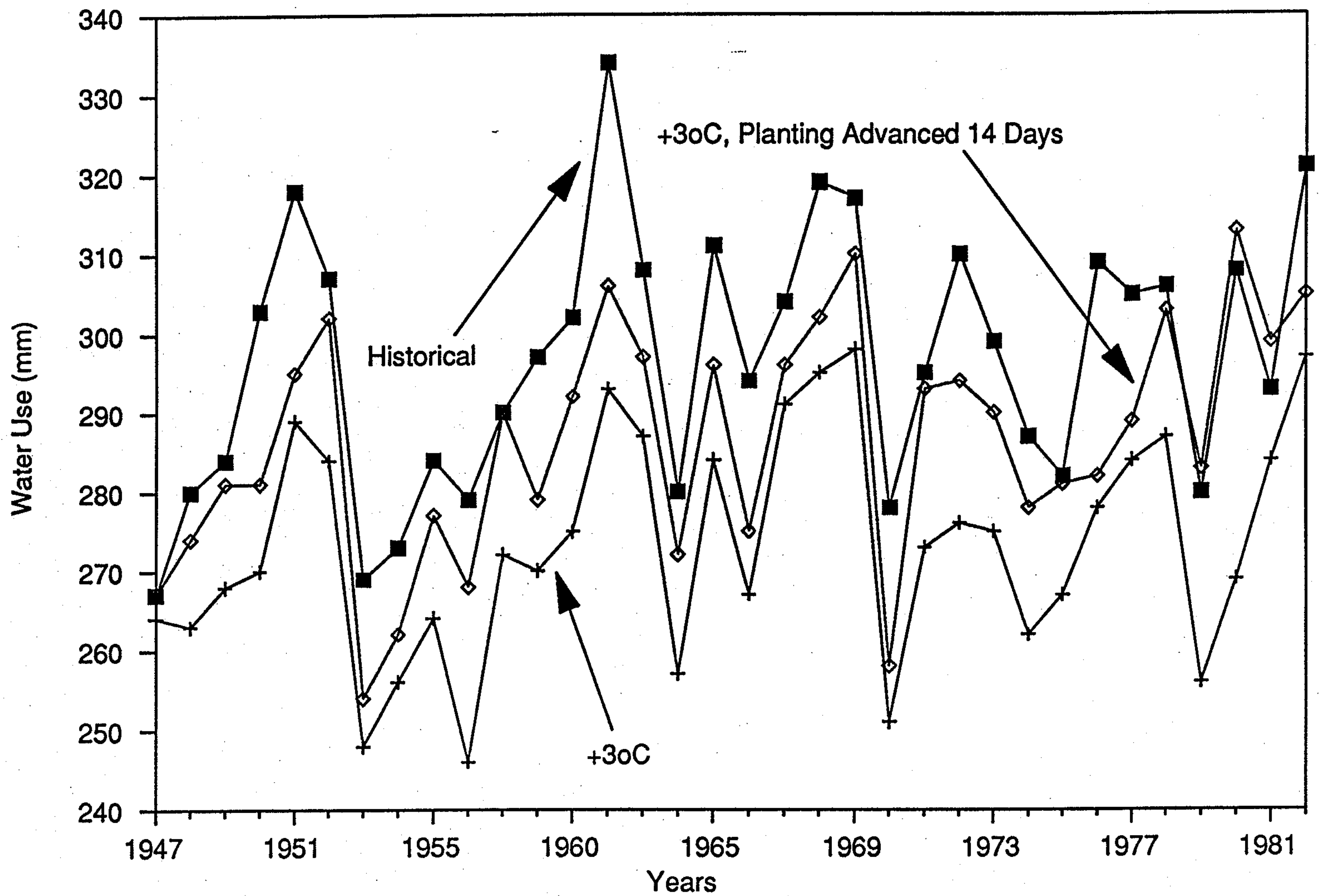
Days to Maturity, Wheat.

Dauphin A

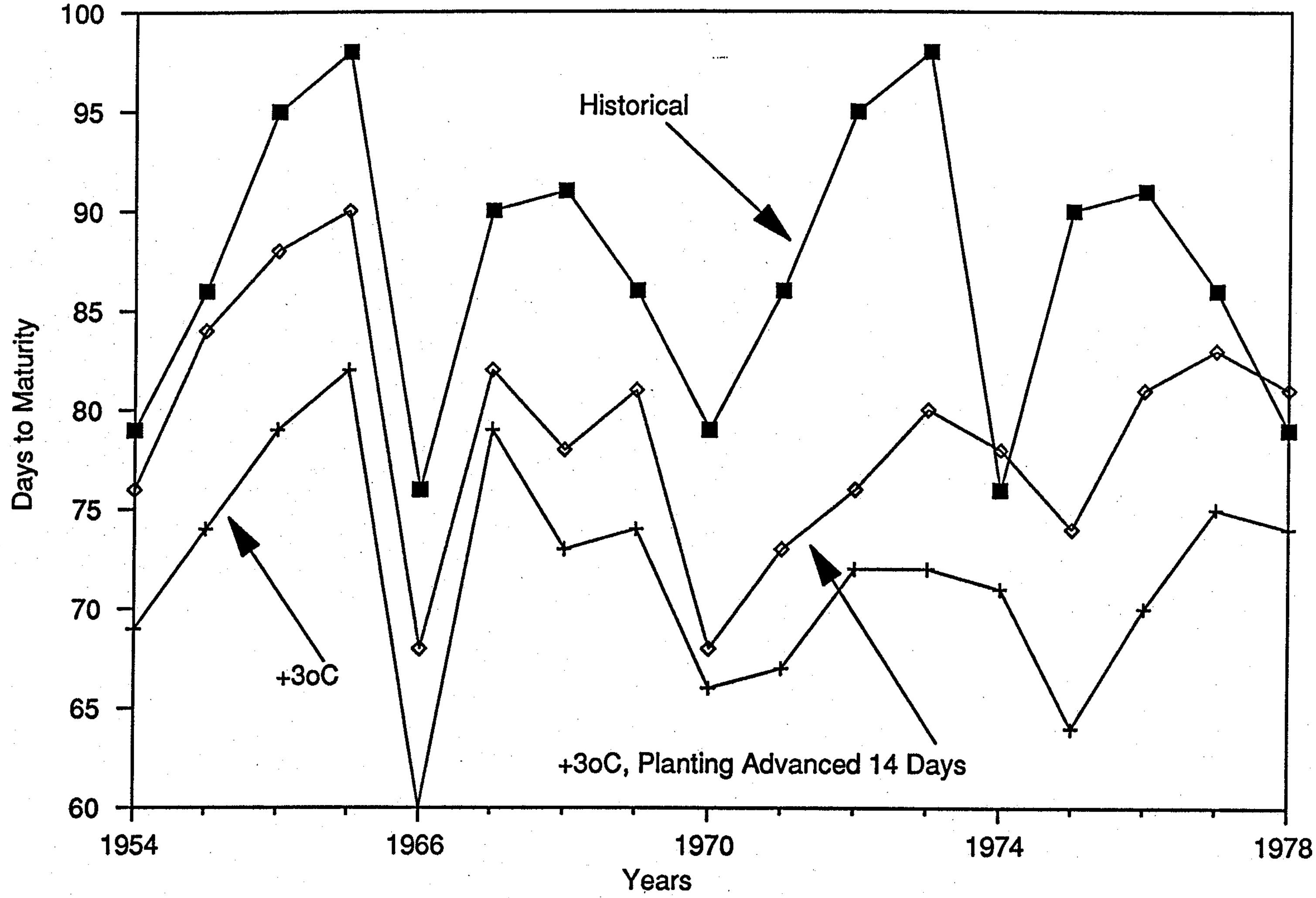



Soil Water Status, Wheat.
Dauphin A.
Historical
+3oC
+3oC, Planting Advanced 14 Days
Soil Water Status (mm)
100
50
0
-50
-100
-150
-200
-250
-300
1947
1951
1955
1960
1965
1969
1973
1977
1981
Years

Water Use, Wheat.
Dauphin A.

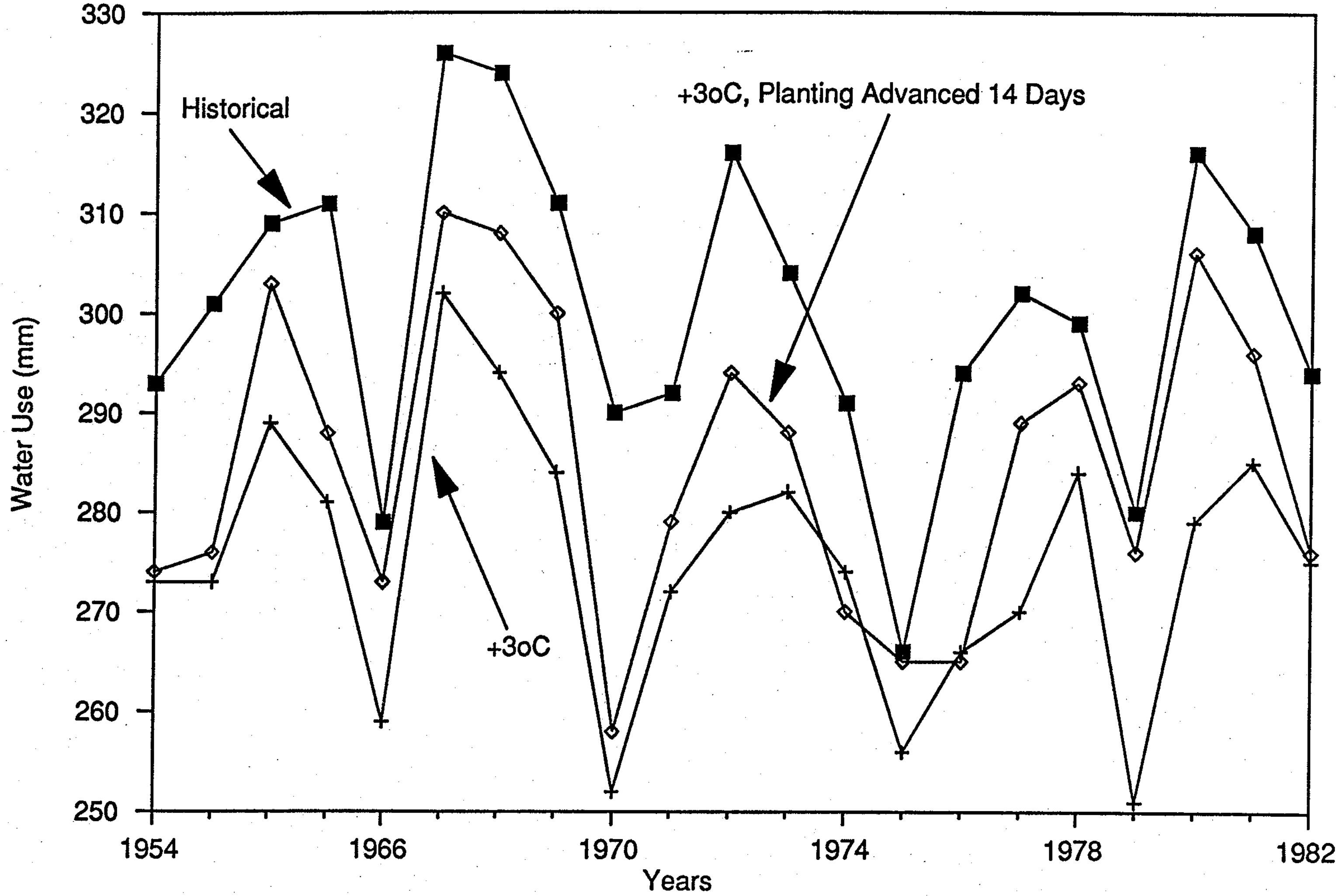


Days to Maturity, Wheat.
Deloraine.

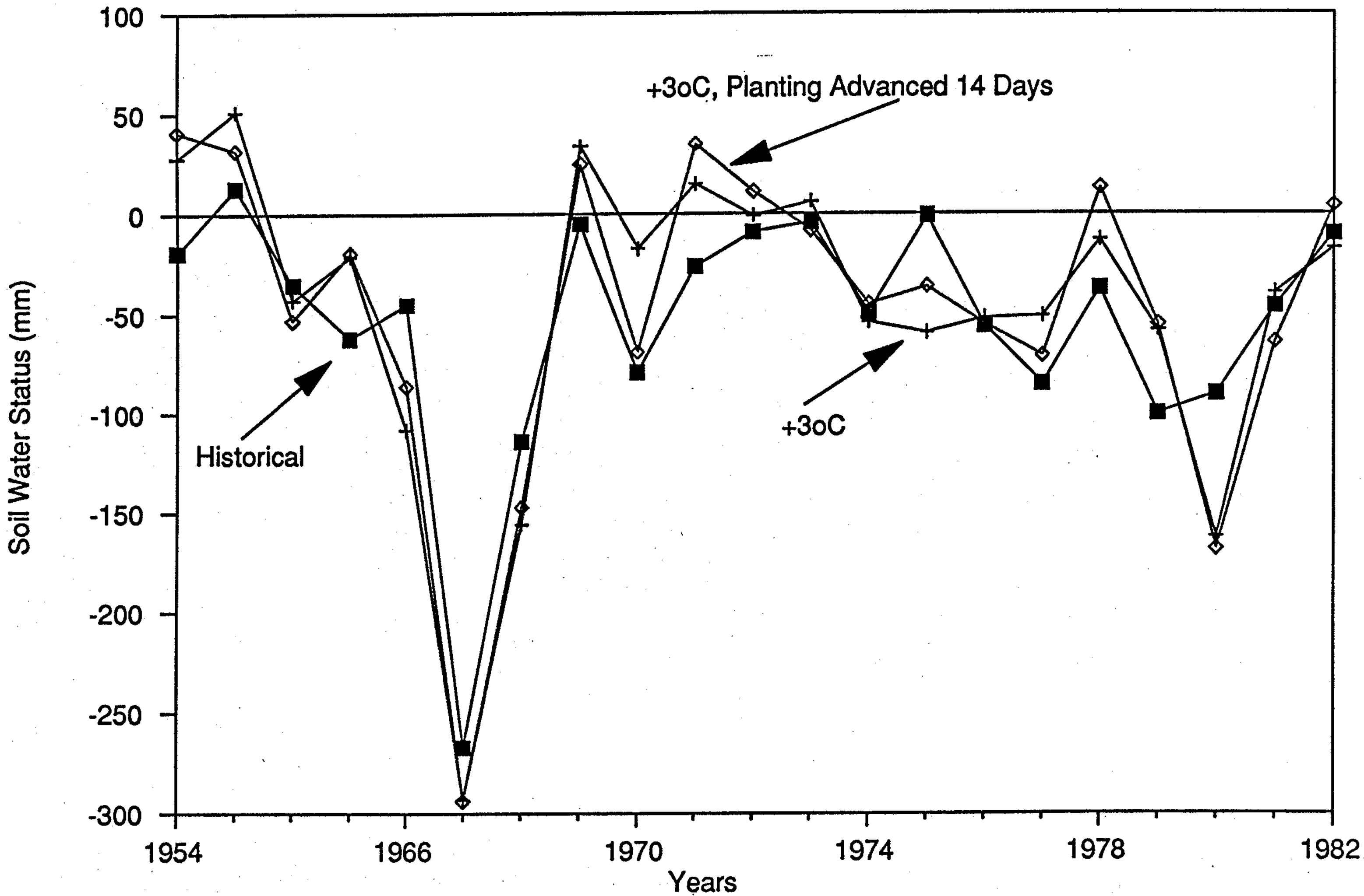


Water Use, Wheat.

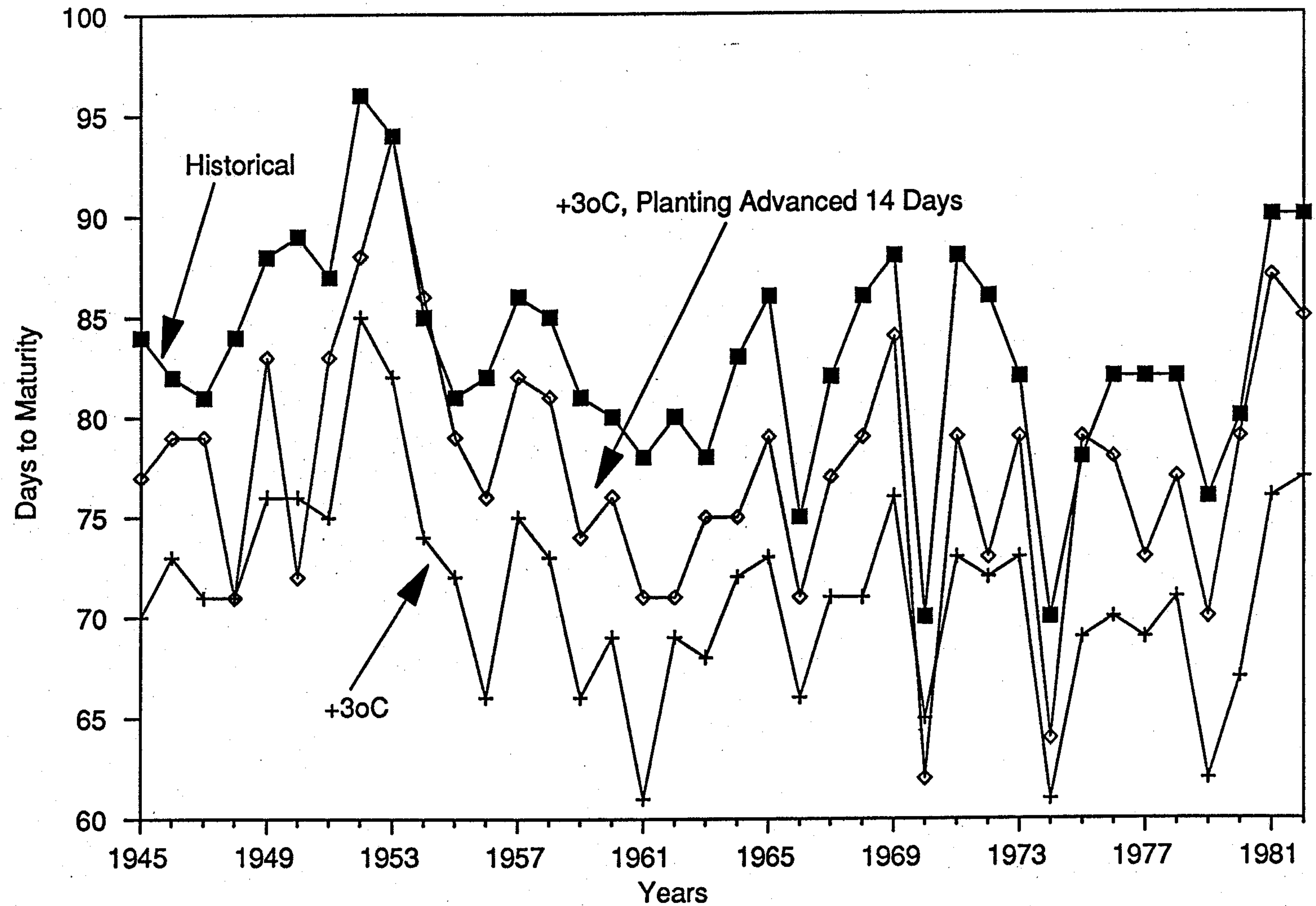
Deloraine.



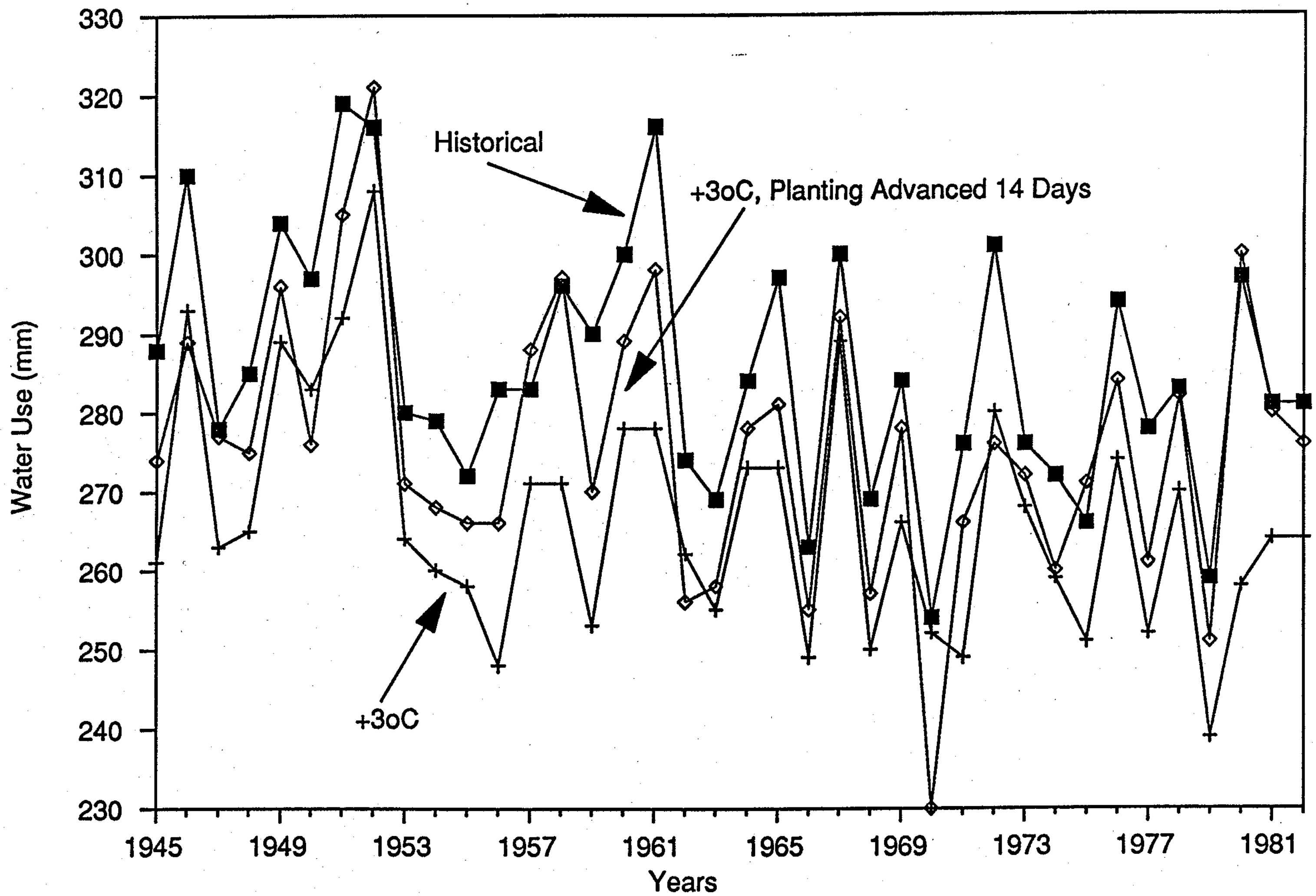
Soil Water Status, Wheat.
Deloraine.



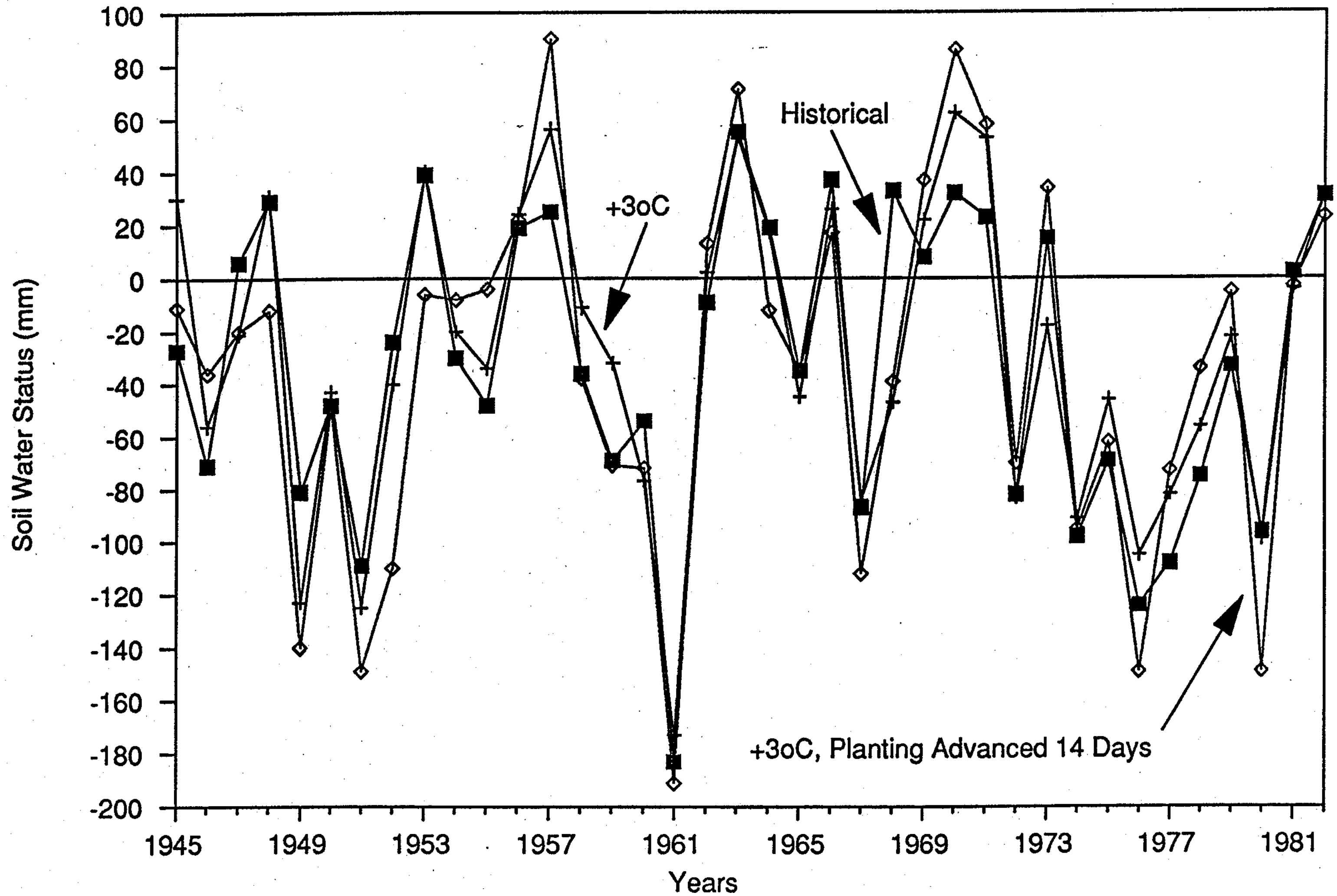
Days to Maturity, Wheat.
Morden.



Water Use, Wheat.
Morden.

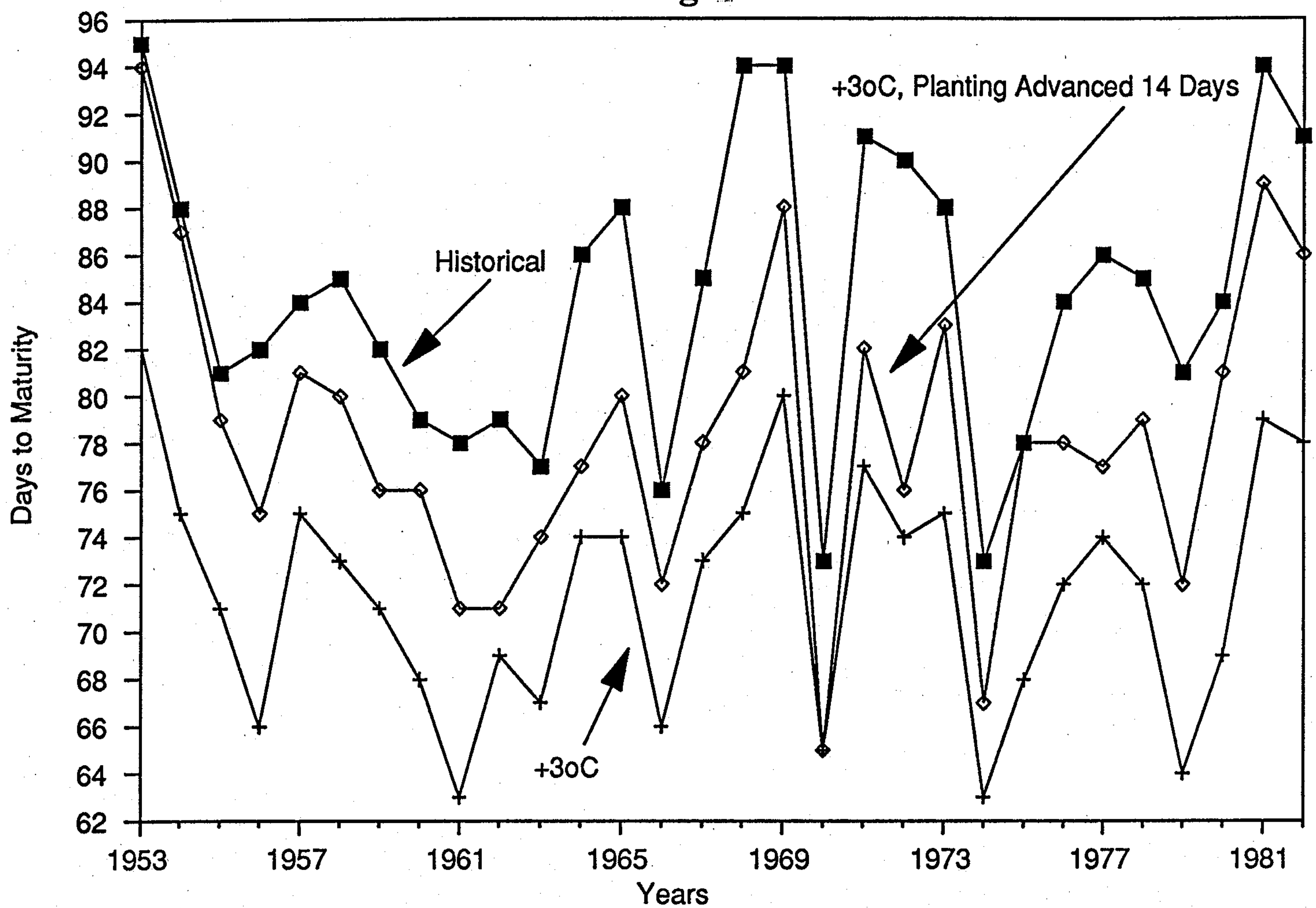


Soil Water Status, Wheat.
Morden.



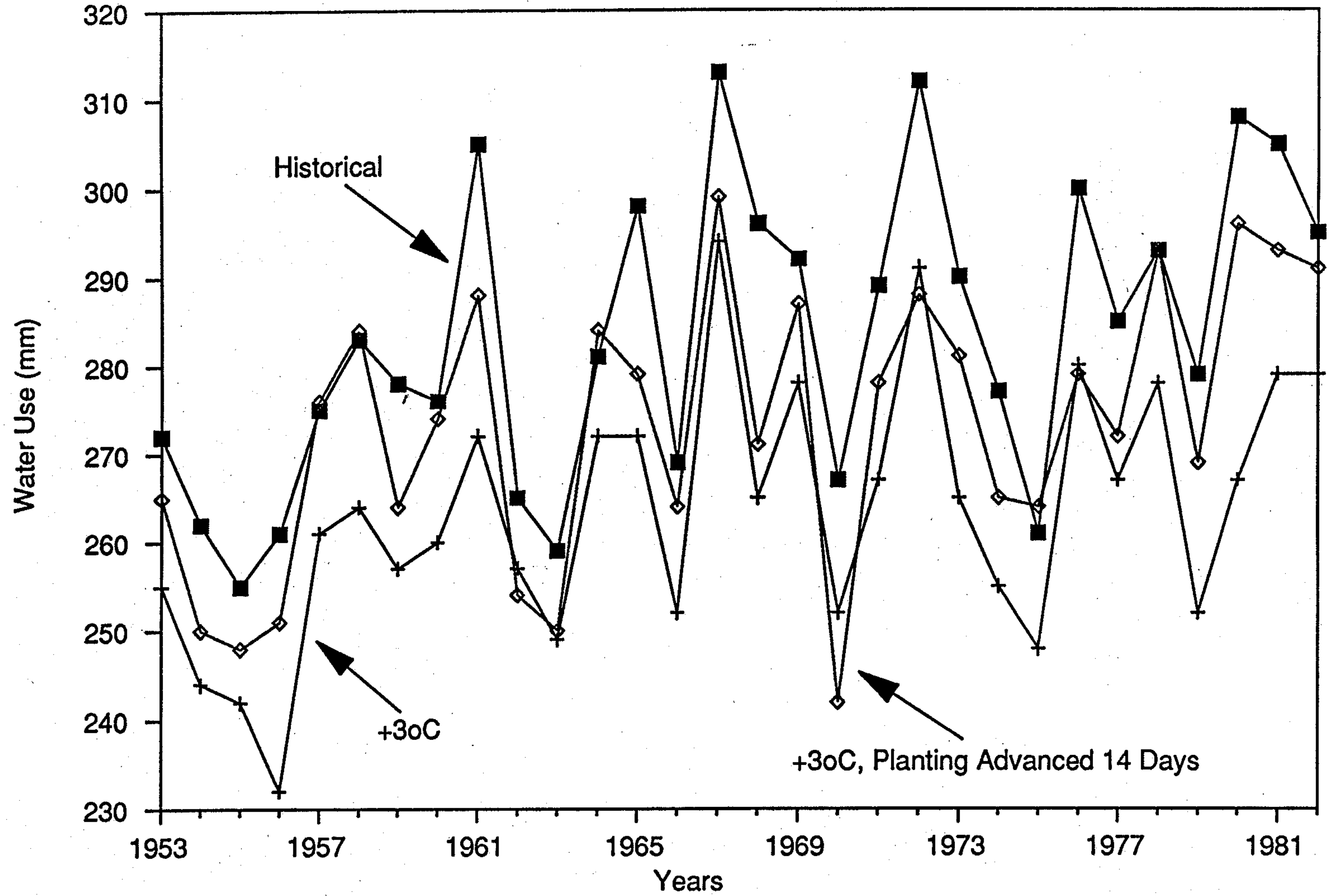
Days to Maturity, Wheat.

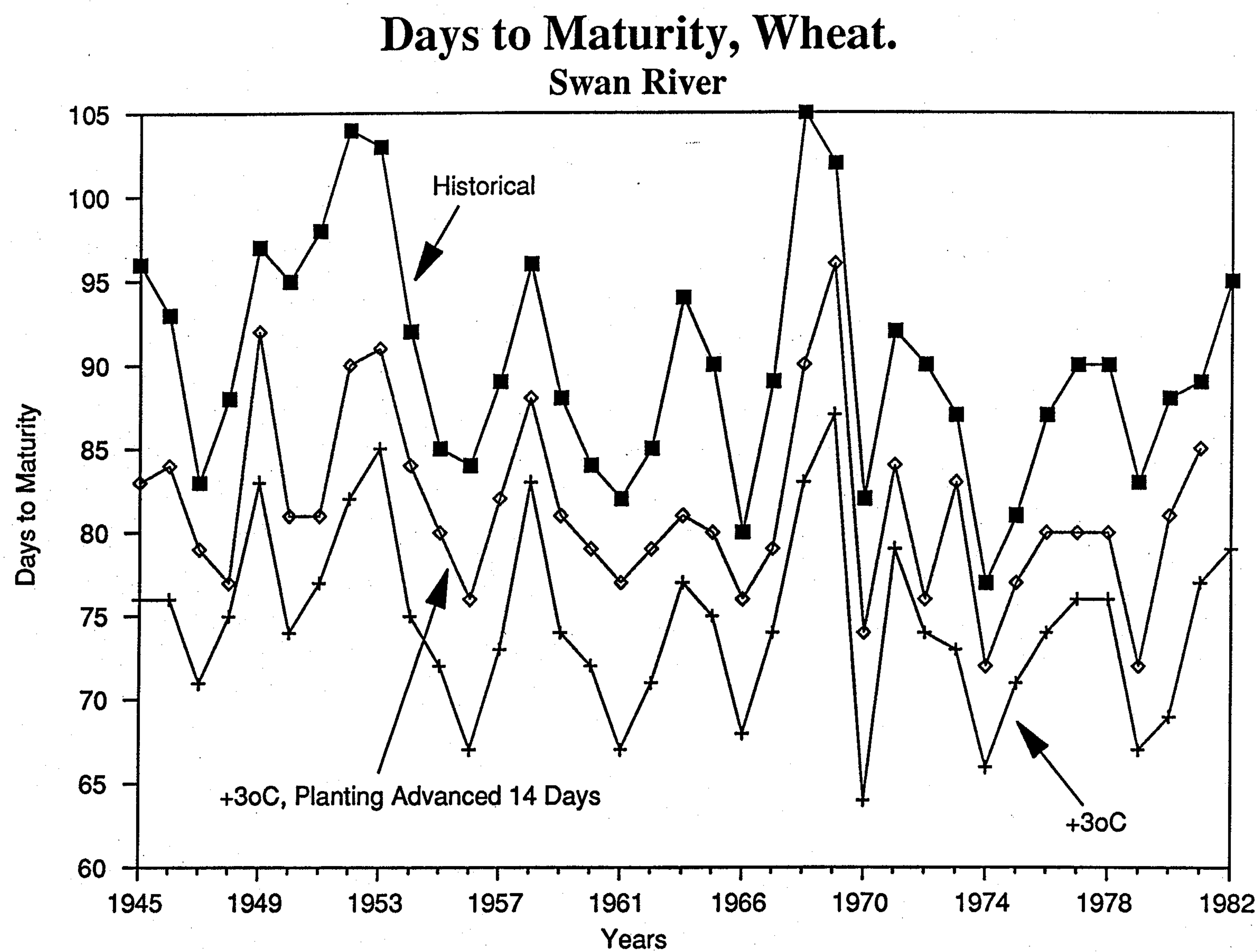
Portage A.



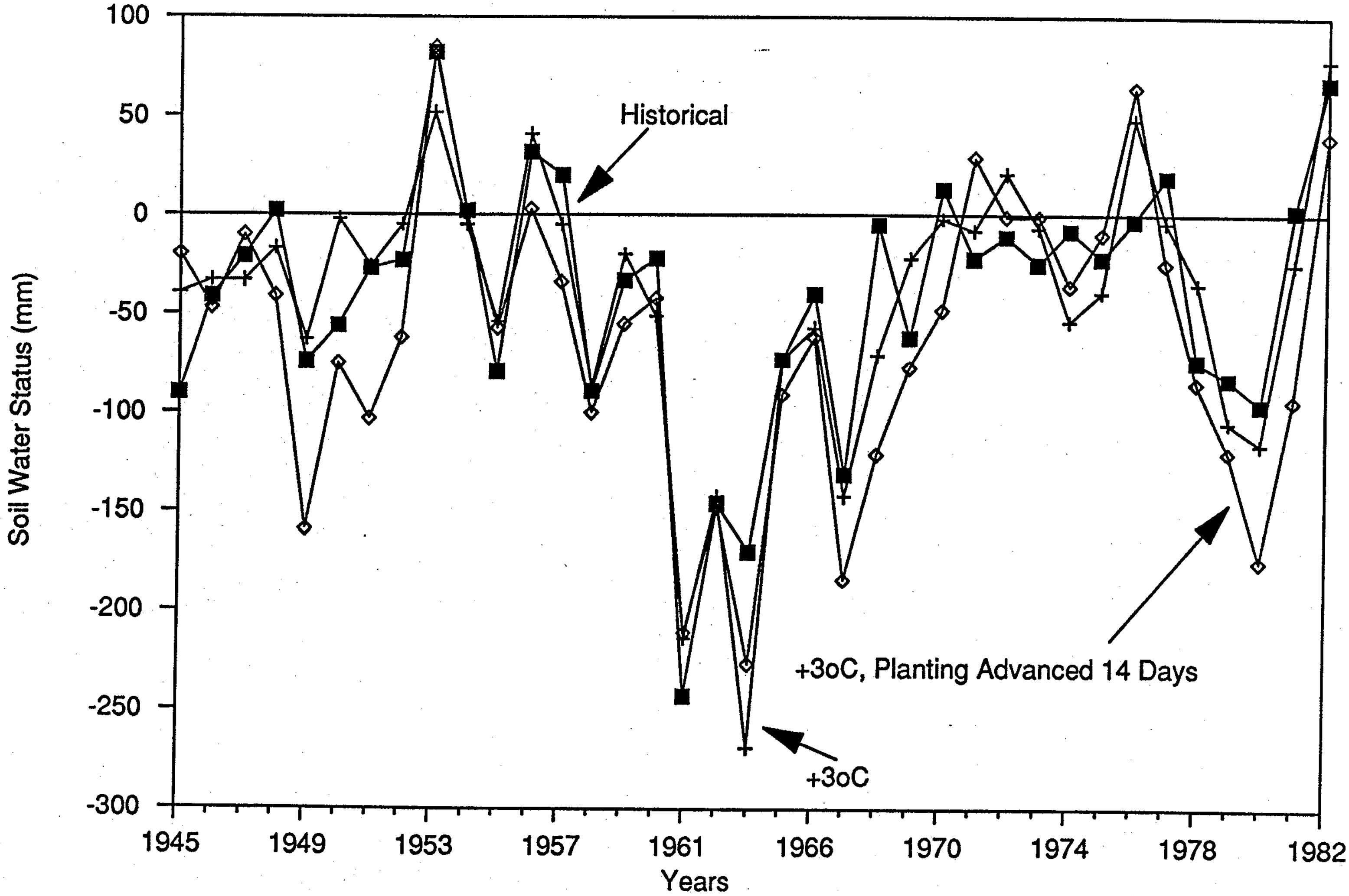
Water Use, Wheat.

Portage A.

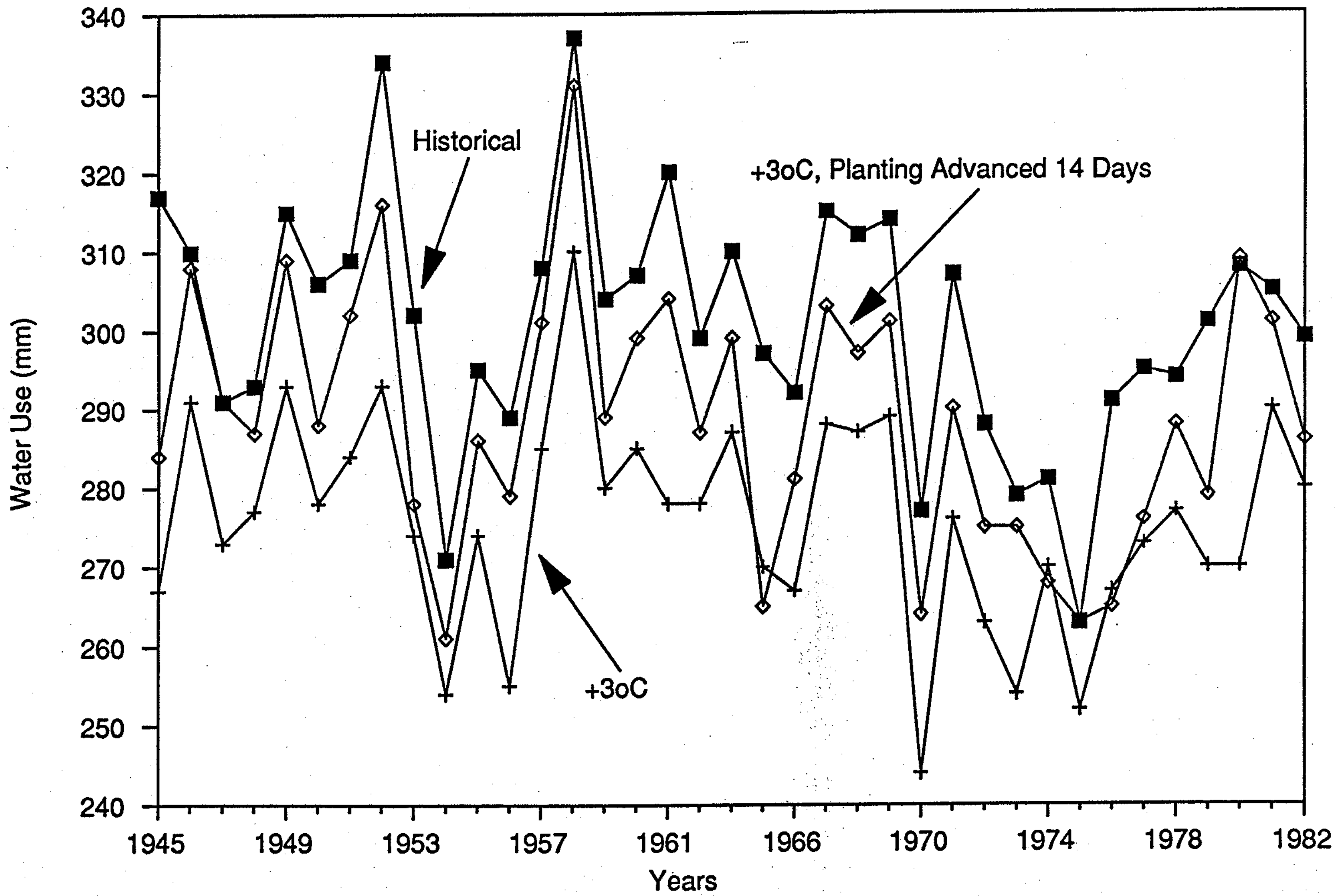



Days to Maturity, Wheat.
Swan River
Historical
+3oC, Planting Advanced 14 Days
+3oC
Days to Maturity
Years
105
100
95
90
85
80
75
70
65
60
1945
1949
1953
1957
1961
1966
1970
1974
1978
1982

Soil Water Status, Wheat.
Swan River.



Water Use, Wheat.
Swan River.



APPENDIX FOUR

Data for the Linear Programming Model

Variable Cost and Yield Data (Historical and 2*CO2 FAO) Averaged over the Four Linear Programming Areas

(Table 1 of 3)

	Wheat 1	Wheat 2	Wheat 3	Wheat 4	Barley 1	Barley 2	Barley 3	Barley 4	Canola 1	Canola 2	Canola 3	Canola 4	Flax 1	Flax 2	Flax 3	Flax 4
Seed and Treatment	21.84	21.84	21.84	21.84	17.82	17.82	17.82	17.82	19.83	19.83	19.83	19.83	25.65	25.65	25.65	25.65
Fertiliser	53.85	53.85	53.85	53.85	53.85	53.85	53.85	53.85	58.16	58.16	58.16	58.16	28.14	28.14	28.14	28.14
Chemicals	43.24	43.24	43.24	43.24	38.30	38.30	38.30	38.30	24.71	24.71	24.71	24.71	35.83	35.83	35.83	35.83
Fuel	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24	22.24
Mach Op Costs	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91	17.91
Other	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83	14.83
V.C. Per Hectare	173.91	173.91	173.91	173.91	164.95	164.95	164.95	164.95	157.68	157.68	157.68	157.68	144.60	144.60	144.60	144.60
Average Yield/Ha (10Yr)	1.91	2.01	1.97	2.16	2.52	2.46	1.94	2.85	1.19	1.23	0.95	1.31	0.92	1.06	0.83	1.12
FAO Changes	-0.32	-0.29	-0.34	-0.31	-0.24	-0.21	-0.21	-0.20	-0.31	-0.33	-0.34	-0.29				
2*CO2 Yield/Ha	1.31	1.42	1.30	1.49	1.91	1.95	1.52	2.29	0.82	0.83	0.62	0.93	0.92	1.06	0.83	1.12
Price /Tonne	138.20	138.20	138.20	138.20	94.90	94.90	94.90	94.90	290.40	290.40	290.40	290.40	254.60	254.60	254.60	254.60
Rev/Ha	264.40	278.23	272.64	298.51	238.67	233.52	183.98	270.27	344.39	358.01	274.81	381.27	233.76	269.95	211.45	285.30
2*CO2 Rev/Ha	181.12	196.89	180.08	206.57	181.15	185.06	144.52	217.56	239.35	240.41	181.10	270.70	233.76	269.95	211.45	285.30
Rev-Vc/Ha	90.49	104.32	98.73	124.60	73.72	68.57	19.03	105.32	186.71	200.33	117.13	223.59	89.16	125.35	66.85	140.70
2*CO2 Rev-Vc/Ha	7.21	22.98	6.17	32.66	16.20	20.11	-20.43	52.61	81.67	82.73	23.42	113.02	89.16	125.35	66.85	140.70

Source: Manitoba Agriculture. Manitoba Agriculture Yearbook 1987.
Manitoba Agriculture. Farm Planning Guide 1989 Crop Estimates.

(Table 2 of 3)

	Corn 1	Corn 2	Corn 3	Corn 4	Sunflowe 1	Sunflowe 2	Sunflowe 3	Sunflowe 4	Oats 1 (a)	Oats 2	Oats 3	Oats 4	Corn/S 1 (b)	Corn/S 2	Corn/S 3	Corn/S 4
Seed and Treatment	42.65	42.65	42.65	42.65	34.72	34.72	34.72	34.72								
Fertiliser	90.68	90.68	90.68	90.68	64.01	64.01	64.01	64.01								
Chemicals	54.36	54.36	54.36	54.36	24.71	24.71	24.71	24.71								
Fuel	24.71	24.71	24.71	24.71	23.47	23.47	23.47	23.47								
Mach Op Costs	22.86	22.86	22.86	22.86	20.39	20.39	20.39	20.39								
Other	16.06	16.06	16.06	16.06	16.06	16.06	16.06	16.06								
V.C Per Hectare	251.32	251.32	251.32	251.32	183.36	183.36	183.36	183.36	159.15	159.15	159.15	159.15	251.32	251.32	251.32	251.32
Average Yield/Ha (10Yr)				5.40	1.31	1.31	1.31	1.31	1.93	1.99	2.03	2.23	17.12	17.12	17.12	17.12
FAO Changes	-0.05		-0.07	-0.09	-0.31	-0.33	-0.33	-0.31	-0.31	-0.31	-0.33	-0.29	-0.05	0.07	0.06	-0.09
2*CO2 Yield/Ha	0.00	8.02	0.00	4.94	0.90	0.87	0.88	0.90	1.33	1.37	1.36	1.59	16.27	18.39	18.13	15.65
Price /Tonne	114.80	114.80	114.80	114.80	259.80	259.80	259.80	259.80	94.10	94.10	94.10	94.10	18.98	18.98	18.98	18.98
Rev/Ha	0.00	0.00	0.00	619.92	339.17	339.17	339.17	339.17	181.54	187.42	190.87	209.88	325.01	325.01	325.01	325.01
2*CO2 Rev/Ha	0.00	920.12	0.00	566.61	232.67	226.56	227.58	235.04	124.90	129.04	128.17	149.64	308.76	349.06	344.03	297.06
Rev-Vc/Ha	-251.32	-251.32	-251.32	368.60	155.81	155.81	155.81	155.81	22.39	28.27	31.72	50.73	73.69	73.69	73.69	73.69
2*CO2 Rev-Vc/Ha	-251.32	668.80	-251.32	315.29	49.31	43.20	44.22	51.68	-34.25	-30.11	-30.98	-9.51	57.44	97.74	92.71	45.74

Source: Manitoba Agriculture. Manitoba Agriculture Yearbook 1987.
Manitoba Agriculture. Farm Planning Guide 1989 Crop Estimates.
(a) Variable costs are those for barley but adjusted according to the recommendations of Manitoba Agriculture personnel
(b) Variable costs for corn silage are the same as those used for corn grain.

(Table 3 of 3)

	Soybean 1 (a)	Soybean 2	Soybean 3	Soybea 4	Potato 1 (b)	Potato 2	Potato 3	Potato 4
Seed and Treatment								
Fertiliser								
Chemicals								
Fuel								
Mach Op Costs								
Other								
V.C. Per Hectare	76.98	76.98	76.98	76.98	1598.25	1598.25	1598.25	1598.25
Average Yield/Ha (10Yr)	1.08	1.08	1.08	1.08	18.64	18.64	18.64	18.64
FAO Changes	-0.26	-0.17	-0.19	-0.29	-0.17	0.01	-0.04	-0.21
2*CO2 Yield/Ha	0.80	0.89	0.87	0.76	15.55	18.83	17.90	14.82
Price /Tonne	171.66	171.66	171.66	171.66	118.43	118.43	118.43	118.43
Rev/Ha	184.71	184.71	184.71	184.71	2207.93	2207.93	2207.93	2207.93
2*CO2 Rev/Ha	136.87	153.49	149.33	130.40	1841.41	2230.01	2119.61	1755.30
Rev-Vc/Ha	107.72	107.72	107.72	107.72	609.68	609.68	609.68	609.68
2*CO2 Rev-Vc/Ha	59.88	76.51	72.35	53.42	243.16	631.76	521.36	157.05

Source: Manitoba Agriculture. Manitoba Agriculture Yearbook 1987.
Manitoba Agriculture. Farm Planning Guide 1989 Crop Estimates.
(a) Variable Costs adapted from budgets relevant to US States bordering Manitoba
(b) Variable costs updated from a 1982 budget provided by the Manitoba Vegatable Groweres Association.

2*CO2 Scenario Yields Obtained from the States using Cluster Analysis

	Wheat 1	Wheat 2	Wheat 3	Wheat 4	Barley 1	Barley 2	Barley 3	Barley 4	Flax 1	Flax 2	Flax 3	Flax 4
NCE2 NE1 SC7 EC8	2.00				2.31				0.00			
East Central ND		2.69				3.23				0.94		
RR Valley ND				3.16				3.50				1.13
Areas 2,3,5,6 Min			2.26				2.12				0.74	
Area 4 Min				2.87				3.07				1.01
Total Yield	2.00	2.69	2.26	3.02	2.31	3.23	2.12	3.29	0.00	0.94	0.74	1.07
Price	138.20	138.20	138.20	138.20	94.90	94.90	94.90	94.90		254.60	254.60	254.60
Variable Cost	173.91	173.91	173.91	173.91	164.95	164.95	164.95	164.95		144.60	144.60	144.60
Rec - VC/Ha	102.49	197.85	138.42	242.76	54.27	141.58	36.24	146.80	0.00	94.72	43.80	127.82

	Corn 1	Corn 2	Corn 3	Corn 4	Sunflower 1	Sunflower 2	Sunflower 3	Sunflower 4	Oats 1	Oats 2	Oats 3	Oats 4
NCE2 NE1 SC7 EC8	3.87				1.42				2.52			
East Central ND		4.39				1.62				2.67		
RR Valley ND				5.34				1.96				3.05
Areas 2,3,5,6 Min			5.74				1.23				1.80	
Area 4 Min				6.62				1.41				2.27
Total Yield	3.87	4.39	5.74	5.98	1.42	1.62	1.23	1.69	2.52	2.67	1.80	2.66
Price	114.80	114.80	114.80	114.80	259.80	259.80	259.80	259.80	94.10	94.10	94.10	94.10
Variable Cost	251.32	251.32	251.32	251.32	183.36	183.36	183.36	183.36	159.15	159.15	159.15	159.15
Rec - VC/Ha	192.96	252.65	407.63	435.18	185.56	237.52	136.19	254.40	77.98	92.10	10.23	91.16

	Corn/S 1	Corn/S 2	Corn/S 3	Corn/S 4	Soybean 1	Soybean 2	Soybean 3	Soybean 4	Potato 1	Potato 2	Potato 3	Potato 4
NCE2 NE1 SC7 EC8	0.00				1.82				0.00			
East Central ND		26.89				0.00				0.00		
RR Valley ND				31.37				1.68				18.49
Areas 2,3,5,6 Min			25.03				1.92				24.24	
Area 4 Min				26.59				2.14				36.19
Total Yield	0.00	26.89	25.03	28.98	1.82	0.00	1.92	1.91	0.00	0.00	24.24	27.34
Price		18.98	18.98	18.98	171.66		171.66	171.66			118.43	118.43
Variable Cost		251.32	251.32	251.32	76.98		76.98	76.98			1598.25	1598.25
Rec - VC/Ha	0.00	259.05	223.75	298.72	235.44	0.00	252.61	250.89	0.00	0.00	1272.49	1639.63

Source: Previous Tables.

Crop Yields Minnesota

Crop Area	Wheat 2,3,5,6	Wheat 4	Barley 2,3,5,6	Barley 4	Flax 2,3,5,6	Flax 4	Corn 2,3,5,6	Corn 4	Sunflower 2,3,5,6	Sunflower 4
1987	30.60	41.20	34.00	58.20	10.90	12.30	95.08	109.20		
1986	32.13	32.70	39.60	44.80	10.00	14.80	96.80	105.00	1293.00	1493.00
1985	38.05	54.10	44.68	68.00	14.30	21.00	82.50	102.00	895.75	1032.00
Av bu/ac	33.59	42.67	39.43	57.00	11.73	16.03	91.46	105.40	1094.38	1262.50
Tonnes/ha	2.26	2.87	2.12	3.07	0.74	1.01	5.74	6.62	1.23	1.41

Crop Area	Oats 2,3,5,6	Oats 4	Corn/s 2,3,5,6	Corn/s 4	Soybean 2,3,5,6	Soybean 4	Potato 2,3,5,6	Potato 4
1987	42.38	61.10	10.83	12.00	32.40	33.80	242.50	352.00
1986	41.43	46.70	12.80	13.10	28.77	31.50	193.33	305.00
1985	58.08	70.60	9.88	10.50	24.33	30.00	213.33	312.00
Av bu/ac	47.29	59.47	11.17	11.87	28.50	31.77	216.39	323.00
Tonnes/ha	1.80	2.27	25.03	26.59	1.92	2.14	24.24	36.19

Source: Minnesota Department of Agriculture and USDA. "Minnesota Agriculture Statistics 1988".
Crop Reporting Disricts
2 = North Central
3 = North East
4 = West Central
5 = Central
6 = East Central

Crop Yields South Dakota

	Spr. Wht (bu/ac)	W Wheat (bu/ac)	Oats (bu/ac)	Barley (bu/ac)	Flax (bu/ac)	Soybean (bu/ac)	S'FlowerO (lbs/ac)	Corn G (bu/ac)	Corn S (tons/ac)	Potato F (cwt/ac)	Sorghum G (bu/ac)	Sorghum S (tons/ac)
1987 (a)	27.00	34.00	46.00	40.00	13.00	32.50	1300.00	83.00	7.30	210.00	53.00	7.30
1986 (a)	25.00	32.00	44.00	42.00	14.00	30.50	1380.00	82.00	7.50	210.00	46.00	7.60
Average	26.00	33.00	45.00	41.00	13.50	31.50	1340.00	82.50	7.40	210.00	49.50	7.45
North East NE1 (b)	32.00		70.00	45.00		25.00	1300.00					
EastNorth (b) Central NCE2	26.00	35.00	60.00	42.00			1200.00	55.00				
E.Central EC8 (b)	35.00		75.00	45.00		31.00	1300.00	75.00				
S.Central SC7 (b)	26.00		60.00	40.00		25.00		55.00			50.00	
Conversion factor	67.25	67.25	38.11	53.80	62.77	67.25	1.12	62.77	2240.75	112.04	56.02	2240.75
Kg/ha	1748.50	2219.25	1714.95	2205.80	847.40	2118.38	1501.30	5178.53	16581.52	23527.84	2772.92	16693.56
NE1 Kg/ha	2152.00	0.00	2667.70	2421.00	0.00	1681.25	1456.49	0.00	0.00	0.00	0.00	0.00
NCE2Kg/ha	1748.50	2353.75	2286.60	2259.60	0.00	0.00	1344.45	3452.35	0.00	0.00	0.00	0.00
EC8 Kg/ha	2353.75	0.00	2858.25	2421.00	0.00	2084.75	1456.49	4707.75	0.00	0.00	0.00	0.00
SC7 Kg/ha	1748.50	0.00	2286.60	2152.00	0.00	1681.25	0.00	3452.35	0.00	0.00	2800.93	0.00
Tonnes/ha	1.75	2.22	1.71	2.21	0.85	2.12	1.50	5.18	16.58	23.53	2.77	16.69
Tonnes/ha NE1	2.15	0.00	2.67	2.42	0.00	1.68	1.46	0.00	0.00	0.00	0.00	0.00
Tonnes/ha NCE2	1.75	2.35	2.29	2.26	0.00	0.00	1.34	3.45	0.00	0.00	0.00	0.00
Tonnes/ha EC8	2.35	0.00	2.86	2.42	0.00	2.08	1.46	4.71	0.00	0.00	0.00	0.00
Tonnes/ha SC7	1.75	0.00	2.29	2.15	0.00	1.68	0.00	3.45	0.00	0.00	2.80	0.00

(a) South Dakota Agricultural Statistics 1987-1988.
(b) Co-operative Extension Service, SDSU and USDA. "Comparative Crop Budgets for Planning a Cropping Programme in South Dakota".

Crop Yields North Dakota

	Spr. Wht (bu/ac)	W Wheat (bu/ac)	Oats (bu/ac)	Barley (bu/ac)	Flax (bu/ac)	Soybean (bu/ac)	S'FlowerO (cwt/ac)	Corn G (bu/ac)	Corn S (tons/ac)	Potato F (cwt/ac)
1987 (a)	31.00	32.00	52.00	48.00	16.50	32.50	15.20	93.00	7.50	185.00
1986 (a)	31.00	29.00	55.00	51.00	17.50	35.00	13.50	93.00	7.50	180.00
Average	31.00	30.50	53.50	49.50	17.00	33.75	14.35	93.00	7.50	182.50
Red Riv. Valley (b)	47.00		80.00	65.00	18.00	25.00	17.50	85.00	14.00	165.00
East Central (b)	40.00		70.00	60.00	15.00		14.50	70.00	12.00	
Conversion factor	67.25	67.25	38.11	53.80	62.77	67.25	112.04	62.77	2240.75	112.04
Kg/ha	2084.75	2051.13	2038.89	2663.10	1067.09	2269.69	1607.74	5837.61	16805.60	20446.81
Kg/ha R.R. Valley	3160.75	0.00	3048.80	3497.00	1129.86	1681.25	1960.65	5335.45	31370.45	18486.16
Kg/ha E.Central	2690.00	0.00	2667.70	3228.00	941.55	0.00	1624.54	4393.90	26888.96	0.00
Tonnes/ha	2.08	2.05	2.04	2.66	1.07	2.27	1.61	5.84	16.81	20.45
Tonnes/ha R.R. Valley	3.16	0.00	3.05	3.50	1.13	1.68	1.96	5.34	31.37	18.49
Tonnes/ha E.Central	2.69	0.00	2.67	3.23	0.94	0.00	1.62	4.39	26.89	0.00

(a) North Dakota Agricultural Statistics 1988.
(b) Co-operative Extension Service, NDSU. "Farm Management Planning Guide".

Average Yields over 10 Years for Selected Manitoba Crops by Crop District

10 Yr Av	Wheat	Oats	Barley	Canola	Flax	Corn/G
Region 1	1.874	1.905	2.482	1.176	0.945	5.400
Region 2	1.953	1.953	2.548	1.196	0.982	5.400
Region 3	2.090	2.094	2.700	1.239	1.086	5.400
Region 4	1.993	1.980	2.375	1.269	1.053	5.400
Region 5	2.024	1.942	2.368	1.151	1.114	5.400
Region 6	1.945	1.951	2.400	1.271	0.989	5.400
Region 7	2.114	2.163	2.736	1.279	1.069	5.400
Region 8	2.206	2.298	2.960	1.347	1.173	0.000
Region 9	2.099	2.143	2.696	1.310	1.150	0.000
Region 10	1.814	1.902	2.230	1.138	0.949	0.000
Region 11	2.064	2.142	2.564	1.204	1.112	0.000
Region 12	1.915	0.207	0.265	0.133	0.112	0.000

Source: Calculated from Previous Table.

Average Yields Over 10 Years for Selected Manitoba Crops, by Model Area.

	Wheat	Oats	Barley	Canola	Flax	Corn/G	Sunflower	Corn/S	Potato
Field 1	1.913	1.929	2.515	1.186	0.963	5.400	1.306	17.124	18.643
Field 2	2.013	1.992	2.461	1.233	1.060	5.400	1.306	17.124	18.643
Field 3	1.973	1.599	1.939	0.946	0.831	0.000	1.306	17.124	18.643
Field 4	2.160	2.230	2.848	1.313	1.121	2.700	1.306	17.124	18.643

Source: Calculated from Previous Tables.

10 Year Average Yields by Crop District, Manitoba

	Wheat	Oats	Barley	Canola	Flax	Corn/G	Sunflower	Corn/S	Potato
Region 1									
1987	1.514	1.529	2.234	1.466	1.154	5.400	1.570	20.700	23.400
1986	2.184	2.471	2.984	1.465	1.405		1.430	21.100	19.309
1985	2.687	2.526	3.538	1.510	1.203		1.190	15.900	18.900
1984	1.801	1.684	2.324	0.833	0.705		1.150	13.500	16.200
1983	1.692	1.730	2.265	0.960	0.904		1.120	15.250	16.100
1982	2.262	2.400	2.982	1.183	1.088		1.235	15.420	16.500
1981	2.018	1.917	2.480	1.164	0.848		1.455	17.520	18.775
1980	1.123	1.229	1.466	1.021	0.544		1.225	12.530	17.862
1979	1.471	1.554	1.918	0.854	0.662		1.355	17.970	18.827
1978	1.983	2.010	2.631	1.302	0.934		1.325	21.350	20.560
Region 2							All	All	All
1987	1.905	1.857	2.717	1.418	1.203	5.400	Districts	Districts	Districts
1986	2.335	2.655	3.074	1.463	1.442				
1985	2.459	2.235	3.140	1.459	1.116				
1984	1.835	1.546	2.302	0.915	0.763				
1983	1.824	1.854	2.356	1.129	0.985				
1982	2.222	2.500	3.004	1.195	1.067				
1981	1.994	1.745	2.297	1.204	0.810				
1980	1.317	1.403	1.771	1.021	0.647				
1979	1.545	1.500	1.976	0.854	0.734				
1978	2.093	2.239	2.841	1.302	1.053				
Region 3									
1987	2.206	2.111	3.103	1.531	1.378	5.400			
1986	2.387	2.529	3.202	1.571	1.585				
1985	2.635	2.450	3.207	1.594	1.244				
1984	1.797	1.562	2.200	0.875	0.738				
1983	1.979	2.010	2.472	1.171	1.115				
1982	2.222	2.400	2.893	1.176	1.014				
1981	2.159	2.024	2.507	1.299	0.982				
1980	1.705	1.933	2.460	1.021	0.903				
1979	1.631	1.656	2.052	0.854	0.767				
1978	2.182	2.262	2.901	1.302	1.132				
Region 4									
1987	1.945	2.250	2.815	1.521	1.300	5.400			
1986	2.128	2.333	2.786	1.494	1.388				
1985	2.626	2.417	3.000	1.699	1.389				
1984	2.043	1.692	2.333	1.091	0.833				
1983	1.910	1.856	2.082	1.111	1.000				
1982	1.817	1.800	2.112	1.087	0.839				
1981	2.286	1.997	2.324	1.373	1.058				
1980	1.719	1.870	2.411	0.987	0.923				
1979	1.305	1.436	1.485	0.936	0.634				
1978	2.153	2.153	2.406	1.392	1.167				

Source: Manitoba Agriculture Yearbook (Various Years).

	Wheat	Oats	Barley	Canola	Flax	Corn/G
Region 5						
1987	1.826	2.000	2.581	1.250	1.236	5.400
1986	2.140	2.125	2.522	1.259	1.266	
1985	2.554	2.500	3.161	1.460	1.470	
1984	1.990	1.727	2.235	1.120	1.264	
1983	1.649	1.750	1.783	0.888	1.033	
1982	2.369	2.100	2.646	1.101	1.032	
1981	2.208	1.898	2.286	1.121	0.978	
1980	1.638	1.550	1.971	0.987	0.803	
1979	1.667	1.840	1.929	0.936	0.893	
1978	2.200	1.933	2.568	1.392	1.162	
Region 6						
1987	1.849	1.826	2.750	1.367	1.130	5.400
1986	2.022	2.381	2.750	1.427	1.373	
1985	2.591	2.400	3.154	1.634	1.262	
1984	2.122	1.970	2.636	1.233	0.933	
1983	1.674	1.741	1.886	1.050	0.898	
1982	2.057	2.200	2.598	1.449	1.025	
1981	2.132	1.921	2.254	1.239	0.847	
1980	1.582	1.507	2.013	0.987	0.726	
1979	1.453	1.581	1.693	0.936	0.791	
1978	1.972	1.980	2.262	1.392	0.900	
Region 7						
1987	2.291	2.194	3.105	1.500	1.323	5.400
1986	2.299	2.781	2.963	1.329	1.224	
1985	2.748	2.742	3.571	1.662	1.277	
1984	2.221	2.143	2.979	1.240	1.113	
1983	1.867	1.886	2.322	1.089	0.956	
1982	2.427	2.500	3.172	1.264	1.230	
1981	2.145	2.027	2.593	1.270	0.937	
1980	1.238	1.308	1.644	0.874	0.582	
1979	1.886	1.974	2.437	1.213	0.996	
1978	2.021	2.078	2.576	1.352	1.047	
Region 8						
1987	2.216	2.462	3.047	1.482	1.300	
1986	2.288	2.917	3.140	1.465	1.449	
1985	3.095	2.895	4.096	1.687	1.499	
1984	2.370	2.210	3.261	1.281	1.186	
1983	2.036	1.969	2.618	1.156	1.057	
1982	2.513	2.800	3.431	1.235	1.315	
1981	2.179	2.066	2.760	1.384	1.036	
1980	1.267	1.442	1.751	1.005	0.696	
1979	1.954	2.025	2.686	1.287	1.051	
1978	2.138	2.189	2.806	1.483	1.137	

Source: Manitoba Agriculture Yearbook (Various Years).

Region 9					
1987	2.250	2.353	3.167	1.491	1.362
1986	2.181	2.533	2.825	1.418	1.353
1985	2.824	2.667	3.635	1.729	1.585
1984	2.267	2.267	3.039	1.351	1.389
1983	1.854	1.956	2.366	1.120	1.014
1982	2.397	2.300	2.929	1.222	1.202
1981	2.058	1.928	2.486	1.299	0.954
1980	1.713	1.777	2.158	1.116	0.803
1979	1.624	1.727	2.159	1.076	0.870
1978	1.819	1.925	2.196	1.282	0.970
Region 10					
1987	1.889	1.800	2.429	1.265	1.188
1986	1.824	2.000	2.143	1.225	1.208
1985	2.136	2.600	2.429	1.215	1.000
1984	1.905	2.167	2.250	1.136	1.035
1983	1.557	1.500	1.760	1.105	0.868
1982	1.868	2.300	2.567	0.806	0.800
1981	1.890	1.616	2.050	1.154	0.742
1980	1.647	1.575	1.930	1.116	0.893
1979	1.454	1.725	2.000	1.076	0.710
1978	1.973	1.738	2.740	1.282	1.043
Region 11					
1987	2.141	2.455	3.000	1.333	1.295
1986	2.129	2.500	2.703	1.342	1.411
1985	2.430	2.500	3.024	1.345	1.359
1984	2.354	2.300	3.184	1.401	1.342
1983	1.659	1.700	1.880	0.901	0.784
1982	2.346	2.700	3.050	1.311	1.252
1981	2.074	1.844	2.340	1.196	1.110
1980	1.560	1.467	1.772	0.968	0.679
1979	1.904	1.909	2.384	1.027	0.855
1978	2.038	2.044	2.300	1.215	1.029
Region 12					
1987	2.039	2.067	2.654	1.329	1.115
1986	2.028	2.333	2.500	1.281	1.107
1985	2.137	2.067	2.576	1.257	1.158
1984	2.135	2.190	2.500	1.207	1.075
1983	1.455	1.557	1.514	0.822	0.714
1982	1.853	1.900	2.169	1.071	0.807
1981	1.910	1.662	1.888	1.062	0.720
1980	1.661	1.600	1.919	0.968	0.821
1979	1.774	1.875	2.030	1.027	0.848
1978	2.155	2.013	2.212	1.215	0.986

Source: Manitoba Agriculture Yearbook (Various Years).

Five Year Average of Prices for Selected Crops Within Manitoba

Price Per Tonne (Dollars)	Wheat	Barley	Canola	Flax	Corn	Sunflower	Oats	Soybean (a)	Corn/S	Potatoes
1987	100.00	62.50	255.00	195.00	92.00	202.00	89.50		15.00	117.00
1986	97.00	75.00	197.00	173.00	92.00	209.00	74.00		15.90	96.07
1985	148.00	96.00	266.00	265.00	120.00	230.00	88.00		21.00	111.70
1984	172.00	121.00	351.00	317.00	140.00	360.00	109.00		22.00	126.93
1983	174.00	120.00	383.00	323.00	130.00	298.00	110.00		21.00	140.46
Average	138.20	94.90	290.40	254.60	114.80	259.80	94.10	171.66	18.98	118.43

Source: Manitoba Agriculture. Manitoba Agriculture Yearbook 1987.
(a) Soybean Price Quoted by CSP Foods, Altona.