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**THE SENSITIVITY OF CEREAL CROP PRODUCTIVITY
TO A CO₂ - INDUCED CLIMATIC CHANGE:
A CASE STUDY
IN THE MACKENZIE BASIN, CANADA.**

By

Douglas P. Brunt

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Arts

Department of Geography

Carleton University

Ottawa, Canada

November 15 1995

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THE SENSITIVITY OF CEREAL CROP PRODUCTIVITY
TO A CO₂ - INDUCED CLIMATIC CHANGE.
A CASE STUDY IN THE MACKENZIE BASIN, CANADA

submitted by

Douglas P. Brunt, B.A.

in partial fulfillment of the requirements
for the degree of Master of Arts

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January 8, 1996

ABSTRACT

Current climatic conditions impose limitations on agricultural opportunities in the Mackenzie River Basin. Anthropologically-induced changes to the composition of the Earth's atmosphere could affect these opportunities. A crop-weather model was used to evaluate wheat and barley potential under a range of future climate regimes at 15 sites in 3 ecoclimatic regions (ECR) located in the Basin. The altered climate regimes were based on an effective doubling of atmospheric CO_2 given the baseline weather set; a Composite climate scenario developed for the region; and, scenarios generated by the Geophysical Fluid Dynamics Laboratory (GFDL) and the Canadian Climate Centre (CCC) global circulation models (GCMs). The effects of altered climates were estimated for seeding dates, days to maturity, crop moisture stress, grain weight to canopy weight ratios, and crop yields.

Estimated seeding dates were earlier and the estimated days to maturity were reduced in all ECRs under all climatic change scenarios. The 2XCO_2 regime generated large increases in estimated yields at nearly all sites. Estimated yields tended to be lower under the other regimes when compared to estimated yields under baseline conditions, except at the sites located in the High Boreal ECR. In most cases, there was little change in the estimated grain to canopy ratio, and there was a decrease in estimated crop moisture stress. These results imply that the beneficial direct impacts of elevated levels of atmospheric CO_2 on estimated cereal yields could be offset by changes in the climatic conditions that may result from these higher levels of CO_2 . Estimated

changes to the variables analyzed often varied greatly between the specified climatic change scenarios, but a pattern of regional variation was not generally apparent.

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This work is dedicated to my wife, Mary, for her unending patience and support. Finding words to express my gratitude is difficult; to express my love, impossible.

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Table of Acronyms

CCC	- Canadian Climate Centre
CMS	- Crop Moisture Stress
CERES	- Crop-Environment Resource Synthesis
DTM	- Days to Maturity
DSSAT	- Decision Support System for Agrotechnology Transfer
ECR	- Ecoclimatic Region
EGE	- Enhanced Greenhouse Effect
GCM	- General (or Global) Circulation Model
GFDL	- Geophysical Fluid Dynamics Laboratory
G:C	- Grain to Canopy Ratio
GHG	- Greenhouse Gas
HB	- Sub Humid High Boreal ECR
IBSNAT	- International Benchmark Sites Network for Agrotechnology Transfer
LB	- Sub Humid Low Boreal ECR
MB	- Sub Humid Mid-Boreal ECR
PD	- Planting Date

1.0 INTRODUCTION

1.1 Background

The composition of the Earth's atmosphere is being altered by human activity in ways that could impact agricultural production directly by affecting plant processes, and indirectly, by bringing about significant climatic change (IPCC 1990a, 1990b). Deforestation, the burning of fossil fuels, and other human activities are thought to be responsible for a substantial increase in the atmospheric concentration of many trace gases (Graedel and Crutzen 1990; Jager and Barry 1990). The most significant of these to this research are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs). All of these gases, with the exception of CFCs are naturally occurring. These gases, and others (most notably, water vapour), through their interactions with solar radiation and emitted terrestrial radiation, have a strong insulating effect on the planet and are often referred to as greenhouse gases (GHGs). Though the GHGs constitute less than 1% of the atmosphere by volume, it is estimated that in their absence the global mean temperature would be about 33°C cooler than currently (Barry and Chorley 1992, p.35).

There is concern that as the concentration of GHGs increases the greenhouse effect will be "enhanced", and this will result in climatic warming on a global scale. The current scientific consensus is that global mean temperature could increase by 1°C from 1990 to 2025, and by 3°C by the end

of the next century (IPCC 1990a, p.xi). Scientists are less confident about estimates of possible changes in global precipitation patterns. The degree of certainty as to the regional characteristics of climatic change and the rate at which change may occur also remains low (Schneider 1991, p.2).

The benefits of elevated CO₂ levels on plant growth, water use efficiency (WUE), and crop yield have been well documented (e.g. NDU 1980; Acock and Allen 1985). However, much of this research has been conducted in controlled environments and the extent to which crop yields might be impacted under field conditions remains a topic of debate. The impact of increased CO₂ combined with climatic change on general crop productivity has received considerable attention recently, and there are several studies suggesting that impacts on yields may be expected to vary according to crop and location (e.g. Parry et al. 1988a and 1988b; Kane et al. 1991; Rosenzweig and Parry 1994; Rosenzweig and Iglesias 1994). These studies also suggest that given the intensive nature of current agricultural practices in the major cereal growing regions of the world and the limited availability of "prime" agricultural land, those lands that are now considered agriculturally marginal may become important in meeting future demands for food. These demands will continue to increase, as it is estimated that the global population will surpass 8 billion by the year 2020 (Demeny 1990). At the agricultural margins, crop yields will be sensitive to atmospheric change, and, in turn could have relatively large impacts (either positive or negative) on food supply. While there has been some research into the impacts of climatic variability and change on

agricultural production potential, and on the location of the agricultural frontier, (e.g. Rosenzweig 1985; Williams et al. 1988; Hunt 1991; Brklacich and Dumanski 1993), most of the research has focused on agriculture-climate relationships in established agricultural regions.

The research presented in this thesis will add to this body of knowledge by investigating the direct and indirect impacts of atmospheric change on crop yields in an area of northwestern Canada. The Mackenzie River Basin, which includes the Mackenzie, Liard, Hay, Athabasca, and Peace River watersheds, could represent an important agricultural resource for Canada with changing atmospheric conditions (Figure 1). Presently it now lies on the northern margin of the Canadian agricultural ecumene. The Peace River Region of northern British Columbia and Alberta has 1.2 million hectares (ha) of land currently in agricultural production (Agriculture Canada 1986). But another 10.3 million hectares throughout the upper Basin are believed to have soil characteristics capable of supporting agricultural activity (Brklacich and Curran 1994). The current climatic regime, which allows for only a very short growing season, is a major limiting factor on the agricultural productivity of this land (Tollenaar 1983, p.1). However, the effects of increased atmospheric CO₂ and global climatic change stemming from an "enhanced" greenhouse effect on plant productivity, could contribute to new agricultural opportunities in the Mackenzie Basin.

Figure 1. The Mackenzie Basin.

1.2 Purpose

The purpose of this study is to analyze the potential effects of an increase in the concentration of atmospheric carbon dioxide and concomitant climatic change on crop productivity levels for two commercial crops, wheat and barley, in the Mackenzie Basin.

1.3 Objectives

To ensure a thorough and comprehensive analysis of the effects of atmospheric change on crop productivity, this study will:

- i. Review the impacts of atmospheric and climatic change on agricultural production;
- ii. Review methodologies for assessing the effects of atmospheric and climatic change on crop productivity, and select an appropriate method for use in this study;
- iii. Test the selected crop productivity model(s) for applications under northern Canadian conditions;
- iv. Identify, collect, and organize the data required for this assessment including possible future climate regimes;
- v. Determine the impacts of a doubling of atmospheric CO₂ and selected climatic change scenarios on wheat and barley productivity levels in the Mackenzie Basin; and,
- vi. Compare and contrast the results among selected scenarios for possible future climatic change and among subregions in the

Mackenzie Basin.

1.4 Scope of the Study

This study was designed to provide an indication of how wheat and barley productivity in the Mackenzie Basin would be affected by an increased concentration of atmospheric carbon dioxide. These two crops were selected for study because they are important commercial crops in the region. In the Peace River region of Alberta and British Columbia alone, an average of 331,800 ha of barley and 378,480 ha of wheat were grown each each year during the 1980s (Agriculture Canada 1986 and 1990). The research will not address the economic or social factors that may influence current or future crop production. Other biophysical changes stemming from climate change, such as the potential change in the range of pests and diseases, will not be discussed. The results of this study could be used in a comprehensive study of crop productivity that would necessarily include all these issues.

This thesis deals specifically with the impacts of atmospheric change, caused by anthropological activity, on commercial agricultural productivity. The term "climatic change", as used in the remainder of this thesis, encompasses changes in the composition of the atmosphere and the changes in climate, as both may impact on agriculture, separately and in the aggregate. The terms anthropogenically-induced climate change, carbon dioxide-induced climate change, and the enhanced greenhouse effect (EGE) will be used interchangeably.

1.5 Organization of Paper

This paper consists of 6 chapters. The first chapter introduces the research problem and outlines the purpose and objectives of the research. Figure 2 provides a graphic overview of the study. Chapter Two summarizes how climatic change may impact agricultural production and reviews selected impact methodologies. From this discussion, a method to investigate the impacts of climate change on crop productivity in the Mackenzie Basin is selected. A research framework and the specific methods employed in this study are described in Chapter Three. Chapters Four and Five present selected findings and discuss the results of the analysis. Chapter Four focuses on the impacts of atmospheric and climatic change on agroclimatic variables that may affect productivity, and Chapter 5 examines the impacts on crop productivity. The study's major findings and conclusions are summarized in Chapter Six. Detailed findings for all sites in the study can be found in the Appendix.

Figure 2. Study Overview.

2.0 ATMOSPHERIC AND CLIMATIC CHANGE IMPACTS ON AGRICULTURAL PRODUCTIVITY

This chapter reviews how atmospheric and climatic change could affect crop productivity, and reviews and appraises methods for assessing these impacts. The chapter concludes with the selection of the method to be employed in this study.

2.1 Impact Pathways

The impacts of atmospheric change on crop productivity can be classified into two broad categories (Parry 1990, p.37):

- i. The direct effects of an increase in CO₂ concentrations on the process of photosynthesis and water use of food plants and weeds; and,
- ii. The indirect effects of CO₂-induced changes which alter temperature, rainfall, and sunshine that can influence plant productivity.

The direct and indirect effects will be reviewed separately in this chapter to illustrate the various pathways by which atmospheric change might alter crop productivity. It is important to note that although these effects are treated independently here, under actual field conditions the impacts will occur simultaneously. These multiple impacts may heighten individual effects and/or mute others.

2.1.1 Direct Effects

2.1.1.1 Photosynthesis

Photosynthesis is the process by which green plants utilize carbon dioxide, water, and solar radiation to produce organic matter plus oxygen (Houghton and Skole 1990 p.393). The chemical reaction is:

This molecule of organic matter, or reduced carbon, is the building block of cellulose, carbohydrates, protein, and fat, all of which are necessary for plant growth. An increase in the concentration of atmospheric carbon dioxide would mean more CO_2 is available to the plant, thus, the rate of plant growth and total plant matter would increase, *ceterus paribus*.

The photosynthetic pathway that results in the creation of organic matter differs between plant species. The two major types of plants, called "C3" and "C4", differ in the way they take up CO_2 from the surrounding atmosphere due to differences in plant structure and biochemical processes (Goudriaan 1990, p.23). Ninety-five percent of the earth's biomass is produced from C3 plants, such as wheat, rice, soybean, and the majority of common weeds. However, a number of crops that are important to humans, including maize, sorghum, sugarcane, millet, and other members of the grass family, are C4 plants (Melillo et al. 1990, p.289). C4 plants are largely tropical, and while they make up only one-fifth of the world's food production, they are important food crops, particularly in Africa (IPCC 1990b, p.2-5).

Under current levels of CO_2 , C4 plants are photosynthetically more efficient than C3 plants. However, C4 plants are less responsive to increases in CO_2 levels. Another important consideration is the effect on weeds found in agricultural crops. Fourteen of the seventeen most troublesome weeds are C4 weeds in C3 crops (Parry 1990, p.39). An increase in levels of atmospheric carbon dioxide may mean less competition for C3 crops. Conversely, C3 weeds in C4 crops could become more of a problem. Due to the regional ranges of these crops, it has been suggested that, in broad geographical terms, temperate and humid tropical agriculture will benefit more from increases in the concentration of atmospheric carbon dioxide than semi-arid agriculture (Kane et al. 1991, p.5). Wheat and barley, both C3 crops, are major crops presently grown in the upper Mackenzie Basin.

2.1.1.2 Water use by plants

Increased amounts of atmospheric carbon dioxide also tend to reduce the amount of water required by both C3 and C4 plants (IPCC 1990b, p.2-6). The stomata are the small openings on the surface of leaves through which CO_2 is absorbed and water vapour is released by transpiration. Elevated CO_2 levels reduce stomate size and thereby improve plant water use efficiency (WUE), which is the ratio of crop-biomass to the water used in evapotranspiration (ET). The IPCC (1990b) concluded that smaller openings may mean less moisture is transpired, and this might be beneficial to plants in semi-arid regions where water is a limiting factor to growth.

The relationships between changes in atmospheric conditions and plant processes, including the uptake of water, are complex. Under controlled conditions, it has been found that the net effect of a doubling of atmospheric CO₂ from 330 parts per million (ppm) by volume to 660 ppm was a 10 to 50% increase in plant growth and yield in C3 crops and a 0 to 10% increase in plant growth and yield in C4 crops (Parry 1990, p.41). While estimates of increased CO₂ effects on crop biomass and yield are generally positive, many uncertainties as to the net effect of increases in carbon dioxide. For example, does increased WUE lead to greater grain productivity, or just to more biomass accumulation? Larger, leafier plants will have more stomata, which may lead to greater ET, or more water use, per plant. In regions where adequate moisture is a concern, changes to the total amount of water required per plant could have a significant impact on crop yields.

2.1.2 Indirect Effects

Climate change can be expected due to the enhanced greenhouse effect (World Resources Institute 1992, p.205). The IPCC (1990b, pp.2-7 to 2-10) suggests four climate-related effects on agriculture due to the EGE:

- i. the agroclimate;
- ii. pests and diseases;
- iii. other aspects of the agricultural environment, e. g. soils and water resources; and,
- iv. crop yields.

2.1.2.1 Agroclimate

Temperature is a major limiting factor to crop growth in high latitude regions like the Mackenzie Basin. Should temperatures increase significantly during the spring to autumn period, the growing season would be extended and a shift in the thermal boundaries which confine commercial agriculture would be likely. Given the existence of soils that could support crop production near the current thermal boundary for agriculture, a longer growing season could contribute to an expansion of the area physically capable of supporting crop production in these regions. Exploitation of these poleward shifts will vary greatly from region to region, depending on such factors as the quality of soils, the prevailing economic conditions, and global and regional food demands. Nevertheless, it is important to note that global climate change could contribute to an extension of the area usable by commercial agriculture. Studies have concluded that a 1°C increase in the annual mean temperature in the northern mid-latitudes would advance the thermal limit of cereal crops by 150-200 km, and raise the altitudinal limit to arable agriculture by about 150-200 m (e.g. Parry and Carter 1988).

The IPCC (1990b, p.2-8) states that there is much less certainty about the impacts of the EGE on precipitation than on temperature. Uncertainty about changes in amount, as well as spatial and temporal distribution of precipitation, make it difficult to express the effects on agriculture with a high degree of confidence. However, IPCC scientists have predicted an increase in winter precipitation of 5-10 percent in the mid and high latitude continents (35-

55°N), and reduced summer precipitation and soil moisture in southern Europe and central North America. Depending on the seasonal timing, small changes in the amount of rain may have either positive or negative effects on food production potential. This is particularly true in regions where farming is carried out at the subsistence level. At higher latitudes, where growing seasons are shorter, excessive spring moisture may delay planting such that there is an increased risk of the crop being struck by a killing frost before maturity.

Just as significant from an agricultural perspective are extreme climatic events. The effects of the EGE on the occurrence of drought, storms, heatwaves, and severe frosts are poorly understood. Should these events become more intense, in magnitude and/or frequency, there could be serious impacts on agriculture. This would be especially critical if these changes occur in regions that are already prone to these types of events.

2.1.2.2 Pests and diseases

The spatial range of some insect pests could be extended as climate regimes shift. First, the overwintering ability of some pests in mid to high-latitude regions may improve should winter temperatures become less severe. A consequence of this could be infestation earlier in the growing season, at susceptible stages of plant development. Second, insects could also migrate along with shifts in the spatial range of the host plants. The result may be increased insect population density and a greater number of insect species (IPCC 1990b, p2-9).

Plant and animal diseases are generally more active under warmer conditions, particularly when combined with more humid conditions. Humid and warm conditions are also favourable for most fungal and bacterial pathogens (Parry 1990, p.55). The impacts of both insects and diseases are greatest when crops are under stress, and these impacts are almost always negative with respect to crop productivity.

2.1.2.3 The agricultural environment

The EGE may affect future agricultural production in many indirect ways by altering the physical conditions which influence of agricultural production. Soil and ground water resources are two elements of the physical environment that may be altered due to climate change, but potential indirect impacts of changes in these systems have not been comprehensively studied.

An increase in temperature may accelerate the rate at which organic matter is decomposed, thus having a negative long term effect on soil fertility. However, this effect could be offset by the increased amount of root biomass (Chapter 2.1). In areas where the amount of precipitation decreases, particularly in the summer, the dryness may lead to increased wind erosion. Areas receiving more rain or more intense rainfall events could experience an increase in soil erosion by water and in the leaching of minerals, including nitrates, thereby reducing soil productivity. The degree of these potential impacts will vary with soil texture, cohesiveness, and water holding capacity, as well as other factors such as wind velocity.

In regions where relatively large crop moisture deficits are currently common, or may increase, the use of irrigation may be hampered by changes in the recharge rates of groundwater resources. For major food producing areas in the mid-latitudes, especially in North America, several climate change scenarios suggest reductions in precipitation which, in turn, could reduce soil moisture recharge (e.g. Williams et al. 1988). This potential negative impact on groundwater resources is significant as irrigation is often suggested as one method of adapting to climate change (e.g. Rozenzweig and Iglesias 1994). An alternative is to divert surface water for irrigation. However, the viability of this option for adaptation to climate change is questionable given the environmental, economic, and political issues associated with this type of project.

2.1.2.4 Crop yields

Two important factors that determine crop yields are plant growth (or development) rates and the length of the growing season. Plant development is strongly affected by temperature. Plant development usually begins at a base temperature and the rate of development increases linearly to an optimal level before beginning to decline (Parry 1990, p.42). Response to temperature increases differs between determinant and indeterminate plants. Determinants are plants whose life cycle ends as their grain matures, e.g. cereals. In these plants, an increase in temperature shortens the reproductive phase, reducing the time the canopy exists, thus, reducing the total length of time that light can be intercepted and turned into biomass. The net result is that the grain will not

"fill out", meaning it will weigh less and the overall yield will be reduced. This may have a serious impact on the core agricultural regions of the northern mid-latitudes where much of the world's supply of cereals is grown.

Indeterminants will continue to grow until some other factor, such as frost, kills the plant. Grasses and rootcrops fall into this category. As long as the increase in temperature does not exceed the optimal level, above which temperature and/or water stress will occur, indeterminants' yields increase as temperature increases.

As mentioned in Chapter 2.1.2.1, an increase in temperature could extend the growing season and the thermal boundary for commercial agriculture. Though these benefits could be offset by the increases in crop pests and diseases and less favourable moisture regimes, an extended growing season could reduce risk in the upper latitudes. A longer growing period reduces the chances of crops being struck with either a late frost in the spring, after the crop has been planted, or killing fall frost before the crop has fully matured. Therefore, farming could become less risky in those areas and the food output less variable.

2.2 Methods for Assessing the Impacts of Atmospheric Change

There is a wide range of methods that can be used in assessing the impacts of atmospheric change on agriculture (Carter et al. 1992 and 1994). This section provides an overview and appraisal of 3 methods that have been used to assess the impacts of global climatic change on agricultural opportunities. The main features of analogue approaches, agroclimatic and land suitability indices, and crop-yield models will be presented and this review will provide a foundation for selecting a method to fulfill the stated purpose of the study.

2.2.1 Analogue approaches

The use of analogy is likely the oldest method of assessing the potential impacts of altered conditions on crop productivity at a particular site. The method is based on (i) specifying the changed conditions for a designated site, (ii) searching for an alternate site(s) which presently approximates the changed conditions, and (iii) employing observed trends in yield patterns at the alternate site as a prediction of future productivity at the designated sites (Nix 1985, p.108). Analogue studies can employ either a temporal or spatial approach.

Temporal or historical analogues employ previous periods that possess pre-defined attributes that might characterize climate at some future time. This previous period is then used to provide insight into how biophysical and/or socioeconomic characteristics of some system, such as agriculture, might respond to climate change (e.g. Williams et al. 1988; Wigley et al. 1981). A

portion of the Williams et al. (1988) study used the "Dust Bowl" conditions of 1933-1937, when temperatures on the Prairies were slightly higher and precipitation less than the 1951-1980 baseline period, as an analogue for future conditions that might be associated with global warming. The basis of this analogue was that the climatic conditions experienced during the Dust Bowl were found to be generally similar to those predicted by the GISS GCM given an effective doubling of atmospheric carbon dioxide.

Spatial or regional analogues are based upon similar concepts used in the historical analogues, but in this approach the analogue is derived from a comparison of two locations in the current context. For example, Site 1 is determined to have a climate similar to projected climatic conditions in Site 2. Therefore, agricultural suitability or productivity at Site 2 is calculated under the climatic regime of Site 1. Bergthorsson et al. (1988) used this technique to model the future agricultural potential for grass growth under warmer conditions in Iceland based on the plant species and the climate currently found in Northern Britain.

One of the strengths of the analogue approach is that it captures actual biophysical and behavioural responses to changing conditions. However, the approach also has several limitations. The analogy is often limited to a few climatic variables, and it is usually difficult to find suitable regions or periods which capture the full set of environmental and management factors which ultimately impact crop development and productivity (Carter et al. 1992, p.8). Analogues also fail to establish the explicit links between biophysical and

behavioural changes and changes in climate. That is, are these biophysical and behavioural changes *responses* to climate change, or just changes caused by several factors which may or may not include climate? Further limitations, which are particularly significant for this research, are that estimated increases in atmospheric levels of CO₂ are higher than observed levels during the period of modern agriculture and the magnitude of the predicted temperature increases is also unprecedented over this time frame (Rosenzweig 1986, p.71).

The overall purpose of this study is to evaluate the combined effects of increased levels of CO₂ and climate change on crop productivity in the Mackenzie Basin. Analogue approaches to impact assessment are unable to separate effects of changes in these factors from other non-climate factors such as changes in technology, farm management practices, and economic conditions. Given these limitations associated with analogue approaches and that the levels of atmospheric CO₂ and climate change may exceed recent fluctuations in these properties, the analogue is inappropriate for this study.

2.2.2 Agroclimatic and land suitability indices

Agroclimatic and land suitability indices measure the general agricultural suitability of an area, based upon certain environmental variables. Generally speaking, the indices are derived from a comparison of the physical requirements for crop growth and the availability of these physical attributes. Agroclimatic indices focus on how well the climate provides a suitable environ-

ment for crop growth. Growing degree-days (GDD), for example, is a measure of the availability of heat for plant growth. While this type of index is straightforward to calculate and easy to use, "... represent[s] a crude approximation of a complex biological response to temperature and daylength" (Major and Kiniry 1991, p. 23). Eley and Findlay (1977) used agroclimatic indicators to assess the agricultural potential of the southern Yukon and Northwest Territories. Their study compared the length of the growing season, based on the weather record, to the days required to mature several crops, including wheat.

The assessment of soil and other landscape characteristics with respect to crop production is the general function of land suitability indices, such as the Canada Land Inventory (CLI) for agriculture. This is a land suitability index which categorizes land into seven classes based on factors limiting to production, from minimal (Class 1) to prohibitive (Class 7) (Canada Land Inventory 1969). Factors include, in part, drainage, slope, and stoniness. Preliminary land suitability studies for agriculture have been conducted in selected areas of the Northwest Territories (e.g. Rostad and Kozak 1977; Northwest Research Group 1978).

Recent research has attempted to incorporate aspects of both agroclimate and land suitability into more comprehensive forms of agricultural classifications or indices (e.g. Thornton et al. 1991; Curran and Brklacich 1995). This type of approach is data intensive and work in this area has been

greatly aided by the spatial analysis capabilities of computer-based Geographical Information Systems (GISs).

Agroclimatic and land suitability indices have been employed extensively in the assessment of the impacts of climatic change on agriculture. By altering one or more of the variables in the index, spatial and/or temporal shifts in the tolerable limits of production can be determined. For example, Norman (1980) and Blasing and Solomon (1983) used GDD and potential evapotranspiration to study possible shifts in the North American Corn Belt due to arbitrary changes in climate. Rosenzweig (1985) estimated shifts in the production areas of North American wheat cultivars (e.g. spring to winter; hard to soft) based on GCM-generated 2 X CO₂ climatic scenarios.

In the Mackenzie River Basin, two recent studies have examined the changes to land suitability under 2 X CO₂ climatic scenarios. Mills (1994) correlated the results from several land suitability studies to estimate the changes in land suitability. That study concluded that the area of potential arable land in the region could increase from an estimated 15.3 million ha to 15.5 million ha (p.122). Brklacich and Curran (1994) applied a cereal crop land rating scheme to the Mackenzie Basin. Land suitability was estimated for a baseline weather record (1951-81) and compared to the land ratings calculated assuming 2 X CO₂ climate conditions predicted using selected GCM outputs. This helped identify areas where agricultural suitability would change under future climate conditions.

Crop productivity can be indirectly inferred or estimated from agroclimatic or land suitability indices either by intuitive estimates based on the "known or assumed relationships" between crop performance and observed conditions, or from statistical regression models which relate empirical yield data to selected factors in the index (van Diepen et al. 1991, p. 178). Under changing climatic conditions, these indices can be useful in determining the direction of change, if any, in crop productivity. For example, if an area was classified as "unsuitable" under the baseline conditions, and "suitable" under a climate change scenario, it could be reasonably concluded, *ceteris paribus*, that crop productivity in that area will increase. However, it is difficult to determine the magnitude of any changes using this approach without the support of empirical production data.

In many areas of the Mackenzie Basin this data does not exist, and could only be provided through long-term experimental field trials or by the use of a crop-yield model. In addition, while this approach can capture changes in productivity due to changing climatic conditions, it cannot be used to determine the direct effects of an increase in the atmospheric concentration of CO₂ on plant growth. These effects, as stated earlier, can have a significant impact on crop productivity. Agroclimatic and land suitability indices do not provide a means for addressing the impacts of elevated levels of atmospheric CO₂ and associated climatic change on productivity and, therefore, these methods are not suitable for use in this study.

2.2.3 Crop-yield modelling

A crop-yield model expresses crop productivity, or yield, as a function of the physical interaction of a crop with its surrounding environment. The approaches to crop-yield modelling can be categorized into three groups (after Baier 1979; McBride 1984; and Rosenzweig 1986):

- i. Crop-growth simulation models;
- ii. Empirical-statistical models; and,
- iii. Crop-growth analysis (or crop-weather) models.

A short overview and appraisal of each of these approaches to crop yield modelling follows.

i. Crop-growth simulation models are mathematical representations of plant-environment interactions based on controlled atmosphere studies or available knowledge of a particular process (Baier 1979, p. 140). This is a process-oriented approach which focuses on how environmental factors, such as temperature and radiation, affect photosynthesis and transpiration and other plant processes. The direct effects of increases in CO₂ on plant growth have been modelled based on controlled atmosphere experiments (e.g. Goudriaan 1990; Lawlor et al. 1993). Historic climate regimes and climate regimes from climate change projections have rarely been used in the development of this type of model (Rosenzweig 1986, p. 78). Simulation models, therefore, are limited in their ability to reflect long-term fluctuations in crop productivity due to year-to-year variations in climate. In addition, to fully address the issues in this study, an extensive set of controlled experiments would have to be set up to

represent the current and predicted conditions at each site in the study area from which simulation models could be generated. This was not practical for this study.

ii. Empirical-statistical models attempt to establish a statistical relationship between recorded yield data from an area and predictor variables such as weather, soil characteristics, and management practices from the same area. Multiple regression analysis is one technique often employed in this approach. Williams (1975) and Baier (1973) used this type of analysis to model wheat yields in Canada. The results of this "black box" approach are not necessarily based on the cause-and-effect relationship between the crop yield and the factors included in the equation (Parry 1990, p. 33). There is also concern over the independence, or lack thereof, between predictor variables, particularly those related to climate, which may influence the variances in the estimated regression coefficients (McBride 1984, pp. 4-5). Even when a sound relationship has been established, that is, the model can consistently and accurately predict yields, the relationships tend not to hold firm outside the area tested (Baier 1979, p. 141). For these reasons the method's applicability to climate change and crop productivity research has been questioned. Further, there is no evidence in the literature to suggest that this method can be used to evaluate the direct effects of elevated levels of atmospheric carbon dioxide on crop yields.

iii. Crop-growth analysis (or crop-weather) models represent a system-oriented approach to crop-yield modelling. These models integrate chrono-

logical or phenological timescales with weather and other yield-determining factors, such as soil moisture and soil bulk density, to predict crop development, growth, and, eventually, yield. Since these models are driven by weather variables, usually temperature, precipitation, and solar radiation, and incorporate simplified models of plant processes, they can be used to study crop responses to both the direct effects of an increase in the level atmospheric CO₂ and the indirect effects of climate change (Rosenzweig 1986, p. 81). They necessarily include some of the features used in the other crop-yield approaches but are less disaggregated than crop-growth simulators, and provide a better representation of the statistical variability of biological responses to external environmental conditions than empirical-statistical models (McBride 1984, p. 6). Crop-weather models tend to have more demanding requirements for data inputs and data processing than the other approaches to crop-yield modelling. Their level of sophistication and robustness, and their use in general, has been greatly facilitated by advances in computer technology and the development of related software packages. Several major studies into the effects of increases in atmospheric carbon dioxide and climate change on agriculture, including Rosenzweig and Iglesias (1994) and Rosenzweig and Parry (1994), have used crop-growth models as their primary analytical tool.

2.3 Method selection

Section 2.2 outlines limitations and advantages associated with 3 approaches which have been used to assess climatic change-agricultural potential relationships. The purpose of this study is to analyze the potential combined effects of increased concentrations of atmospheric carbon dioxide and climate change on crop productivity levels. Analogue approaches, land suitability and agroclimatic indices, and the empirical-statistical approaches to crop modelling fail to fully capture the potentially significant direct effects of an increase in the atmospheric concentration of CO₂ on plant growth, and therefore, are not suitable for application in this study.

Crop-growth simulation models and crop-weather models both can provide estimates on the direct effects of CO₂ enrichment on plant growth. However, only the crop-weather models can also incorporate predicted future climate regimes into its yield estimates. This is significant because, as stated earlier, climate an important factor limiting agriculture in the study area, and climate change is expected to be pronounced in the upper latitudes. Since crop-weather, or crop-growth analysis models provide a direct measure of crop productivity, capture the direct effects of CO₂ enrichment on plant growth, operate with historical or predicted weather regimes, and consider the environmental and management factors of crop production, the use of this type of model is the most appropriate approach to the research questions at hand. For the remainder of this research crop-weather models will be referred to as simply "crop models".

3.0 IMPLEMENTING THE MACKENZIE BASIN CASE STUDY

3.1 Research Framework

Chapter 2 identified some of the impacts that elevated levels of atmospheric CO₂ and climatic change could have on agriculture, and determined an appropriate method to quantify these impacts. This chapter will explain the research framework (refer to Figure 2), describe data requirements and procedures, and state the assumptions made during the course of the analysis. The key elements of this research will be: weather data (baseline and predicted), soil characteristics, management variables, and levels of CO₂ concentration. A crop model will be used to analyse this data and estimate changes in crop productivity, in terms of total grain weight and changes to biomass accumulation. In addition, agroclimatic factors, such as planting dates, days to maturity, and crop moisture stress, will be assessed.

3.2 Ecoclimatic Regions and Agriculture in the Basin

Ecoclimatic regions (ECRs), as defined by Environment Canada, are "gradients of ecologically effective macroclimate (as expressed by vegetation)" (1989, p.1). That is, a particular set of macroclimatic conditions are associated with each ECR. The deliniation of the Basin in terms of macroclimate, as indicated by the ECRs, is a convenient basis for assessing the impacts of climate change on agriculture in the region. Spatial differences in the agricultural response to climate change should be evident with this classification.

A wide range of ecoclimatic regions are found in the Basin; from the Arctic ECR, characterized by treeless tundra in the north, to the edge of the Grassland ECR in the south of the Basin, however, the vast majority of the Basin lies within the Boreal ECR. All of the sites selected for this study fall into the "Boreal " ecoclimatic province, or group of regions, of which there are three primary regions evident in the Basin: the Subhumid High Boreal (HB); the Subhumid Mid-Boreal (MB); and, the Subhumid Low Boreal (LB) (See Figure 3). As the name "Boreal" suggests, the natural vegetation in these regions is dense conifer or conifer-hardwood mixed forests. Continentality strongly influences these subhumid boreal regions, resulting in mid-summer peaks in both temperature and precipitation (Environment Canada 1989, p.5). The transition from the HB to the LB is characterized by longer summers and higher mean temperatures. Currently, commercial cereal production occurs primarily in the main river valleys of the LB. The Peace River region is the main farming area in the Basin with 1.2 million hectares of land currently in agricultural production (Agriculture Canada 1986). Wheat and barley have traditionally been the key cash crops in the area, while canola has become increasingly important in the last 10 years. During the 1980s an average of 335,800 ha of barley and 383,100 ha of wheat were seeded in the Peace River region of Alberta and British Columbia (Agriculture Canada 1986 and 1990). Even in these areas, the soils do not have a naturally high nutrient content and commercial fertilizers are used to maintain productivity (See Section 3.5.5). The main focus of farming in the MB is on forage and pasture production, while only

a small area in the HB is devoted to any cereal production (Statistics Canada 1993).

Figure 3. Ecoclimatic Regions and Indicator Sites
In the Mackenzie Basin.

Notes: S = Subarctic ECR
 C = Cordilleran ECR
 HB = High Boreal ECR
 MB = Mid-Boreal ECR
 LB = Low Boreal ECR

3.3 The Crop Models

3.3.1 Overview

The CERES-Wheat and CERES-Barley crop models were employed in this study. A complete description of the Crop-Environment Resource Synthesis (CERES)-Wheat crop model can be found in Godwin et al. (1989) and CERES-Barley is described in Otter-Nache et al. (1991). These models include components that simulate 3 key processes: the water balance, growth and development, and the nitrogen balance. Potential evapotranspiration (PET), drainage, runoff, and infiltration, and the effects of water deficits on plant growth are considered in the water balance component. The effects of nitrogen deficits on plant growth are also calculated based on factors such as nitrogen uptake and leaching. The nitrogen and water balances are integrated with the growth and development processes. Photosynthesis, radiant energy interception, photoperiod, and temperature are included in the growth and development component. Phenological development in these models is based on the accumulation of daily thermal time (DTT) and they simulate dry matter production and leaf, root, and cereal growth based on the environmental factors used as input (Jones et al. 1983).

These models have been incorporated into the Decision Support System for Agrotechnology Transfer (DSSAT) software package. This package includes a database management system that facilitates the entry and maintenance of soil, weather, crop management, and experimental and crop trial data. They have been widely tested and validated, and can provide sound

predictions of crop performance irrespective of season or location (IBSNAT 1993, p.23). Fei and Ripley (1985) and Brklacich et al. (1994) have employed the CERES-Wheat model to study wheat yields in some of the major wheat growing regions on the Canadian Prairies.

3.3.2 Crop Model Testing

Long term yield data are not readily available for a wide range of sites throughout the Mackenzie Basin, and, therefore, it was not possible to calibrate the crop models under the full set of environmental conditions represented in the Basin. The most reliable crop trial data was based on 1981-85 data collected at, or near Beaverlodge, Fort Vermilion, Keg River, and Fort St. John. Estimated yield averages were based on the test results for the 5 main barley varieties (Otal, Johnson, Bonanza, Klages, and Diamond) which accounted for 76% of the barley acreage in the Peace River Region, and the 4 main spring wheat varieties (Neepawa, Park, Katepwa, and Columbus) which accounted for 84% of the wheat acreage in the region (Agriculture Canada 1986 and 1990). A provincial average was used for the estimated days to maturity for barley, while an estimate derived from Bootsma and deJong (1988) for Ft. Vermilion was applied for wheat. This information was compared to the averages generated by the crop models, which were calculated using 1951-80 daily weather records. Management variables, including the rates of fertilizer application, were fixed at 36 kg/ha of nitrogen to reflect known practices (See Section 3.5.5). The results of these comparisons are found in Table 1.

The model appears to reproduce the actual yields for both crops quite well at most sites. Many factors may have contributed to the discrepancies between the observed and model-generated yields. For instance, the model was run on point data for weather, and soil and management factors were fixed over the course of the analysis, and the recorded yields are an average derived from a number of test plots located throughout each area. In addition, the management factors, including seed variety selection, and soil conditions will vary over time. Other impacts not captured in the model that may influence the results include field and crop conditions at harvest, and the effects of pests and diseases. However, given the results of these comparisons, it was concluded that the models should be able to provide a reasonable indication of the direction and magnitude of changes in the number of days to maturity and crop yields due to climate change and CO₂ enrichment. By extension, it was assumed that the models could also provide a reasonable indication of the impacts that changing conditions will have on planting date, crop moisture stress, and the ratio of grain weight to canopy weight. These variables are also examined, but no comparable historic data was available.

Table 1. Comparison of the CERES Crop Models Relative to Existing Conditions in the Mackenzie Basin.

SITE	WHEAT		BARLEY	
	Days to Maturity*	Yield kg/ha‡	Days to Maturity**	Yield kg/ha‡
BEAVERLODGE				
Estimated	119	2914	97	4005
CERES	123	4592	114	5117
% Difference	3	58	15	28
FT. VERMILION				
Estimated	119	2526	97	2907
CERES	113	2246	103	2471
% Difference	-5	-11	6	-15
FT. ST. JOHN				
Estimated	119	2917	97	4159
CERES	118	3330	109	3655
% Difference	1	14	11	-12
KEG RIVER				
Estimated	119	3924	97	4272
CERES	120	3754	110	4203
% Difference	1	-4.5	12	-2

* Derived for Ft. Vermilion by Bootsma and de Jong 1988

** Provincial average based on field test results for 5 main varieties in Peace River Region (Agriculture Canada 1986 and 1990).

‡ Average of field test results for 5 main varieties in each area (Agriculture Canada 1986 and 1990).

3.4 Selection of Indicator Sites

This study used several sites throughout the Basin to provide an indication of the possible impacts of climate change on crop yields. In order to adequately capture the year to year variations in yield, it was decided that the daily weather record should be at least 25 years in length. The availability of daily weather data, therefore, was the determining factor in site selection. The weather records maintained by the Atmospheric Environment Service (AES), Environment Canada were screened to find sites within the Basin that met this criterion. The original search yielded 28 sites, but upon closer examination several years of data had to be discarded from some sites, and some sites had to be discarded altogether due to missing data. Peace River, which had less than 25 years of daily weather records, was included in the study in order to increase the spatial coverage of the study and because it is an area of known agricultural activity. The net result of this data search was 15 sites over a study area covering approximately 1.8 million km² (see Figure 3).

A greater spatial coverage of the study area would have been desirable, but due to several factors this was not possible. Nonhebel (1990, p.49), in modelling wheat yields in France and the Netherlands, found that the results were very sensitive to the weather data used as input. Due to microclimatic influences, some yield simulations differed by more than a tonne from actual yields even though the test sites were in close proximity to the weather recording station. One of the conclusions of Fei and Ripley (1985) was that their model could not capture the wide range of weather and soil conditions in

the study area. This likely accounted for some of the differences between the observed and simulated yields. For these reasons, it was decided to limit the analysis to the area immediate to the weather station.

3.5 Development of Crop Model Runs and Input Data

3.5.1 Crop Model Runs

Table 2 outlines the data inputs to various crop model runs which portray a range of conditions for atmospheric CO₂, climate, and fertilizer applications. At each indicator site, the wheat and barley crop models were run under 10 sets of conditions. Runs 1 and 2 depict current (baseline) conditions given 2 levels of fertilizer application. Runs 3 and 4 assume atmospheric CO₂ concentration increases to 555 ppm but the current climate prevails. Effectively, these model runs address concerns that increases in atmospheric CO₂ concentration might not alter climate on a global scale. Then in model runs 5-10, it is assumed that the changes in atmospheric CO₂ will alter climate, and the uncertainties regarding possible changes in the long term climate are captured to some extent by employing 3 scenarios for climatic change (see Section 3.5.3.2). The Composite scenario, based on Stewart (1993) is used for runs 5 and 6. Runs 7 and 8 are based upon the estimates of the equivalent of a 2XCO₂ atmosphere on climate as generated by the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model (GCM). Whereas run 9 and 10 are derived from the application of the Canadian Climate Centre (CCC)

GCM. Overall, the wheat and barley crop models were run a total of 20 times at each of the 15 sites.

Table 2. Components of the Crop Model Runs for Wheat and Barley.

Run No.	Atmospheric CO ₂ (ppm)	Climate Regime	Nitrogen (kg/ha)
1	360	Baseline	36
2	360	Baseline	50
3	555	Baseline	36
4	555	Baseline	50
5	555	Composite	36
6	555	Composite	50
7	555	GFDL	36
8	555	GFDL	50
9	555	CCC	36
10	555	CCC	50

Note: Soils and cultivars were considered constant for all runs.

3.5.2 Current and Predicted Levels of Atmospheric CO₂

As outlined earlier in the paper, the concentration of CO₂ in the atmosphere directly influences the rate of photosynthesis and the water use efficiency (WUE) of plants. Increasing the level of atmospheric CO₂ can be beneficial to plant growth. Based on the data published by the World Resources Institute (1993, p.205), the current level of carbon dioxide in the atmosphere is approximately 360 parts per million (ppm). The outputs of the climate scenarios suggested above are based on "equivalent" 2 X CO₂ conditions. Because of the contributions to the GHE of other trace gases, including CFCs,

N₂O, and CH₄, the climatic change associated with these scenarios may occur well before the atmospheric concentration of CO₂ actually doubles. In crop model simulations, such as this study, in which the direct effects of CO₂ enrichment are considered, a level of 555 ppm is often applied (Rosenzweig and Parry 1994, p. 133).

3.5.3 Weather

3.5.3.1 Baseline data set (1951-80)

Weather conditions at particular stages of plant development and growth will have a direct impact on crop productivity. A baseline data set consisting of actual daily weather values (minimum and maximum temperature, precipitation, and solar radiation) was used to allow the crop model to reflect these impacts. Daily weather records for 1951-80 were used as the baseline for the following sites: Ft. Reliance, Yellowknife, Ft. Smith, Hay River, Ft. Nelson, Ft. Vermillion, Keg River, Ft. St. John, Beaverlodge, Grande Prairie, Campsie, and Sion. For Ft. Resolution, Peace River, and Whitecourt, the longest weather records that could be obtained were 24, 21, and 28 years, respectively.

Many of the weather records contained missing data. This ranged from the odd day to entire months. To deal with this problem, a simple procedure was employed to ensure that actual recorded values were preserved whenever possible in the weather record. The following rules were applied for minimum and maximum temperature: if the number of consecutive days of missing data was less than 7, the values were linearly interpolated; if there was 7 or more

consecutive days of missing data, that entire month of data was discarded and was replaced by data for the same month from a randomly selected year in that weather record. It was possible to do this because it was found, statistically, that the weather of any particular month is not influenced by the weather in the preceding month (Curran, 1995, pers. comm).

If there were 7 or more consecutive days of missing precipitation data, the same rule was applied as above: that month's data was replaced. For cases where less than 7 days of precipitation data were missing, the number of recorded precipitation events was compared to the 30 year normal of precipitation events for that month. If the recorded number was greater than the normal, the missing values were assigned a value of zero. If it was less, the average recorded precipitation per precipitation event was calculated for that month and that amount was allocated to each missing day. Again, the goal of this approach was to rely as much as possible on the actual weather record: if a 30-day month contained the allowable maximum of 6 missing data values for any or all of the variables, 80 per cent of the data would still be actual recorded data.

Solar radiation data is not collected regularly at most sites. Daily values of solar radiation were calculated using a method developed by deJong and Stewart (1993). This method employs temperature and precipitation data, and was originally developed and tested using data from seven wheat growing areas in Western Canada. This method relates the ratio of global solar radiation at the Earth's surface (Q) to solar radiation at the top of the

atmosphere (Q_0) to daily observations of maximum and minimum air temperature ($T_{\max}(j)$, $T_{\min}(j)$) and total precipitation (P):

$$Q/Q_0 = a(\Delta T)^b (1 + cP + dP^2)$$

where: a, b, c , and d are empirical coefficients

at each site which vary with time of year; and,

$$\Delta T = T_{\max}(j) - (T_{\min}(j) + T_{\min}(j+1))/2$$

The value of Q_0 , which varies with the day of year and latitude, was taken from tables compiled by Russelo et al. (1974). Q was then determined for each day of the weather record at each site.

The values for the empirical coefficients at the Beaverlodge site were assumed to be most appropriate for use in this particular study area (de Jong 1994, pers. comm.). deJong and Stewart (1993) also found that with the CERES crop model there was no significant difference between wheat yields estimated using solar radiation data calculated in this way and wheat yields estimated using observed solar radiation data.

3.5.3.2 Climatic change scenarios

This study employed two methods which are often used in predicting weather conditions under an equivalent 2 X CO_2 climate scenario. The first set of scenarios was derived from the output of two general circulation models (GCMs): the Canadian Climate Centre (CCC) GCM (AES 1991), and, the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Manabe and Wetherald 1987). GCMs, using the laws of physics, simulate the major mechanisms that

control the global climate system, although these are highly simplified representations of an extremely complex set of relationships. The usefulness of GCMs lies in their ability to provide plausible climate "scenarios" based on variations of some key variables that may influence long term weather patterns, e.g. the atmospheric concentration of CO_2 . For an in depth description of GCMs see Environment Canada (1994) **Modelling the Global Climate System**.

Changes in monthly weather variables, that is, the difference between 1 X CO_2 conditions and 2 X CO_2 conditions, are calculated for a selected grid of latitude-longitude positions on the Earth's surface. For each site in this study the closest GFDL and CCC grid points were determined and the differences in monthly mean temperature and percentage change in precipitation were calculated. The spacing of this grid of points, which varies between GCMs, indicates of the spatial resolution of the GCM (see Table 3). The ability of these models to capture local, or even regional variations in climate is somewhat limited by the coarseness of these grids.

Table 3. Spatial Resolution (Latitude X Longitude) of the General Circulation Models used in this Study.

MODEL	SPATIAL RESOLUTION
Geophysical Fluid Dynamics Laboratory (GFDL)	4.5° X 7.5°
Canadian Climate Centre (CCC)	3.75° X 3.75°

An alternate climate scenario for the Mackenzie Basin has been developed and will be employed in this study. It is based on the expert opinion of several climatologists familiar with the climate of the Basin and the results of GCM outputs for the region and is referred to as the "Composite" scenario (Cohen

1993, p.123). Historical analogues and the paleoclimatic records were also considered in the development of this scenario. Possible weather regimes were developed for the southern Basin (below 57°N , approx.), the Mackenzie Valley (57°N to 67°N , approx.), and the northern Basin (above 67°N). Changes under the Composite scenario were applied to the weather data set at each site based on which of these regions the site was located.

Figures 4 and 5 indicate the monthly means for temperature and precipitation, respectively, based on the 1951-80 weather record and the change in these means under the climate change scenarios at 6 sites in the Basin. This information for the other 9 sites can be found in Appendix A. Both GCMs indicate a general increase in monthly mean temperatures, ranging from approximately 2.5 to 5.5°C during the growing season. The magnitude of these changes, in general does, not appear to differ greatly between the sites in the southern Basin and those further north; for example, compare Beaverlodge (55°N) and Ft. Nelson (58°N). Under the composite scenario, temperatures in the southern Basin are expected to increase by an average 3.5°C in the winter and 1.0° in the summer months, and greater increases will be experienced at higher latitudes in the Basin.

Precipitation estimates vary widely between the GCM scenarios, with the GFDL results tending to be more variable and extreme. At Beaverlodge, for example, the percentage change in precipitation for the months of May, June, July, and August under the GFDL model were -18, 25, 94, and -34%

respectively. For the same four months the CCC estimates were 3, -9, 9, and 15% respectively. While there was a general indication from both models that overall precipitation would increase, it is significant to note that most decreases in precipitation tended to occur between April and September. The composite scenario predicts that precipitation will be lower by 15% in all summer months except in April where precipitation may rise due to an earlier spring. Precipitation is expected to increase slightly further north under composite conditions.

Monthly changes to the weather variables under each of these climate scenarios were applied to the daily baseline data record at each site. Since the scenarios only provide changes to the monthly mean temperature this change was applied equally to the mean and maximum temperatures. The estimated changes in solar radiation under each $2XCO_2$ scenario are very small (Brklacich et al. 1994, p. C-6), therefore, for this study, solar radiation was assumed to be unchanged between current and possible future climatic conditions.

Figure 4. Monthly Temperature Means (1951-80) and Change in Means Under Climatic Change Scenarios for Yellowknife, Ft. Nelson, and Beaverlodge.

Figure 4 continued. Monthly Temperature Means (1951-80) and Change in Means Under Climatic Change Scenarios for Hay River, Ft. Vermilion, and Whitecourt.

Figure 5. Monthly Precipitation Means (1951-80) and Change in Means Under Climatic Change Scenarios for Yellowknife, Ft. Nelson, and Beaverlodge.

Figure 5 continued. Monthly Precipitation Means (1951-80) and Change in Means Under Climatic Change Scenarios for Hay River, Ft. Vermilion, and Whitecourt.

3.5.4 Soils

Soil characteristics at each of the selected sites were obtained from the soil carbon data base (Agriculture Canada 1993) using the latitude-longitude position of each weather station. The basis of the soil carbon data base is the 1:1 million Soil Landscape of Canada (SLC) maps. In this study, only the dominant soils were included in the analysis. Information necessary for input into the crop-weather model was extracted from data base and the appropriate soil files were constructed. Texture, bulk density, organic carbon, pH, coarse fractions, layer thickness, and soil classification were included in these files. A general soil description for each site is provided in Table 4.

A wide range of soils are found throughout the Basin, however, some generalities are evident:

- the HB sites are very stoney;
- the HB and MB sites have soils that are poorly drained with shallow rooting depths relative to the soils at most of the LB sites; and,
- brunisolic soils are present at both HB sites and luvisolic and chernozomic soils dominate the LB sites.

Table 4. General Soil Descriptions.
(Source: Agriculture Canada 1993.)

ECR/ Site	Lat(N), Long(W); Elevation	Texture	Slope (°)	Drainage	% Coarse Fractions	% Organic Carbon	Bulk Density	pH	Rooting Depth	Soil Order
HBs										
Ft. Reliance	62.4.109.1; 164m	Loamy sand	4-9	Imperfect	30-65	0.3	1.36	5.0	20-75	Brunsollic
Yellowknife	62.3.114.3; 205m	Sand	4-9	Imperfect	10-30	0.1	1.36	6.0	20-75	Brunsollic
MBs										
Hay River	60.5.115.5; 164m	Loamy sand	<4	Imperfect	<10	0.3	1.40	6.5	20-75	Gleysolic
Ft. Nelson	58.5.122.4; 382m	Clay loam	4-9	Moderate	<10	0.8	1.47	6.0	20-75	Gray luvisolic
Ft. Resolution	61.1.113.4; 164m	Silty Clay	<4	Imperfect	<10	0.9	1.28	6.5	20-75	Regosolic
Ft. Smith	60.0.111.6; 203m	Loam	<4	Poor	<10	0.8	1.30	6.5	20-75	Gleysolic
LBs										
Ft. Vermilion	58.3.116.0; 280m	Sand	<4	Rapid	<10	0.3	1.50	6.0	75-150	Gray luvisolic
Beaverlodge	55.1.119.2; 762m	Clay	<4	Well	<10	0.6	1.49	6.0	75-150	Black chernozomic
Whitecourt	54.1.115.5; 740m	Sandy loam	<4	Rapid	10-30	0.2	1.40	6.0	75-150	Regosolic
Campsie	40.114.4; 670m	Loam	10-15	Well	<10	0.5	1.47	6.5	75-150	Black chernozomic
Ft. St. John	56.1.120.4; 694m	Clay	4-9	Moderate	<10	0.6	1.49	6.5	20-75	Gray solonetzic
Grande Prairie	55.1.118.5; 669m	Clay	<4	Well	<10	0.6	1.49	6.0	75-150	Black chernozomic
Keg River	57.5.117.5; 428m	Loam	<4	Well	<10	0.2	1.45	6.5	75-150	Dark Gray luvisolic
Peace River	56.1.117.3; 571m	Hard Clay	<4	Well	<10	0.6	1.50	6.0	75-150	Dark Gray luvisolic
Sion	53.5.114.1; 706m	Clay loam	10-15	Well	<10	0.3	1.55	6.5	20-75	Brunsollic

3.5.5 Management Variables and Cultivars

Though many varieties of each crop are grown in the study area, only one variety of each was selected for analysis: Manitou wheat and Robust barley. The use of one variety for all sites facilitated analysis by eliminating concern over variation due to crop variety. Further, some of the differences in crop performance between varieties, such as susceptibility to lodging, are not considered in the CERES models. Many of today's wheat varieties grown in the region have been derived from the Manitou variety and it has been used as a representative variety in previous studies (Brklacich et al. 1994). Robust barley, a six row malting variety, was selected because it too has genetic coefficients that are similar to many of the varieties of barley currently grown in the region (Jedel 1995, pers. comm.).

The application of fertilizer, particularly nitrogen, on commercial crops is considered very important for most regions in the Basin (BC Ministry of Agriculture 1977). The recommended levels of application for cereals in the Basin, including wheat and barley, are 34 kg/ha of phosphorus (P), and 22 to 50 kg/ha of nitrogen (N). For this study, the crop model was run with two treatments of fertilizer in order to bracket a wide range of possible application rates: A. 36 kg/ha N, 34 kg/ha P; and, B. 50 kg/ha N, 34 kg/ha P. As recommended, the higher rate of nitrogen was applied by broadcasting while the lower rate was applied with the seed. Fertilizer was applied at the time of seeding and crop residue was disced in prior to planting. Since the crop model showed little sensitivity to the different fertilizer applications, only the results of the 36 kg/ha N

will be presented in this thesis. Results of the 50 kg/ha N experiments are available, on request, from the author.

Once air and soil temperatures are above 0 °C plant growth will occur, though most measures of heat accumulation commence only after daily air temperature averages 5 °C for 5 consecutive days (Dzikowski and Heywood 1990, p.12). Planting dates for the model were set to occur automatically anytime after the 91st day of the year (April 1st or 2nd), but before day 156 (June 4th or 5th) once the soil temperature had risen to 5 °C. The models calculated soil temperature only as it related to seeding conditions. Low soil temperatures throughout the entire rooting zone were not considered to be a limiting factor for two reasons: first, most of the sites selected are located in the southern portion of the Basin, where low soil temperatures or permafrost conditions are not currently a factor; and second, it is recognized that the "steady state" climatic change scenarios used in this study may not occur until the latter half of the next century. The cumulative effects of increasingly warmer conditions leading up to the scenarios may remove soil temperature constraints that currently exist. A planting depth of 4 cm was selected based on Hud and Baker (1990), and the planting rate of 390 plants per square metre was taken from a previous crop model study in the area (Brklacich et al. 1994).

4.0 IMPACTS OF ATMOSPHERIC AND CLIMATIC CHANGE ON AGROCLIMATIC VARIABLES IN THE MACKENZIE BASIN

This chapter summarizes the estimated impacts of potential atmospheric and climatic changes on agroclimatic variables in the Mackenzie Basin, and discusses the implications of these estimated impacts on the future prospects for the agricultural sector in the Basin. The agroclimatic variables considered are planting date (PD), days to maturity (DTM), and crop moisture stress (CMS).

For high latitude areas, like the Basin, earlier planting dates may indicate a longer frost-free period, which, in turn, may lead to greater agricultural opportunities. Warmer conditions during the growing season will speed plant development and the plants will reach maturity in a shorter period of time. However, under these conditions, fewer days to maturity could result in a shortening of the reproductive phase of crop development, which, in turn, may have a negative impact on grain weight at harvest. In carbon dioxide enriched environments, it has been demonstrated that water use efficiency (WUE) of plants increases and improved WUE can alter the potential for CMS. Overall, the analysis of PD, DTM, and CMS provides insight into a wider range of factors which influence crop productivity.

Detailed findings at all 15 sites, for both wheat and barley, are presented in Appendix B. To assist with the presentation of the results, Chapter 4 focuses on 6 sites, one crop (wheat), and one fertilizer application (36 kg/ha N). It was found that the responses of wheat and barley to atmospheric and climatic

changes were similar, and that the 2 rates of fertilizer applications considered in this study did not significantly affect the crop modelling results.

The 6 sites selected are Yellowknife NWT, Hay River NWT, Ft. Nelson BC, Ft. Vermilion Alta., Beaverlodge Alta., and Whitecourt, Alta. . These sites were selected as they represent sites which:

- are in current agricultural regions or are on soils that could potentially support agriculture;
- are distributed across the three major ECRs (Subhumid High Boreal (HB), Subhumid Mid-Boreal (MB), and Subhumid Low Boreal (LB)) in the Mackenzie Basin which could potentially support commercial agriculture; and,
- had 30-year baseline weather records available (with the exception of Whitecourt, where a 28-year record was employed), and thereby provide insight into the possible temporal distribution of impacts on agroclimatic variables.

Following a brief summary of the agroclimatic variables under baseline conditions, each subsection discusses the results from 3 perspectives: an enriched CO₂ perspective¹, an atmospheric and climate change perspective, and a spatial perspective. The analysis presents estimated changes from the mean value for each agroclimatic variable, and changes in variability. Variability

¹ Planting Date and Days to Maturity are not sensitive to CO₂ changes, and therefore, Sections 4.1 and 4.2 do not address this perspective.

is estimated as the range in annual values that were calculated over a 30 year period. To reduce the possibility of being misled by highly anomalous events, the extreme 10% of each end of the range of values was eliminated and, therefore, the range reported in these analyses represents the values that could be expected 8 years out of 10. Cumulative frequency graphs are used to display the findings and only years where the crop reached maturity are included in the presentation.

The enriched CO₂ perspective is based upon the carbon dioxide concentration of 555 ppm and is presented immediately after the subsection summarizing conditions under the baseline climate. This departure point stems from the overwhelming evidence that human activities have altered and will continue to alter the atmospheric concentration of CO₂. However, there is less certainty about the extent to which the changes in the atmosphere will alter global and regional climates. Hence it is logical to start the assessment with the comparison of the agroclimatic factors under baseline to 2XCO₂ conditions, and to then to move onto the cumulative impacts of 2XCO₂ and climate change.

Three climatic change scenarios, Composite, GFDL, and CCC, which are summarized in Section 3.5.2, are employed to capture some of the uncertainty with respect to future climates at global and regional levels. The analyses in the CO₂ enriched and the atmosphere-climatic change perspective focus on the differences in the estimated impacts amongst the climatic change

scenarios, illustrating the sensitivity of the selected agroclimatic variables to the specified scenarios for climatic change.

Each subsection concludes with an assessment from a spatial perspective. These analyses are aimed at detecting if the estimated impacts are distributed uniformly amongst the 3 ECRs, or whether the impacts are greater in one of the ECRs with respect to the others.

4.1 Planting Date (PD)

Baseline Conditions

In the boreal regions of the Basin, where the study sites are located, the current frost-free period is relatively short and spring-seeded cereals must be planted at the earliest possible date. Planting Date (PD) is calculated by the model on the basis of soil temperature as estimated from air temperatures, and soil moisture levels, and represents the earliest opportunity for seeding.

The mean planting date under current conditions varies considerably throughout the Basin, ranging from April 27 to May 1 (day 116-120) in the LB to May 14 (day 133) in the HB (Figure 6). However, interannual variability in the range of planting dates is similar at most of the sites. At all sites except Hay River, the estimated PD is within ± 13 to 16 days of the mean 90% of the time. For Hay River, the range is somewhat greater, with PD being within ± 19 days of the mean.

A Climatic Change Perspective

All three climatic change scenarios imply an earlier PD, although the magnitude of these impacts is not uniform across the scenarios. Generally, mean PD is least sensitive to the climatic changes specified under the GFDL scenario; relative to the baseline conditions, the GFDL estimated mean PD is typically 7 -10 days earlier. A mean PD that occurs 12-16 days earlier than the current estimate is characteristic of both the CCC and Composite scenarios. This appears to be due to the fact that, relative to the other scenarios, the GFDL tends to predict higher precipitation rates from January-March, yet predicts much smaller increases in the mean temperatures over that same period (See Figures 4 and 5).

LOW BOREAL ECR: FT. VERMILION

LOW BOREAL ECR: BEAVERLODGE

LOW BOREAL ECR: WHITECOURT

The result is wetter and cooler soil conditions in the early spring and later planting dates relative to the other scenarios. Therefore, the estimated advance in the mean PD is more pronounced under the CCC and Composite than under the GFDL scenario.

While the GFDL scenario implies the least change in the mean PD, it also implies the largest change in PD variability. It is estimated that the GFDL scenario would widen the window for seeding by about 1 week, whereas adjustments to variability would be less pronounced under the CCC and Composite scenarios. This increased variability may not represent increased opportunity under the GFDL as much as it is a reflection of the spring conditions outlined above. That is, the soil requires a longer period of time to become fit for planting relative to the other scenarios. This is apparent in Figure 6 which indicates that the differences in the planting date range between the GFDL and the other scenarios tend to be greatest later in the planting season.

From a PD perspective, the CCC and the Composite scenarios offer greater enhancement to opportunities for spring-seeded cereal production. Earlier seeding dates of about 2 weeks would help offset the crop production constraints imposed by relatively short frost-free seasons. Benefits stemming from earlier PDs would also be expected under the GFDL scenario, but advances in the PD under this scenario would be limited to 7-10 days on average.

A Spatial Perspective

It would appear that the estimated changes for PD across the selected sites do not present a readily identifiable spatial pattern under the 3 selected scenarios for climatic change. Under the CCC scenario, the largest advances in PD mean tend to occur in the LB ECR, whereas the more substantial advances in mean planting date under the Composite scenario are associated with the HB and MB ECRs. Overall, this suggests that changes in PD stemming from different climatic change scenarios obscure any influence of the location of the selected sites.

4.2 Days to Maturity (DTM)

Baseline Conditions

To reach maturity, a cereal crop must receive a specific amount of heat. At higher latitudes, where the growing season is shorter, accumulation of adequate heat can be a problem. Any reduction in the DTM can translate into earlier harvests, and thus reduce the risk of the crop being damaged by early fall frost. However, fewer DTM also implies more rapid plant development and a shortening of the plant's reproductive phase, potentially resulting in lower grain weights (Section 2.1.2.4). Figure 7 displays the impacts of varying climatic and atmospheric conditions on the days to maturity.

Under baseline conditions, the model calculated that the means for DTM ranged from 113 to 128 days at the selected sites. From a spatial perspective, the uncertainty of cereal crops reaching maturity was greatest at the northern

most sites where, over the 30-year weather record, there was a 0.1 and a 0.3 probability that the wheat crop would not mature at Hay River and Yellowknife, respectively. Compared to Yellowknife and Hay River, the variability in the range in DTM at the other sites was much smaller, being within ± 9 to 13 days of the mean at the other sites.

Overall, these findings illustrate current constraints on the potential for commercial cereal production in the Mackenzie Basin. The southern reaches of the Basin (represented by the LB ECR) represent the northern frontier of the commercial cereal production zone. Beyond the LB, climatic conditions impose larger constraints on agriculture, and insufficient heat accumulation over the relatively short frost-free season results in considerable increases in crop failure.

A Climatic Change Perspective

Experiment results indicate that the average DTM would be considerably less under all climate change scenarios, compared to the mean under baseline conditions. The GFDL and Composite climate regimes have similar impacts on the DTM at all sites. Under these scenarios, the mean DTM is reduced 12-19 days. Relative to the other scenarios, the CCC has the largest impact on the DTM, shortening it by 18-27 days. This appears to be due to the particular combination of temperature and precipitation changes, and the timing of these changes, predicted by the CCC. For example, at Beaverlodge during the growing season, the precipitation changes are similar between the CCC and the Composite scenarios (Figure 5), but the temperature is much

warmer under the CCC compared to the Composite (Figure 4). In comparison with the GFDL, the CCC has similar temperature changes, but conditions are much drier. At this site, the unique combination of warmer and drier conditions leads to a faster maturing crop relative to the other scenarios.

At nearly all the sites, and under nearly all scenarios, the variability in the range of DTM would be reduced. This is particularly true at Yellowknife and Hay River where the crop would reach maturity with greater certainty compared to baseline conditions.

LOW BOREAL ECR: FT. VERMILION

LOW BOREAL ECR: BEAVERLODGE

LOW BOREAL ECR: WHITECOURT

Of the other 4 sites, Beaverlodge shows the greatest decrease in variability. The decrease there is 6-13 days across all scenarios, compared to a reduction of 1-7 days at the other sites. Ft. Vermilion and Ft. Nelson are the exceptions, where, under the GFDL the range in DTM would increase 5 and 6 days, respectively. This general decrease in variability can be attributed primarily to the warmer conditions under each of the scenarios, which impacts directly on plant development.

A Spatial Perspective

The most significant impacts on DTM occur at the HB site and at Hay River in the MB. Under baseline conditions, it was estimated that climatic conditions would prevent spring-seeded wheat from reaching maturity 2 and 8 years in 30 at Hay River and Yellowknife, respectively. This uncertainty, however, was eliminated under all scenarios at these sites. At the other 4 sites, there were apparent differences in variability between the 2 southern-most LB sites and the sites of Ft. Vermilion and Ft. Nelson. Under each scenario the reduction in variability was greater at the southern locations. The reduction of the mean DTM under the GFDL and CCC was 5-9 days greater at Whitecourt and Beaverlodge compared to Ft. Nelson and Ft. Vermilion. Under the Composite scenario, the difference in the reduction of mean DTM between these sites was only 2-3 days. This difference between the Composite results and the results of the GFDL and CCC is likely due to the warmer conditions predicted under the CCC and GFDL relative to the temperature changes under the composite scenario.

In summary, spatial differences in changes to DTM are apparent across all scenarios. The impacts of the climatic change scenarios on the cumulative probability distributions (Figure 7) were generally similar for the HB, the MB, and for Ft. Vermilion. Though the direction of the shifts in the distributions was the same at all sites, Beaverlodge and Whitecourt exhibited greater differences between scenarios, indicating that results at these sites were more sensitive to the climatic change scenarios than the results at the other sites.

4.3 Crop Moisture Stress (CMS)

Baseline Conditions

Crop moisture stress is defined in this study as the total water balance from planting to maturity². The model calculates water availability and water use, including soil moisture conditions at planting and potential evapotranspiration (PET), based on the daily weather data (IBSNAT 1993). It is used in this study to provide an indication of possible changes in plant moisture requirements. Climatic change may impact on CMS by altering the heat regime (affecting the amount of evapotranspiration), changing the atmospheric concentration of CO₂ (increasing the WUE of the crop), and by modifying the timing and the amount of precipitation the crop receives.

With the exception of Whitecourt, the model predicted that the mean CMS would be negative at all sites in the three ECRs under baseline conditions. An

² In this study, it was assumed that harvest occurred at maturity.

examination of the charts in Figure 8, indicates that a moisture deficit can be expected for most years. The mean CMS is lower in the HB (-51 cm) relative to the MB and the LB (-69 to -126 cm), again, with the exception Whitecourt, where, a moisture surplus of 30 cm was calculated. The range about the mean is lowest at Ft. Vermilion and the highest at Whitecourt. There is no obvious spatial pattern in the variability of the range in CMS.

2XCO₂ Conditions

A doubling of atmospheric CO₂ tends to reduce the CMS at all sites, though the effect is slightly more pronounced in the LB. This is likely due to the relationship between CO₂ enrichment and WUE as explained in Section 2.1.1.2. In the HB the impact on mean CMS was a marginal increase (0.4%). The range in CMS increased 3-32 cm at the MB and LB sites, and decreased slightly (-5 cm) in the HB. It could not be determined why the impact of CO₂ enrichment varied to such an extent between sites.

A Climate Change Perspective

The estimated CMS tends to be reduced across all scenarios. However, the overwhelming trend is that seasonal crop moisture deficits would continue at most sites. The predicted impacts are not uniform, with the GFDL scenario having the most significant impact on CMS. Under the GFDL, the CMS is reduced considerably at all sites. At Hay River CMS was reduced by 20%, while the reduction at the other sites ranged from 77-108%, and the moisture surplus at Whitecourt increased 300%. For example, the mean CMS at Beaverlodge is reduced from -69 cm under baseline conditions to +5.8 cm under the GFDL.

This is obviously due, in large part, to the fact that GFDL predicts greater precipitation for the Basin compared to the other climate regimes (see Figure 5).

Figure 8 continued. Impacts of Climatic Change Scenarios on Crop Moisture Stress.

The impacts of the CCC and Composite scenarios on CMS are more varied but less dramatic across all regions. CMS will increase by 10-20% at Yellowknife under both scenarios and CMS will also increase by 8% at Beaverlodge under Composite conditions. Decreases of 0-46% were calculated at the other sites which experienced a moisture deficit under baseline conditions.

Though the mean CMS decreases in most cases, the range of the results tends to increase. The range increased at all sites under the GFDL, and at all sites, except Yellowknife, under the CCC. Under the Composite scenario, the range increased at 3 sites and decreased at 3 sites. Figure 5 indicates that these differing impacts on the range of the values could be attributed to larger and more varied changes in precipitation predicted by the GFDL and CCC relative the changes under the Composite scenario.

In general, it appears that CMS would be reduced under all climatic change scenarios. The degree to which this effect takes place is dependent on the scenario in use. Clear reductions in CMS are evident under the GFDL, which can be linked to the increased precipitation predicted by this GCM. Under the CCC and the Composite scenarios, it appears that any possible increases in the WUE of the crop, due to the increased concentration of atmospheric concentration, that could lower the CMS, may have been offset by a reduction in precipitation.

A Spatial Prespective

The greatest impacts on CMS under each of the scenarios occur in the LB. At only one site, Beaverlodge, and under one scenario, the Composite, is

an increase in the mean CMS predicted for this ECR. The decreases in CMS range from 14 to 108% for the sites which have recorded moisture deficits. The impacts on CMS were not as great in the HB and MB as compared to the LB. This result held across all of the scenarios. For reasons mentioned earlier, the greatest decreases come under the GFDL and the smallest decreases occur under Composite conditions. Therefore, though there does appear to be a spatial pattern to changes in CMS, the crop model results are very sensitive to the climate scenarios used as input. Finally, it should be noted that all sites, with the exception of Whitecourt, will still have a moisture deficit most years regardless of scenario.

5.0 IMPACTS OF ATMOSPHERIC AND CLIMATIC CHANGE ON PRODUCTIVITY VARIABLES IN THE MACKENZIE BASIN

The impacts of potential atmospheric and climatic change on selected productivity variables are discussed in this chapter. These variables are the grain weight to canopy weight ratio (G:C) and grain yield weight at harvest. The reasons for selecting these variables are outlined in their respective subsections. As in Chapter 4, the discussion will focus on the same 6 presentation sites and on the wheat crop. The discussion will follow the format established in the previous chapter, that is, the experiment results under baseline and $2\times\text{CO}_2$ will be studied first. Then the results will be analyzed from a climate change and spatial perspective. It should be noted that G:C ratio at Yellowknife and Hay River was evaluated only for the years the crop reached maturity.

5.1 Grain Weight to Canopy Weight Ratio (G:C)

Baseline Conditions

The allocation of plant resources between reproductive activities, i.e., grain formation, and the accumulation of non-reproductive biomass, (root and canopy growth) under changing atmospheric conditions may have important implications for plant productivity (See Section 2.1.1.2). To address this issue, the ratio of grain weight to canopy weight was used to assess changes in biomass accumulation. An increase in the canopy growth relative to grain production would result in a ratio decrease, and, conversely, if the weight of the

grain increased relative to the canopy a ratio increase. Figure 9 indicates the impacts of atmospheric and climatic change on the grain weight to canopy weight ratio.

The mean G:C ratio under baseline conditions is fairly constant across all ECRs, with the means ranging for 0.41 to 0.46. The variability of the G:C ratio was similarly uniform across the LB and the MB, ranging from ± 0.05 to 0.11 of the mean, while in the HB the range was wider (± 0.14). It appears that the partitioning of plant resources between canopy and grain production may remain fairly constant over a wide range of climatic conditions.

2XCO₂ Conditions

An increase in atmospheric carbon dioxide with no change in climate produces an increase in the mean G:C (up to 8.7%) for 5 of the 6 sites. At Whitecourt, the ratio decreases by 2.3%. This is the same site where a moisture surplus was reported in Section 4.3. These results suggest that while a CO₂-enriched environment may slightly increase grain production relative to non-reproductive biomass when plants are under moisture stress, these benefits may not be realized when there is a moisture surplus. Further research is required to establish if this is indeed the case. Variability in the G:C ratio was slightly lower under these conditions at all sites, with the largest change at Yellowknife, where the range narrowed from ± 0.14 to 0.10 about the mean.

A Climate Change Perspective

In almost all cases, the scenarios predict a decrease of the G:C ratio of up to 13%. Under the CCC, there would be a decrease at all sites, while there would be a decrease at 4 and 5 sites under the GFDL and Composite scenarios, respectively. The 3 scenarios generated similar results for 4 out of 6 sites. At Hay River, Ft. Nelson, Ft. Vermilion, and Whitecourt, the decrease in the mean G:C ratio was 4.8-13.0%. At Beaverlodge mean G:C ratio increased by 2.3% under the Composite, did not change under the GFDL, and decreased by 7.0% under the CCC. Yellowknife was the only other site where the direction of the change differed across scenarios. There, the GFDL predicted 4.7% increase in the ratio, while the CCC and the Composite predicted the ratio would fall by 9.3 and 11.6%, respectively.

The impact on the variability of the ratio was similar under the climate change scenarios as the impacts under the $2XCO_2$ conditions. That is, the range in values was narrowed, with the largest changes coming at Yellowknife. The G:C ratio, therefore, generally increases with a simple doubling of CO_2 and generally decreases under the climate change scenarios. This indicates that for the sites studied, allocation of plant resources in favour of grain production over canopy that occurred under $2XCO_2$ conditions alone, was more than offset when the effects of climate change were introduced.

A Spatial Perspective

From a spatial perspective the impacts of the climate change on the G:C ratio are quite uniform. This is most apparent in the MB where the results under

all scenarios point to a 4.9-13.0% reduction in the ratio. The results were very similar to those in the MB in 2 out of the 3 sites in the LB. As mentioned above, the only inconsistencies in the the results for the LB were at Beaverlodge. In the HB, the CCC and the Composite predict a 9.3-11.6% reduction in the G:C ratio, while the GFDL predicted a 4.7% increase.

LOW BOREAL ECR: FT. VERMILION

LOW BOREAL ECR: BEAVERLODGE

LOW BOREAL ECR: WHITECOURT

5.2. Yield

Baseline Conditions

An analysis of crop yields is a very direct and useful method of assessing crop productivity. This section provides an indication of the magnitude and direction of change in yields. Perhaps more importantly, from an agricultural planning perspective, changes in the levels of uncertainty in crop yields will be explored.

The data presented in Figure 10 indicates, that under baseline conditions, there is a wide range in expected yields. Mean yields range from 1250-4550 kg/ha as calculated by the crop model. As expected, the lowest yield values occur in the HB, but interestingly, the 2 MB sites out perform 2 of the 3 LB sites. This seems counter-intuitive, but unfortunately, actual field data were not available for comparison. However, it should be noted that the soils at Ft. Vermilion and Whitecourt are sandy and drain rapidly compared to the loamy soils at Hay River and Ft. Nelson (refer to Table 4). Whitecourt is also very stoney. These factors may contribute to lower productivity at these LB sites. Given the main focus of this analysis is on relative change as opposed to absolute change, this information is still quite useful.

Variability was largest at Yellowknife and Hay River, where the crop failed to mature 8 and 2 years, respectively, out of the 30 year baseline record. Large variability is also evident between sites in the same ECR. Differences in soil type and differences in microclimates may contribute to this variability. These results highlight the inaccuracies that could be introduced when daily

weather data is interpolated over wide areas for use in crop-weather modelling.

2XCO₂ Conditions

With the baseline climate regime and a 2XCO₂ atmosphere there was a considerable increase in estimated yields in all regions. At nearly all sites the percentage increase in mean yield was typically in the range of 20-30%. These results are consistent with the results of previous research into the effects of enriched carbon dioxide environments on cereal yields as discussed in Section 2.1.2.4. Whitecourt, in the LB, was the exception, where the increase in yields was only 5.4%.

A Climate Change Perspective

The introduction of climate change scenarios in combination with atmospheric change had the general effect of decreasing mean yield values (Figure 10). The higher temperatures associated with these scenarios leads to a more rapid accumulation of daily thermal time (which the crop model calculates from the daily weather record) and a decrease in the DTM. Each phase of plant development is shortened, including cereal growth, or grain filling, under these conditions. The result tends to be lower grain weights at harvest. These effects are most pronounced under the CCC scenario where mean yields fell 15-24% below baseline levels across all sites. It appears that yields under the CCC have been impacted by a reduction in the DTM and the particular set of conditions that brought about those changes (see Section 4.2). The range expected of values also fell from ± 650 to ± 150 kg/ha of the mean

under baseline conditions, to ± 400 to 1450 kg/ha of the mean under the CCC. Opportunities at the higher end of the range have been severely limited under CCC conditions. This impact on the variability of the yield was similar under all scenarios.

While mean yields under the GFDL and the Composite also tended to fall relative to baseline levels, these reductions were not as substantial as they were under the CCC. Mean yields fell 1-17% at all sites, except Yellowknife, under the GFDL. At that site an increase of 7.5% was calculated for GFDL conditions. Given Composite conditions, increased mean yields of 12 and 4% were projected for Beaverlodge and Whitecourt, respectively, while the experiment results produced decreases ranging from 4-13% at the other 4 sites. Therefore, under each of the climate change scenarios, a loss of agricultural opportunities was evident at most sites, with the greatest losses coming under the CCC scenario.

Figure 10. Impacts of Climatic Change Scenarios on Yields.

2 of/de 2

PM-1 3 1/2"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

LOW BOREAL ECR: FT. VERMILION

LOW BOREAL ECR: BEAVERLODGE

LOW BOREAL ECR: WHITECOURT

A Spatial Perspective

The CCC scenario produced reductions in mean yields apparently irrespective of ECR. However, these results were consistent in direction, if not in magnitude, with the findings under the other scenarios in the MB. All scenarios predicted decreases in mean yields here, though the 4-12% reduction under the GFDL and the Composite was considerably less than the 15-23% reduction under the CCC. Like the CCC, yields also decreased in the LB given a GFDL scenario. Though in the case of the LB, the decrease in the mean yield at Beaverlodge was very slight (less than 1%). Under all scenarios there was a great reduction in the uncertainty of yields in the HB and at Hay River, but productivity was less when compared to successful harvests under baseline conditions. With the exception of the cases mentioned above, evidence of a spatial pattern in terms of yields, is thin, and, therefore, yield sensitivity appears to be more attuned to climate scenario than to location.

6.0 SUMMARY AND CONCLUSIONS

6.1 Summary of Study

The main objectives of this study were:

- to review the combined impacts of atmospheric and climatic change on agricultural production;
- select a method which is appropriate for determining the impacts of climatic change on agricultural productivity in the Mackenzie Basin, and,
- compare and contrast the results among the selected scenarios and between ecoclimatic regions in the Basin

Those atmospheric and climatic changes that impacted on plant processes were termed "direct" impacts, and those changes that affected the plant's environment were identified as having "indirect" impacts (Section 2.1).

The selection of the CERES crop models for application in this research was based on a review and appraisal of the crop modelling literature (Section 2.2). Empirical-statistical models, analogue method, and land suitability and agroclimatic indices were determined to be inappropriate for this research because these approaches fail to fully capture the potentially significant direct effects of an increase in the atmospheric concentration of carbon dioxide on plant growth. In addition to being able to capture these direct effects, the selected crop models consider various environmental and managerial factors, and operate with historical or predicted weather regimes. This research explicitly considers the impacts on selected crop productivity variables for 2 cases: an effective doubling of atmospheric carbon dioxide alone; and, an

effective doubling of atmospheric carbon dioxide in combination with climatic change it employed crop models to estimate the impacts of these atmospheric and climatic changes on planting dates, days to maturity, crop moisture stress, grain to canopy ration, and yields. The research did not address the economic or social factors that may influence current or future crop production. Other biophysical changes stemming from climate change, such as the potential change in the range of pests and diseases, were not discussed. The output generated by the models may also be incorporated into other, more integrated, studies into the impacts of atmospheric and climatic change on agricultural production.

This study's framework was built around the data requirements of the crop models (Section 3.1). The selected crop models require daily weather data and, therefore, are known to be sensitive to microclimates. Weather data derived as an average across many sites is not suitable as input to this type of model and, therefore, observed daily weather for specific sites was employed. These 15 sites are found mainly throughout the southern portion of the Basin and, therefore, do not provide a basis for drawing generalized conclusions with regard to agricultural opportunities throughout the entire Basin. At the 15 selected sites crop model experiments were run for spring-seeded wheat and barley at two levels of fertilizer application (36 and 50 kg/ha of nitrogen). These sites were grouped by ecoclimatic region in order to help identify any spatial variations in the results (Section 3.2). To facilitate analysis and discussion 6

sites were selected for presentation in the body of the paper. Detail results for all sites were presented in tabular form in the appendices.

The estimated results were analyzed with respect to the impacts of atmospheric and climatic change on the agroclimatic variables of planting date, days to maturity, and crop moisture stress (Chapter 4), and on the productivity properties of grain to canopy ratio and grain yield weight at harvest (Chapter 5). These variables were assessed under baseline (1951-80) conditions, under elevated CO_2 conditions, and under elevated CO_2 plus climatic change conditions. A summary of the findings are presented in Table 5

6.2 Conclusions

Estimated mean planting dates and mean days to maturity under current climatic conditions varied greatly throughout the study area. Assuming no changes to agricultural systems in the region (e.g. conversion to winter-seeded cereals, technological innovations), it is estimated that the specified climatic changes and an effective doubling of CO_2 would have considerable impacts on planting dates and days to maturity. The CCC and Composite scenarios had the greatest impact on estimated PD, pushing seeding dates earlier by 1 to 2 weeks in all regions of the Basin. Estimated changes under the GFDL scenario in the LB and MB were similar but of a smaller magnitude. In the HB, it was estimated that PD would be similar under the GFDL and baseline conditions. The most dramatic changes to DTM would be expected to occur under the CCC scenario, with the estimated mean DTM being reduced by 18 to 27 days. A 12

Table 5. Summary of Findings.

AGRICULTURAL ATTRIBUTE	ATMOSPHERIC AND CLIMATE CHANGE SCENARIOS			
	2XCO ₂	Composite	GFDL	CCC
Planting Date	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> 2 weeks earlier Greater certainty at HB 	<ul style="list-style-type: none"> 1 week earlier Greater certainty at HB 	<ul style="list-style-type: none"> 2 weeks earlier Greater certainty at HB
Days to Maturity	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> 12-19 day reduction Greater certainty at HB 	<ul style="list-style-type: none"> 12-19 day reduction Greater certainty at HB 	<ul style="list-style-type: none"> 18-26 day reduction across all regions Greater certainty at HB
Crop Moisture Stress	<ul style="list-style-type: none"> Decrease in all regions, Particularly LB 	<ul style="list-style-type: none"> Varied, less dramatic than GFDL Benefits to WUE offset by lower precipitation 	<ul style="list-style-type: none"> Considerable reduction for all regions due to increased precipitation 	<ul style="list-style-type: none"> Varied, less dramatic than GFDL Benefits to WUE offset by lower precipitation
Grain to Canopy Ratio	<ul style="list-style-type: none"> Increase in grain weight relative to canopy weight in all regions 	<ul style="list-style-type: none"> Decrease in grain weight relative to canopy weight in all regions 	<ul style="list-style-type: none"> Decrease in grain weight relative to canopy weight in all regions 	<ul style="list-style-type: none"> Decrease in grain weight relative to canopy weight in all regions Larger decreases in LBs
Yield	<ul style="list-style-type: none"> 20-30% increase at all sites, except Whitecourt 	<ul style="list-style-type: none"> Smaller impact Marked increase at Beaverlodge Greater certainty at HB 	<ul style="list-style-type: none"> Decrease in MB & LB Greatest decreases at Vermilion & Whitecourt Greater certainty at HB 	<ul style="list-style-type: none"> 15-24% decrease, uniform across all regions Greater certainty at HB

to 19 day reduction in DTM was estimated under the GFDL and Composite scenarios. The greatest impacts under all scenarios were estimated in the two most northerly sites, Yellowknife and Hay River.

The estimated probability of a moisture deficit in any given year was high at most sites under baseline conditions. The exception to this situation was the Whitecourt site where moisture surpluses were common. A doubling of CO_2 reduced the estimated CMS in all regions with the effect being more pronounced at the LB sites where moisture deficits were common. The wetter conditions predicted under the GFDL were reflected in a considerable reduction in the estimated CMS in all regions. Under the CCC and Composite scenarios, possible benefits of elevated CO_2 on the estimated CMS appear to be neutralized by changes in climatic conditions.

A CO_2 -enriched atmosphere generally led to an increase in the estimated G:C ratio, indicating that under these conditions the grain weight would increase relative to the weight of the rest of the plant. The introduction of the climate change scenarios tended to decrease the estimated ratio grain weight to canopy weight relative to the baseline conditions.

It was estimated that CO_2 increases in isolation (i.e. with no accompanying climatic change) would increase mean spring-seeded cereal yields 20% to 30% at most sites. Under the climatic change scenarios, it was estimated the benefits of increased CO_2 to productivity would be offset by the climate effects. The greatest impact was under the CCC climatic change scenario, with estimated yields at the selected sites decreasing 15 to 24%.

relative to estimated baseline yields. Though less dramatic, the estimated results tended to be similar under the other climatic change scenarios.

Estimated mean yields were lower at Hay River and Yellowknife under climatic change scenarios, but it was estimated that the specified climatic changes provided greater assurance that spring-seeded cereals would mature.

This paper estimated the effects of atmospheric and climatic change on selected agroclimatic and productivity properties which may affect cereal crop productivity in the Mackenzie Basin. This research focuses on the combined effects of a carbon dioxide enriched atmosphere and climatic change. Conventional crop models were used to estimate the changes to planting dates, days to maturity, crop moisture stress, grain to canopy ratio, and yields. The estimated results did not indicate any obvious spatial pattern across the ecoclimatic regions in the study area. Climatic conditions at individual sites and the climatic change scenario applied appeared to have a greater impact on the results when compared to spatial variations across ECRs. It was apparent, however, that the estimated benefits to plant growth and crop productivity associated with a carbon dioxide enriched atmosphere could be offset when carbon dioxide induced climatic changes were introduced. Therefore, climatic and atmospheric change alone may not result in a substantial improvement in the physical opportunities for cereal crop productivity in the Mackenzie Basin.

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APPENDIX A.

Monthly Means for Temperature and Precipitation (1951-80) and Changes Under Climatic Change Scenarios.

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Table B3. Ft. Resolution. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)

	Barley	Wheat
Base	124.9	124.9
2XCO2	124.9	124.9
Comp	112.9	112.9
GFDL	118.0	118.0
CCC	109.4	109.4

DAYS TO MATURITY (DTM)

	Barley	Wheat
Base	117.7	123.9
2XCO2	117.7	123.9
Comp	97.3	105.7
GFDL	102.1	108.8
CCC	95.6	104.4

CHANGE IN PLANTING DATE (in days)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-12.0	-12.0
GFDL	-6.9	-6.9
CCC	-15.5	-15.5

CHANGE IN DAYS TO MATURITY (DTM)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-20.4	-18.2
GFDL	-15.6	-15.0
CCC	-22.1	-19.5

YIELD (kg/ha)

	Barley	Wheat
Base	2758.6	2586.8
2XCO2	3433.5	3177.8
Comp	2516.5	2151.5
GFDL	2423.6	2234.3
CCC	2134.6	1989.7

GRAIN TO CANOPY RATIO AT HARVEST (G/C)

	Barley	Wheat
Base	0.53	0.48
2XCO2	0.56	0.51
Comp	0.50	0.41
GFDL	0.50	0.44
CCC	0.51	0.42

% CHANGE IN YIELD (kg/ha)

	Barley	Wheat
2XCO2	24.5	22.8
Comp	-8.8	-16.8
GFDL	-12.1	-13.6
CCC	-22.6	-23.1

% CHANGE GRAIN/CANOPY RATIO (G/C)

	Barley	Wheat
2XCO2	5.3	6.3
Comp	-5.3	-14.9
GFDL	-5.3	-8.3
CCC	-3.8	-12.5

CROP MOISTURE STRESS (cm)

	Barley	Wheat
Base	-121.76	-118.76
2XCO2	-113.38	-109.19
Comp	-99.0	-122.0
GFDL	-87.4	-92.9
CCC	-87.3	-111.3

% CHANGE IN CROP MOISTURE STRESS

	Barley	Wheat
2XCO2	-6.9	-8.1
Comp	-18.7	2.7
GFDL	-28.2	-21.8
CCC	-28.3	-6.3

NOTES 1 Statistics in this table are based on 24 years of data
2 Under Baseline conditions, the crops did not reach maturity 3 out of the 24 years in the record

**Table A2. Monthly Means for Temperature and Precipitation (1951-80) and Changes
Under Climate Change Scenarios for Ft. Resolution, Ft. St. John, and Sion.**

Temperature Means												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FT RESOLUTION	-20.9	-23.3	-17.0	-5.0	5.7	12.4	15.7	14.7	7.2	0.3	-11.0	21.4
FT ST JOHN	-18.0	-11.6	-6.8	2.5	9.1	12.8	15.0	14.7	9.0	3.7	-6.4	-13.5
SION	17.4	-11.1	-6.2	3.0	10.0	13.7	15.8	15.5	9.5	4.4	-5.5	-12.9
Precipitation Means												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FT RESOLUTION	17.0	14.0	13.0	12.0	16.0	22.0	43.0	36.0	39.0	34.0	40.0	18.0
FT ST JOHN	36.0	28.0	30.0	21.0	40.0	68.0	73.0	60.0	39.0	28.0	21.0	36.0
SION	25.0	20.0	18.0	21.0	43.0	82.0	87.0	76.0	37.0	17.0	17.0	24.0
Climate Change Scenarios												
Temperature												
FT RESOLUTION												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	6.0	3.7	3.3	3.0	4.0	5.0	3.0	3.0	1.0	3.6	2.4	4.1
GFDL	0.5	2.4	5.4	7.0	5.1	4.5	5.4	2.5	4.7	4.7	7.3	4.2
CCC	4.0	5.9	6.5	1.7	3.7	5.3	3.8	2.9	3.3	1.8	4.8	7.9
FT ST JOHN												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	3.5	3.5	1.2	1.1	1.0	1.0	1.0	1.0	2.9	2.0	4.5	3.5
GFDL	0.6	3.1	4.6	3.3	4.3	4.9	4.4	4.9	5.1	3.8	4.4	3.2
CCC	3.1	4.7	5.1	2.6	4.1	4.2	3.4	3.6	2.9	2.2	3.3	6.0
SION												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	3.5	3.5	1.2	1.1	1.0	1.0	1.0	1.0	2.9	2.0	4.5	3.5
GFDL	2.1	4.3	5.5	3.6	3.9	4.5	5.7	4.9	4.5	3.6	4.4	4.1
CCC	4.4	6.1	5.4	2.9	4.0	4.1	3.2	3.7	3.4	2.5	2.4	7.1
Precipitation												
FT RESOLUTION												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
GFDL	94.0	7.0	15.0	33.0	50.0	5.0	149.0	192.0	28.0	0.0	40.0	78.0
CCC	6.0	7.0	0.0	25.0	13.0	18.0	12.0	0.0	5.0	18.0	23.0	6.0
FT ST JOHN												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	10.0	0.0	10.0	10.0	0.0	-15.0	-15.0	-15.0	-15.0	0.0	0.0	-10.0
GFDL	39.0	43.0	40.0	24.0	-25.0	50.0	236.0	-7.0	54.0	4.0	43.0	0.0
CCC	19.0	4.0	0.0	14.0	2.0	3.0	10.0	18.0	13.0	18.0	37.0	14.0
SION												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	10.0	0.0	10.0	10.0	0.0	15.0	-15.0	15.0	0.0	0.0	-10.0	-10.0
GFDL	48.0	30.0	44.0	19.0	21.0	7.0	-33.0	-20.0	119.0	76.0	4.0	33.0
CCC	28.0	15.0	6.0	24.0	26.0	-13.0	13.0	0.0	14.0	18.0	21.0	25.0

**Table A3. Monthly Means for Temperature and Precipitation (1951-80) and Changes
Under Climate Change Scenarios for Ft. Vermilion, Peace River, and Campsie.**

Temperature Means												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KEG RIVER	-21.6	-15.4	-9.3	1.8	9.8	14.0	16.2	14.0	9.0	2.7	8.9	17.2
PEACE RIVER	-18.6	-12.5	-7.6	2.9	9.9	14.0	16.0	15.3	9.6	3.9	6.6	13.9
CAMPSIE	-14.5	-8.7	-5.0	3.0	9.2	12.8	15.0	15.0	9.5	4.5	4.4	10.5
Precipitation Means												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KEG RIVER	14.0	12.0	15.0	12.0	34.0	64.0	79.0	51.0	29.0	12.0	13.0	11.0
PEACE RIVER	25.0	22.0	21.0	17.0	38.0	68.0	79.0	52.0	32.0	22.0	21.0	24.0
CAMPSIE	24.0	20.0	18.0	20.0	43.0	83.0	87.0	75.0	38.0	16.0	17.0	24.0
Climate Change Scenarios												
Temperature												
KEG RIVER												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	6.0	3.7	3.3	3.0	4.0	5.0	3.0	3.0	1.0	1.6	2.4	4.1
GFDL	0.1	2.6	5.1	4.5	4.3	4.7	4.6	5.6	4.9	4.1	5.5	3.7
CCC	3.4	5.2	5.4	2.1	4.4	4.5	3.2	3.3	3.0	2.2	2.8	8.0
PEACE RIVER												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	3.5	3.5	1.2	1.1	1.0	1.0	1.0	1.0	2.9	2.0	4.5	3.5
GFDL	0.9	3.7	5.3	3.9	4.2	4.6	4.8	5.1	4.9	4.0	4.9	4.0
CCC	3.6	5.4	5.8	2.1	4.3	4.3	3.3	3.7	2.9	1.7	3.0	8.1
CAMPSIE												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	3.5	3.5	1.2	1.1	1.0	1.0	1.0	1.0	2.9	2.0	4.5	3.5
GFDL	1.0	1.7	3.9	3.3	4.5	5.2	6.3	5.0	4.3	3.5	3.0	1.3
CCC	1.8	3.5	4.2	3.2	3.8	5.0	4.0	4.3	3.4	3.5	1.2	5.9
Precipitation												
KEG RIVER												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
GFDL	14.0	50.0	53.0	-25.0	-15.0	20.0	228.0	31.0	55.0	17.0	23.0	9.0
CCC	14.0	8.0	7.0	17.0	21.0	3.0	6.0	14.0	10.0	25.0	23.0	18.0
PEACE RIVER												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	-10.0	0.0	10.0	10.0	0.0	15.0	15.0	15.0	0.0	0.0	10.0	10.0
GFDL	-4.0	5.0	43.0	53.0	29.0	43.0	25.0	8.0	134.0	50.0	29.0	21.0
CCC	28.0	14.0	-5.0	29.0	18.0	3.0	14.0	6.0	9.0	27.0	24.0	21.0
CAMPSIE												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Composite	-10.0	0.0	10.0	10.0	0.0	15.0	15.0	15.0	0.0	0.0	10.0	10.0
GFDL	38.0	30.0	33.0	15.0	12.0	11.0	30.0	20.0	84.0	75.0	47.0	28.0
CCC	33.0	15.0	0.0	25.0	26.0	14.0	1.0	13.0	19.0	24.0	22.0	27.0

APPENDIX B.

Experiment Results at Each Site for Wheat and Barley with a 36 kg/ha Nitrogen Fertilizer Application.

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Table B1. Ft. Reliance. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)

	Barley	Wheat
Base	133.7	133.7
2XCO2	133.5	133.5
Comp	120.7	120.7
GFDL	130.1	130.1
CCC	121.3	121.3

DAYS TO MATURITY (DTM)

	Barley	Wheat
Base	134.2	137.0
2XCO2	115.1	137.0
Comp	109.3	112.0
GFDL	116.1	121.2
CCC	104.4	109.1

CHANGE IN PLANTING DATE (in days)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-13.0	-13.5
GFDL	-3.6	-4.3
CCC	-12.4	-12.4

CHANGE IN DAYS TO MATURITY (DTM)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-25.0	-25.0
GFDL	-18.2	-15.8
CCC	-29.8	-27.9

YIELD (kg/ha)

	Barley	Wheat
Base	2001	1573
2XCO2	2649	2138
Comp	1708	1454
GFDL	2209	2176
CCC	1773	1623

GRAIN TO CANOPY RATIO AT HARVEST

	Barley	Wheat
Base	0.49	0.42
2XCO2	0.54	0.44
Comp	0.44	0.37
GFDL	0.53	0.49
CCC	0.49	0.41

% CHANGE IN YIELD (kg/ha)

	Barley	Wheat
2XCO2	32.4	36.0
Comp	-14.7	-7.5
GFDL	10.4	38.4
CCC	-11.4	3.2

% CHANGE GRAIN/CANOPY RATIO (G/C)

	Barley	Wheat
2XCO2	10.0	4.8
Comp	-10.0	-11.9
GFDL	8.0	16.7
CCC	0.0	2.4

CROP MOISTURE STRESS (cm)

	Barley	Wheat
Base	-56.9	-55.2
2XCO2	-48.4	-53.0
Comp	-60.3	-64.5
GFDL	-41.4	-39.9
CCC	-55.8	-59.7

% CHANGE IN CROP MOISTURE STRESS

	Barley	Wheat
2XCO2	-14.8	-4.0
Comp	6.0	16.8
GFDL	-27.3	-27.7
CCC	-1.9	8.2

NOTES: 1. Wheat matured 5, 29, and 29 years under the Baseline, Comp, and GFDL climate conditions, respectively
2. Barley matured 9 and 29 years under the Baseline and GFDL climate conditions, respectively.

Table B2. Yellowknife. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	132.4	132.4	Base	115.6	122.6
2XCO2	132.2	132.2	2XCO2	115.6	122.6
Comp	121.3	121.3	Comp	95.3	100.7
GFDL	132.7	132.7	GFDL	96.4	100.5
CCC	117.9	117.9	CCC	91.2	97.1
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-11.1	-11.1	Comp	-20.3	-22.0
GFDL	0.3	0.3	GFDL	-19.2	-22.2
CCC	-14.5	-14.5	CCC	-24.3	-25.5
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	1333.0	1259.4	Base	0.48	0.43
2XCO2	1975.8	1824.6	2XCO2	0.52	0.45
Comp	1508.0	1207.5	Comp	0.47	0.38
GFDL	1420.6	1353.5	GFDL	0.50	0.45
CCC	1090.7	958.7	CCC	0.46	0.39
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	48.2	44.9	2XCO2	8.3	4.7
Comp	13.1	-4.1	Comp	-2.1	-11.6
GFDL	6.6	7.5	GFDL	4.2	4.7
CCC	-18.2	-23.9	CCC	-4.2	-9.3
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-49.4	-51.0	2XCO2	-0.4	0.4
2XCO2	-49.2	-51.1	Comp	11.9	20.2
Comp	-55.3	-61.3	GFDL	-61.4	-76.6
GFDL	-19.1	-11.9	CCC	4.4	9.8
CCC	-51.6	-55.9			

NOTE Under baseline conditions, crops did not reach maturity 8 out of the 30 years in the record

Table B4. Ft. Smith. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	96.6	96.6	Base	126.0	136.8
2XCO2	96.6	96.6	2XCO2	126.0	136.8
Comp	99.5	99.5	Comp	100.5	109.9
GFDL	97.2	97.2	GFDL	110.5	121.4
CCC	98.4	98.4	CCC	97.3	109.6
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	2.9	2.9	Comp	-25.6	-26.9
GFDL	0.6	0.6	GFDL	-15.5	-15.5
CCC	1.8	1.8	CCC	-28.7	-27.3
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	3413.8	2784.6	Base	0.42	0.34
2XCO2	4752.1	3699.9	2XCO2	0.45	0.37
Comp	3661.5	2547.1	Comp	0.46	0.32
GFDL	3076.9	2654.6	GFDL	0.41	0.33
CCC	2891.1	1747.0	CCC	0.43	0.25
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	39.2	32.9	2XCO2	7.1	8.8
Comp	7.3	-8.5	Comp	9.5	-5.8
GFDL	-9.9	-4.7	GFDL	-2.3	-2.9
CCC	-15.3	-37.3	CCC	2.3	-26.5
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-131.5	-137.5	2XCO2	-2.6	-1.3
2XCO2	-128.1	-135.7	Comp	-11.5	-3.9
Comp	-116.4	-132.2	GFDL	-15.3	-8.0
GFDL	-111.4	-126.5	CCC	-11.9	-6.7
CCC	-115.9	-128.3			

NOTE Statistics for wheat production under the CCC climate regime are based on 7 years of data

Table B5. Hay River. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)

	Barley	Wheat
Base	125.4	125.4
2XCO2	125.4	125.4
Comp	111.5	111.5
GFDL	117.0	117.0
CCC	112.1	112.1

CHANGE IN PLANTING DATE (in days)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-14.0	-14.2
GFDL	-8.4	-8.7
CCC	-13.3	-13.6

YIELD (kg/ha)

	Barley	Wheat
Base	3396.6	3086.7
2XCO2	4309.1	3948.2
Comp	3310.4	2694.6
GFDL	3367	2947.4
CCC	3024.2	2614.5

% CHANGE IN YIELD (kg/ha)

	Barley	Wheat
2XCO2	26.9	27.9
Comp	-2.5	-12.7
GFDL	-0.9	-4.5
CCC	-11.0	-15.3

CROP MOISTURE STRESS (cm)

	Barley	Wheat
Base	-127.9	-125.6
2XCO2	-119.4	-117.4
Comp	-109.5	-125.7
GFDL	-99.1	-101.2
CCC	-106.4	-122.9

DAYS TO MATURITY (DTM)

	Barley	Wheat
Base	121.8	127.6
2XCO2	121.8	127.6
Comp	99.6	106.7
GFDL	106.2	112.8
CCC	96.9	105.1

CHANGE IN DAYS TO MATURITY (DTM)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-22.3	-20.8
GFDL	-15.6	-14.7
CCC	-24.9	-22.4

GRAIN TO CANOPY RATIO AT HARVEST (G/C)

	Barley	Wheat
Base	0.50	0.46
2XCO2	0.54	0.50
Comp	0.48	0.40
GFDL	0.48	0.43
CCC	0.48	0.41

% CHANGE GRAIN/CANOPY RATIO (G/C)

	Barley	Wheat
2XCO2	8.0	8.7
Comp	-4.0	-13.0
GFDL	-4.0	-6.5
CCC	-4.0	-10.9

% CHANGE IN CROP MOISTURE STRESS

	Barley	Wheat
2XCO2	-6.6	-6.5
Comp	-14.4	0.1
GFDL	-22.5	-19.5
CCC	-16.8	-2.2

NOTE Under Baseline conditions, there were 2 years out of the 30 that the wheat crop did not reach maturity, and 1 year that the barley crop did not mature

Table B6. Ft. Nelson. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	118.7	118.7	Base	104.3	114.0
2XCO2	118.7	118.7	2XCO2	104.3	114.0
Comp	106.0	106.0	Comp	91.4	98.7
GFDL	107.7	107.7	GFDL	93.6	101.7
CCC	109.2	109.2	CCC	87.9	95.9
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-12.7	-12.7	Comp	-12.9	-15.3
GFDL	-10.9	-10.9	GFDL	-10.7	-12.2
CCC	-9.5	-9.5	CCC	-16.4	-18.1
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	5374.2	4553.2	Base	0.47	0.41
2XCO2	7220.0	5947.5	2XCO2	0.49	0.43
Comp	5293.4	4319.5	Comp	0.49	0.39
GFDL	5016.4	4122.5	GFDL	0.46	0.39
CCC	4305.9	3530.0	CCC	0.46	0.37
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	34.3	30.6	2XCO2	4.3	4.9
Comp	-1.5	-5.1	Comp	4.3	-4.9
GFDL	-6.7	-9.5	GFDL	-2.1	-4.9
CCC	-19.9	-22.5	CCC	-2.1	-9.8
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-76.7	-76.8	2XCO2	-14.0	-13.7
2XCO2	-66.0	-66.3	Comp	-30.4	-23.0
Comp	-53.4	-59.1	GFDL	-94.6	-92.9
GFDL	-4.1	-5.4	CCC	-24.8	-21.0
CCC	-57.7	-60.7			

Table B7. Ft. Vermilion. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	119.8	119.8	Base	103.3	112.7
2XCO2	119.4	119.4	2XCO2	103.3	112.7
Comp	107.5	107.5	Comp	88.2	95.8
GFDL	114.5	114.5	GFDL	89.9	99.4
CCC	107.4	107.4	CCC	85.3	93.3
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-12.3	-12.3	Comp	-15.1	-16.8
GFDL	-5.2	-5.2	GFDL	-13.4	-13.2
CCC	-12.3	-12.3	CCC	-18.0	-19.4
YIELD (kg/ha)			GRAIN/CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	2479.3	2246.7	Base	0.49	0.42
2XCO2	3099.1	2723.1	2XCO2	0.50	0.43
Comp	2411	2068.4	Comp	0.49	0.40
GFDL	2236.4	1953.9	GFDL	0.46	0.38
CCC	2090.4	1724.7	CCC	0.46	0.38
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	25.0	21.2	2XCO2	2.0	2.4
Comp	-2.7	-7.9	Comp	0.0	-4.8
GFDL	-9.8	-13.0	GFDL	-6.1	-9.5
CCC	-15.7	-23.2	CCC	-6.1	-9.5
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-48.8	-82.1	2XCO2	-10.3	-32.3
2XCO2	-43.8	-55.6	Comp	-26.9	-45.1
Comp	-35.6	-45.1	GFDL	-75.3	-77.8
GFDL	-12.0	-18.3	CCC	-12.3	-45.5
CCC	-42.8	-44.7			

Table B8. Keg River. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	116.3	116.3	Base	109.8	119.4
2XCO2	116.3	116.3	2XCO2	109.8	119.4
Comp	104.5	104.5	Comp	94.2	101.2
GFDL	110.3	110.3	GFDL	96.3	105.8
CCC	107.1	107.1	CCC	90.6	98.5
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-11.8	-11.8	Comp	-15.6	-18.2
GFDL	-6.0	-6.0	GFDL	-13.5	-13.6
CCC	-9.2	-9.2	CCC	-19.1	-20.9
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	4202.9	3751.1	Base	0.51	0.42
2XCO2	5321.5	4446.7	2XCO2	0.52	0.43
Comp	3772.9	3448.7	Comp	0.52	0.41
GFDL	3976.8	3488.9	GFDL	0.49	0.39
CCC	3243.7	2830.5	CCC	0.49	0.39
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	26.6	18.5	2XCO2	2.0	2.4
Comp	-10.2	-8.1	Comp	2.0	-2.4
GFDL	-5.4	-7.0	GFDL	-3.9	-7.1
CCC	-22.8	-24.5	CCC	-3.9	-7.1
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-93.7	-100.8	2XCO2	-8.9	-9.2
2XCO2	-85.3	-91.5	Comp	-32.7	-7.3
Comp	-63.1	-93.4	GFDL	-59.3	-42.7
GFDL	-38.1	-57.8	CCC	-19.2	-7.4
CCC	-75.7	-93.3			

Table B9. Peace River. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	116.1	116.1	Base	109.8	115.9
2XCO2	116.1	116.1	2XCO2	109.8	115.9
Comp	109.7	109.7	Comp	98.5	105.6
GFDL	112.0	112.0	GFDL	92.8	101.1
CCC	107.5	107.5	CCC	89.0	96.6
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-6.4	-6.4	Comp	-11.3	-10.3
GFDL	-4.1	-4.1	GFDL	-17.0	-14.8
CCC	-8.6	-8.6	CCC	-20.8	-19.3
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	3137.3	2801	Base	0.51	0.43
2XCO2	4028.7	3375.8	2XCO2	0.52	0.45
Comp	3258.3	3115.3	Comp	0.53	0.44
GFDL	2877.4	2742.7	GFDL	0.49	0.43
CCC	2307.9	2279.8	CCC	0.48	0.40
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	28.4	44.9	2XCO2	2.0	4.7
Comp	3.9	-4.1	Comp	3.9	2.3
GFDL	-8.3	7.5	GFDL	-3.9	0.0
CCC	-26.4	-23.9	CCC	-5.9	-7.0
CROP MOISTURE STRESS (mm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-82.6	-85.1	2XCO2	-6.1	-12.9
2XCO2	-77.6	-74.1	Comp	-35.3	-4.8
Comp	-53.5	-81.0	GFDL	-56.2	-31.9
GFDL	-36.2	-58.0	CCC	-40.3	-12.8
CCC	-49.3	-74.3			
NOTE: Statistics in this table are based on 21 years of data					

Table B10. Ft. St. John. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	122 0	122 0	Base	108 6	117 9
2XCO2	122 0	122 0	2XCO2	108 6	117 9
Comp	110 4	110 4	Comp	99 2	106 4
GFDL	115 0	115 0	GFDL	95 2	103 5
CCC	109 7	109 7	CCC	91 5	99 0
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0 0	0 0	2XCO2	0 0	0 0
Comp	-11 6	-11 6	Comp	-9 3	-11 6
GFDL	-7 0	-7 0	GFDL	-13 3	-14 4
CCC	-12 4	-12 4	CCC	-17 0	-18 9
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	3654 0	3330 1	Base	0 53	0 47
2XCO2	4219 2	3675 4	2XCO2	0 54	0 48
Comp	3933 6	3544 1	Comp	0 54	0 46
GFDL	3342 1	3152 8	GFDL	0 52	0 42
CCC	3337 7	2828 2	CCC	0 52	0 42
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	15 4	14 9	2XCO2	1 9	2 1
Comp	7 6	6 4	Comp	1 9	-12 1
GFDL	-8 6	-5 3	GFDL	-1 9	-10 6
CCC	-8 7	-15 1	CCC	-1 9	-10 6
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-42 7	-51 1	2XCO2	-36 5	-33 5
2XCO2	-27 1	-34 0	Comp	-23 2	-6 1
Comp	-32 8	-48 0	GFDL	-178 2	-141 1
GFDL	33 4	21 0	CCC	-34 4	-21 5
CCC	-28 0	-40 1			

Table B11. BEAVERLODGE. Baseline Mean Experiment Results and Changes in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	118 1	118 1	Base	113 5	123 2
2XCO2	118 1	118 1	2XCO2	113 5	123 2
Comp	109 7	109 7	Comp	101 6	108 6
GFDL	113 3	113 3	GFDL	96 2	104 2
CCC	107 1	107 1	CCC	89 8	96 7
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	0 0	0 0	Base	0 0	0 0
Comp	-8 4	-8 4	Comp	-11 8	-14 6
GFDL	-4 8	-4 8	GFDL	-17 2	-18 9
CCC	-11 0	-11 0	CCC	-23 6	-26 5
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	5117 1	4591 6	Base	0 48	0 43
2XCO2	6863 9	5923 8	2XCO2	0 52	0 45
Comp	5760 5	5133 4	Comp	0 52	0 44
GFDL	5269 0	4558 3	GFDL	0 51	0 43
CCC	4200 9	3602 5	CCC	0 50	0 40
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	34 1	29 0	2XCO2	8 3	4 7
Comp	12 6	11 8	Comp	8 3	2 3
GFDL	3 0	-0 7	GFDL	6 3	0 0
CCC	-17 9	-21 5	CCC	4 2	-7 0
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-63 0	-69 1	2XCO2	-13 3	-13 9
2XCO2	-54 6	-59 5	Comp	-9 4	8 1
Comp	-57 1	-74 7	GFDL	-113 5	-108 4
GFDL	8 5	5 8	CCC	-37 8	-20 8
CCC	-39 2	-54 7			

Table B12. Grande Prairie. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	125.1	125.1	Base	108.2	113.8
2XCO2	125.1	125.1	2XCO2	108.2	113.8
Comp	109.6	109.6	Comp	98.3	105.1
GFDL	112.5	112.5	GFDL	93.1	100.7
CCC	107.0	107.0	CCC	87.1	93.7
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-8.5	-15.7	Comp	-9.9	-8.7
GFDL	-5.6	-12.8	GFDL	-15.0	-13.1
CCC	-11.0	-18.3	CCC	-21.1	-20.1
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	4797.2	4430	Base	0.47	0.42
2XCO2	6430.4	5653.6	2XCO2	0.50	0.44
Comp	5567.1	4852.9	Comp	0.52	0.43
GFDL	4885.6	4291.2	GFDL	0.50	0.42
CCC	3895.7	3360.5	CCC	0.49	0.39
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	34.0	27.6	2XCO2	6.4	4.8
Comp	16.1	9.5	Comp	10.6	2.4
GFDL	1.8	-3.1	GFDL	6.4	0.0
CCC	-18.8	-24.1	CCC	8.5	-7.1
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-65.2	-62.7	2XCO2	-12.4	-17.3
2XCO2	-57.1	-51.9	Comp	-13.5	13.9
Comp	-56.4	-71.4	GFDL	-122.9	-114.7
GFDL	14.9	9.2	CCC	-33.0	-9.6
CCC	-43.7	-56.7			

Table B13. Campsie. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	114 8	114 8	Base	111 5	120 0
2XCO2	114 7	114 7	2XCO2	111 5	120 0
Comp	112 1	112 1	Comp	110 0	117 7
GFDL	106 6	106 6	GFDL	97 5	104 9
CCC	104 9	104 9	CCC	98 9	105 9
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0 0	0 0	2XCO2	0 0	0 0
Comp	-2 7	-2 7	Comp	-1 5	-2 3
GFDL	-8 2	-8 2	GFDL	-13 9	-15 1
CCC	-9 9	-9 9	CCC	-12 5	-14 1
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	3940 7	3486 3	Base	0 51	0 46
2XCO2	4315 0	3770 6	2XCO2	0 50	0 45
Comp	4256 9	3670 7	Comp	0 50	0 44
GFDL	3298 2	2916 2	GFDL	0 48	0 4
CCC	3353 7	2798 5	CCC	0 48	0 40
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	9 5	8 2	2XCO2	-2 0	2 2
Comp	8 0	5 3	Comp	-2 0	4 3
GFDL	-16 3	-16 4	GFDL	-5 9	-10 9
CCC	-14 9	-19 7	CCC	-5 9	-13 0
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-59 8	-66 9	2XCO2	-31 8	-34 4
2XCO2	-40 7	-43 9	Comp	-35 8	-29 4
Comp	-38 4	-47 3	GFDL	-101 1	-96 6
GFDL	0 7	-2 3	CCC	-40 7	-41 9
CCC	-35 5	-38 9			

Table B14. Whitecourt. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)

	Barley	Wheat
Base	115.8	115.8
2XCO2	116.0	116.0
Comp	106.7	106.7
GFDL	103.7	103.7
CCC	100.5	100.5

CHANGE IN PLANTING DATE (in days)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-9.1	-9.1
GFDL	-12.1	-12.1
CCC	-15.3	-15.3

YIELD (kg/ha)

	Barley	Wheat
Base	2577.1	2187.5
2XCO2	2630.9	2304.5
Comp	2625.6	2271.4
GFDL	2129.1	1818.7
CCC	2136.5	1785.3

% CHANGE IN YIELD (kg/ha)

	Barley	Wheat
2XCO2	2.1	5.4
Comp	1.9	3.8
GFDL	-17.4	-16.9
CCC	-17.1	-18.4

CROP MOISTURE STRESS (cm)

	Barley	Wheat
Base	41.5	29.5
2XCO2	63.4	57.6
Comp	40.4	25.5
GFDL	116.0	117.6
CCC	57.8	46.4

DAYS TO MATURITY (DTM)

	Barley	Wheat
Base	115.6	125.5
2XCO2	115.6	125.5
Comp	104.4	111.3
GFDL	100.2	107.8
CCC	93.9	100.5

CHANGE IN DAYS TO MATURITY (DTM)

	Barley	Wheat
2XCO2	0.0	0.0
Comp	-11.2	-14.2
GFDL	-15.4	-17.7
CCC	-21.7	-25.0

GRAIN TO CANOPY RATIO AT HARVEST (G/C)

	Barley	Wheat
Base	0.50	0.44
2XCO2	0.47	0.43
Comp	0.49	0.41
GFDL	0.46	0.39
CCC	0.48	0.39

% CHANGE GRAIN/CANOPY RATIO (G/C)

	Barley	Wheat
2XCO2	-6.0	2.3
Comp	-2.0	-6.8
GFDL	-8.0	-11.4
CCC	-4.0	-11.4

% CHANGE IN CROP MOISTURE STRESS

	Barley	Wheat
2XCO2	52.8	94.9
Comp	-2.5	-13.5
GFDL	179.7	298.1
CCC	39.3	57.2

NOTE Statistics for this table are based on 28 years of weather data

Table B15. Sion. Baseline Mean Experiment Results and Change in Means Under Climate Change Scenarios.

PLANTING DATE (DAY OF YEAR)			DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
Base	115.3	124.2	Base	109.7	113.9
2XCO2	115.3	124.2	2XCO2	109.7	113.9
Comp	107.6	107.6	Comp	99.4	105.7
GFDL	102.7	102.7	GFDL	95.3	102.0
CCC	102.1	102.1	CCC	90.9	97.2
CHANGE IN PLANTING DATE (in days)			CHANGE IN DAYS TO MATURITY (DTM)		
	Barley	Wheat		Barley	Wheat
2XCO2	0.0	0.0	2XCO2	0.0	0.0
Comp	-7.7	-16.6	Comp	-10.2	-8.3
GFDL	-12.7	-21.6	GFDL	-14.4	-12.0
CCC	-13.2	-22.1	CCC	-18.8	-16.7
YIELD (kg/ha)			GRAIN TO CANOPY RATIO AT HARVEST (G/C)		
	Barley	Wheat		Barley	Wheat
Base	3119.7	2766.4	Base	0.51	0.45
2XCO2	3644.3	3148.8	2XCO2	0.50	0.44
Comp	3337.7	2694.4	Comp	0.51	0.42
GFDL	2721.6	2233.5	GFDL	0.47	0.39
CCC	2728.2	2316.4	CCC	0.50	0.41
% CHANGE IN YIELD (kg/ha)			% CHANGE GRAIN/CANOPY RATIO (G/C)		
	Barley	Wheat		Barley	Wheat
2XCO2	16.8	13.8	2XCO2	-2.0	-1.0
Comp	7.0	-2.6	Comp	0.0	-7.1
GFDL	-12.8	-19.3	GFDL	-7.8	-14.9
CCC	-12.5	-16.3	CCC	-2.0	-8.9
CROP MOISTURE STRESS (cm)			% CHANGE IN CROP MOISTURE STRESS		
	Barley	Wheat		Barley	Wheat
Base	-34.4	-42.8	2XCO2	-46.2	-47.2
2XCO2	-18.5	-22.6	Comp	-16.5	3.3
Comp	-28.8	-44.2	GFDL	-174.1	-147.1
GFDL	25.5	20.2	CCC	-79.2	-32.5
CCC	-7.1	-28.9			

END

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FIN