IMPACTS OF PRESENT AND FUTURE CLIMATE CHANGE AND CLIMATE VARIABILITY ON AGRICULTURE IN THE TEMPERATE REGIONS: NORTH AMERICA

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Abstract. The potential impact of climate variability and climate change on agricultural production in the United States and Canada varies generally by latitude. Largest reductions are projected in southern crop areas due to increased temperatures and reduced water availability. A longer growing season and projected increases in CO_2 may enhance crop yields in northern growing areas. Major factors in these scenarios analyzes are increased drought tendencies and more extreme weather events, both of which are detrimental to agriculture. Increasing competition for water between agriculture and non-agricultural users also focuses attention on water management issues. Agriculture also has impact on the greenhouse gas balance. Forests and soils are natural sinks for CO_2. Removal of forests and changes in land use, associated with the conversion from rural to urban domains, alters these natural sinks. Agricultural livestock and rice cultivation are leading contributors to methane emission into the atmosphere. The application of fertilizers is also a significant contributor to nitrous oxide emission into the atmosphere. Thus, efficient management strategies in agriculture can play an important role in managing the sources and sinks of greenhouse gases. Forest and land management can be effective tools in mitigating the greenhouse effect.

1. Introduction

The science of climate is a complex issue. While the physical aspects of this issue are most understood, both climate variability and climate change resulting from natural causes are altered by many anthropogenic influences. Further, the impact of climate variability varies greatly across geographic regions. All ecosystems have evolved to survive changes in climate and environment throughout the ages. Some ecosystems have been able to adjust better than others. The impacts of climate variability and climate change focus on key aspects of this complex issue; i.e., vulnerability and adaptation. Some examples of vulnerability include coastal infrastructure, land use strategy, urban environment, and human health.

Adaptation to changes can be through passive adjustment, reactive response, or proactive action. Passive adjustment is a "survival of the fittest" approach. Adaptation is based on how well the system will adjust to changes after they become the new normal frame of reference. Reactive response is a "wait and see" approach.

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Adaptation measures are not adopted until after the alteration occurs. While the response is measured by the magnitude of change, it is often implemented too late to help the system cope with the consequences. A proactive measure focuses on preparations in advance of the event to help mitigate the impact on the system. The desired adaptation strategy involves proactive measures through long-term planning to mitigate the negative effects of changing climate conditions and to take advantage of the new opportunities of positive effects. However, in order to anticipate and respond to alterations in climate, a thorough understanding of the regional ecosystems is necessary. This section focuses specifically on the vulnerability of agriculture and forestry to climate variability and climate change in North America.

2. Agriculture in North America

The United States is the world's fourth largest country. Nearly 30% of its territory (approximately 260 million hectares) is covered by forests. Over 25% (approximately 240 million hectares) is permanent grassland and other non-forested pasture and rangeland. Approximately 20% of the area (185 million hectares) in the United States is devoted to cropland. The latter category includes land used for crops, land left idle, and land rotated into pasture. Thus, agriculture, including grazing land and forestry represent nearly 75% of the total expanse of the highly industrialized United States (National Assessment Synthesis Team, 2000).

Some interesting trends in agriculture in the United States have been documented. In the past decade, the area of U.S. cropland has declined over 10% as conservation efforts for the most environment-sensitive lands and highly erodible lands have removed about 15 million hectares from the cropping systems (U.S. Department of State, 1997). While there have been declines in area devoted to production, U.S. harvests feed a population that has grown two and a half times in the last century, and its food exports have expanded considerably.

Canada is the second largest country in the world and extends over 997 million hectares in total of which 921.5 million hectares is land area. But the country is sparsely populated, with most of its population concentrated along its southern border. Most of the land area is forested, and only 5% is suitable for farming, mostly in two zones – the Prairies and the mixed Wood Plains of the St. Lawrence River and Great Lakes regions. The Prairies alone account for about 80% of Canada's 68 million hectares of farmland. Two-thirds of all farmland is used for crops and improved pastures (those are seeded, drained, fertilized, or weeded); the rest is occupied by "unimproved" pastures and other land covers. The relative areas devoted to annual crops and animal husbandry vary widely across the country. For example, large areas of the Prairies are used almost exclusively for cropland, whereas small pockets of concentrated livestock production exist in areas of British Columbia and the southern regions of Alberta, Ontario, and Quebec. (Janzen et al., 1998).

Temperate and boreal forests cover nearly half of Canada's land mass. Of the 417.6 million hectares of forests, 234.5 million hectares are considered "commercial forests" – capable of producing commercial species of trees as well as other non-timber benefits. The non-commercial forest area (183.1 million hectares) is made up of open forests comprising natural areas of small trees, shrubs, and muskegs. With about 10% of the world's forests and nearly 25% of the planet's fresh water (much of it in forested areas), Canada's forests play critical roles in moderating climate and filtering air and water (Canadian Forest Service, 2001).

3. Climate of North America

North America has a wide variety of climate conditions, representative of nearly all the major regions of the world. The characteristics of the climatic regimes range from the polar ice cap in the far north of Canada to subtropical conditions in the southern United States. It encompasses arid sections of the western United States to humid regions of the eastern United States. The diverse climate zones, topography, and soils support many ecological communities and supply an abundance of renewable resources. Because of this broad diversity, the effects of changing climatic conditions cannot be oversimplified. Consequently, extensive research has definitely sharpened the focus on trends, impacts, vulnerability, and adaptability of agriculture and forestry to these changes.

Observations over the past century have revealed some interesting trends in U.S. climate. National temperatures, on average, have increased by about 0.6 °C. Regionally, the coastal Northeast, the upper Midwest, the Southwest, and parts of Alaska have experienced increases in annual average temperature approaching 2 °C over the past 100 years. The Southeast and southern Great Plains have actually experienced a slight cooling over the 20th century, but since the 1970s have had increasing temperatures as well, the largest observed warming across the nation has occurred in winter (National Assessment Synthesis Team, 2000).

Focusing on growing season variability in the heart of the Corn Belt, Iowa is the leading corn-producing state in the United States. Figure 1 shows the historical time series of seasonal temperature during the growing season, April to September, during the period 1895–2001. The temperature pattern is quite variable over this time period but there is no clear evidence of warming. However, agriculture was likely impacted by the relatively high degree of temperature variability exhibited throughout the entire period.

One striking feature of temperature records is the influence of urbanization. Studies have documented that urbanization-induced warming can be a full order of magnitude greater than the background trend. While researchers have attempted to remove the urbanization effects, it is a complex issue with spurious urban warming possibly influencing surface-based temperature records. Two methods utilized to

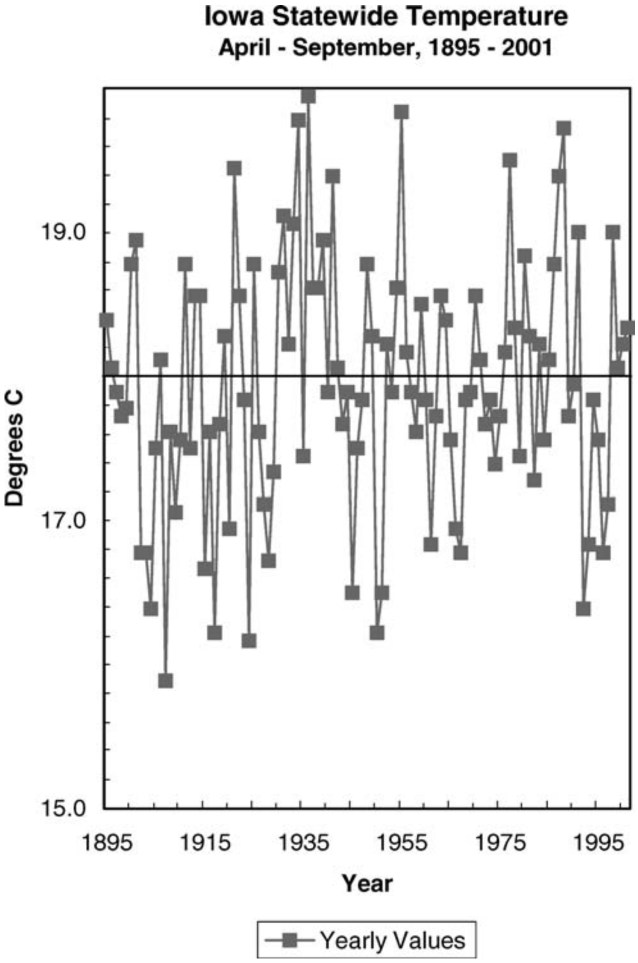

Figure 1. Iowa statewide temperatures (°C) during the growing season, April–September, for the period 1895–2001. Filtered values from a smoothing procedure, computed by NOAA National Climatic Data Center, and the long-term mean value also shown. *Source:* National Climatic Data Center/NESDIS/NOAA.

minimize the urbanization effects include the creation of data sets using a minimum population-based threshold, and, analytical comparisons of soil temperature data at totally rural sites with contemporary air temperature records at nearby towns. Both methods are able to discern an urban warming bias in climatic records (Changnon, 1999; Dow and DeWalle, 2000).

Average U.S. precipitation has increased by 5–10% over the last century, attributable mostly to an increase in the frequency and intensity of heavy rainfall. Precipitation increases have been especially noteworthy in the fertile Midwest, southern Great Plains, and parts of the West and Pacific Northwest. Decreases in annual precipitation were evident in the northern Great Plains (National Assessment

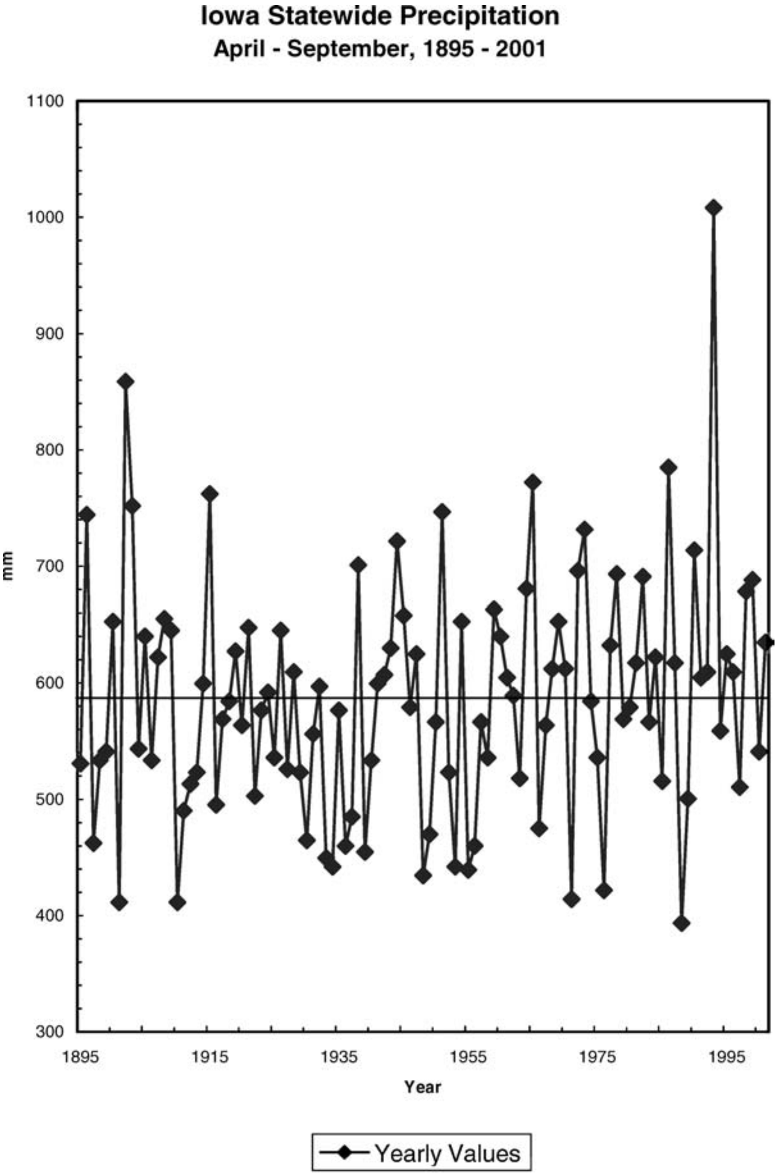

Figure 2. Iowa statewide precipitation (mm) during the growing season, April–September, for the period 1895–2001. Filtered values from a smoothing procedure, computed by NOAA National Climatic Data Center, and the long-term mean value also shown. *Source:* National Climatic Data Center/NESDIS/NOAA.

Synthesis Team, 2000). Figure 2 shows the growing season (April–September) precipitation for the state of Iowa during the time period 1895–2001. As in Figure 1, this chart shows high degree of variability over the entire period. However, the most extreme events occurred within 5 years of each other. The worst drought

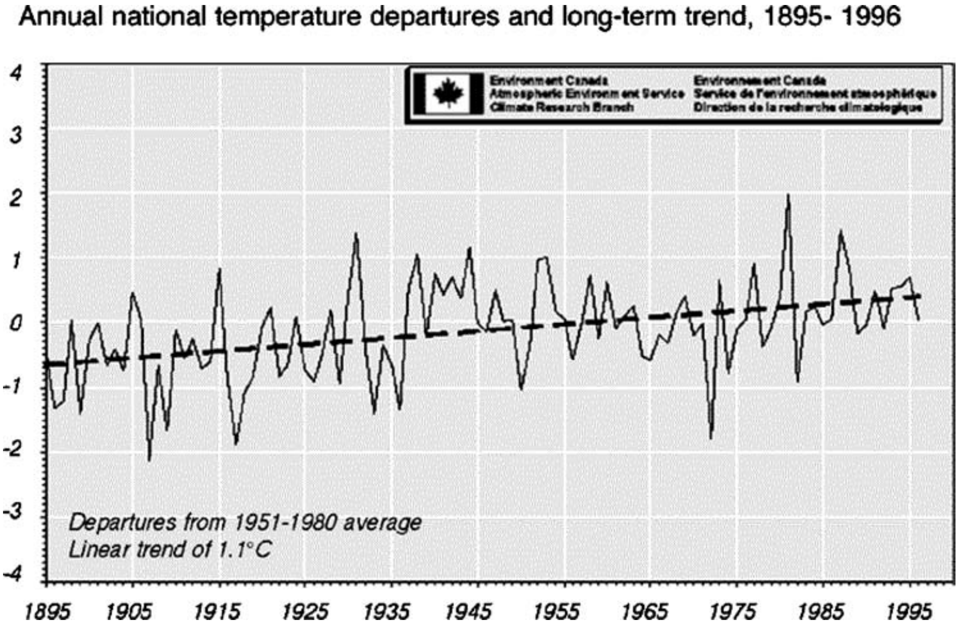

Figure 3. Annual national temperature departures and long-term trend: 1895–1996. *Source:* Environment Canada 1999, p.3.

in this period of record occurred in 1988. The wettest summer growing season occurred in 1993, a year of record flooding in the U.S. Midwest.

In Canada, the average annual climate has warmed by about 1 °C compared to the associated global warming of 0.5 °C. Figure 3 shows the annual national temperature departures and long-term trend, 1895–1996 (Environment Canada, 1999). Regional variations range from a warming of about 1.5 °C in the Northwestern Territories (N.W.T.), to a warming of less than 1 °C over southern Canada, and to a cooling of 0.8 °C in extreme eastern N.W.T. (Environment Canada, 1997a). Consistent with the global precipitation trend, Canada as a whole has also experienced increased annual precipitation (Figure 4). Changes in the mean annual temperature regions of the boreal forests between 1895 and 1994 show a general increase ranging from 0.5 °C over the Northeastern Forest to 1.4 °C over the Northeastern Forest to 1.7 °C over the Mackenzie District (Figure 5).

Zhang et al. (2000) analyzed trends in Canadian temperature and precipitation during the 20th century using recently updated and adjusted station data. Six elements, maximum, minimum, and mean temperatures along with diurnal temperature range (DTR), precipitation totals and ratio of snowfall to total precipitation were investigated. Trends were computed for 1900–1998 (period 1) for southern Canada (south of 60 °N), and separately for 1950–1998 (period 2) for the entire country.

It is interesting to note that the above results for the longer period 1 for southern Canada corroborate those from the Environment Canada (1999), Canada Country

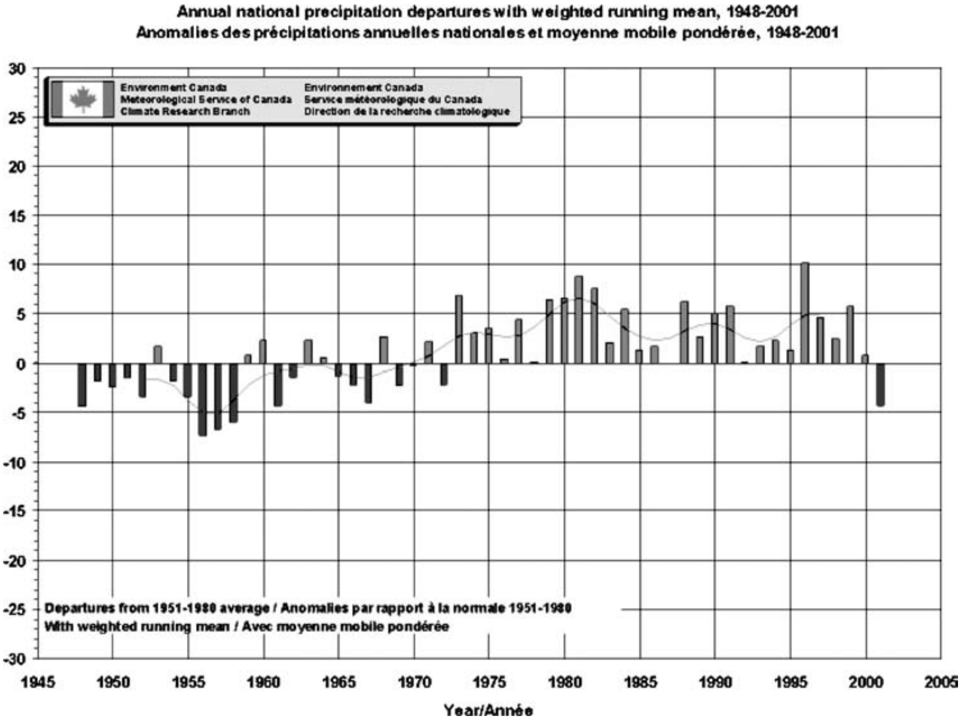

Figure 4. Annual national precipitation with weighted running mean: 1945—2001. (*Source*: Climate trends and variations bulletin for Canada. Annual 2001 temperature and precipitation in historical perspective. *Source:* Environment Canada 2002/2003. Climate trends and variations bulletin for Canada, Annual 2001 temperature and precipitation in historical perspective, p.3. Environment Canada, Meteorological Service of Canada, Climate Research Branch.

Study (CCS) for 1895–1996, whereas those for the shorter and more recent period 2 for the entire country show a somewhat different pattern. From 1900–1998, the annual mean temperature increased between 0.5 °C and 1.5 °C in the south. The warming is greater in minimum temperature than in maximum temperature in the first half of the century, resulting in a decrease of DTR. The greatest warming occurred in the west, with statistically significant increases mostly seen during spring and summer periods. Annual precipitation also increased from 5% to 35% in southern Canada over the same period. In general, the ratio of snowfall to total precipitation has been increasing mostly due to the increase in winter precipitation which generally falls as snow and an increase of ratio in autumn. Negative trends were identified in some southern regions during spring.

From 1950–1998, the pattern of temperature change is distinct: warming in the south and west and cooling in the northeast, with similar magnitudes in both maximum and minimum temperatures. This pattern is mostly evident in winter and spring. Across Canada, precipitation increased from 5% to 35%, with significant

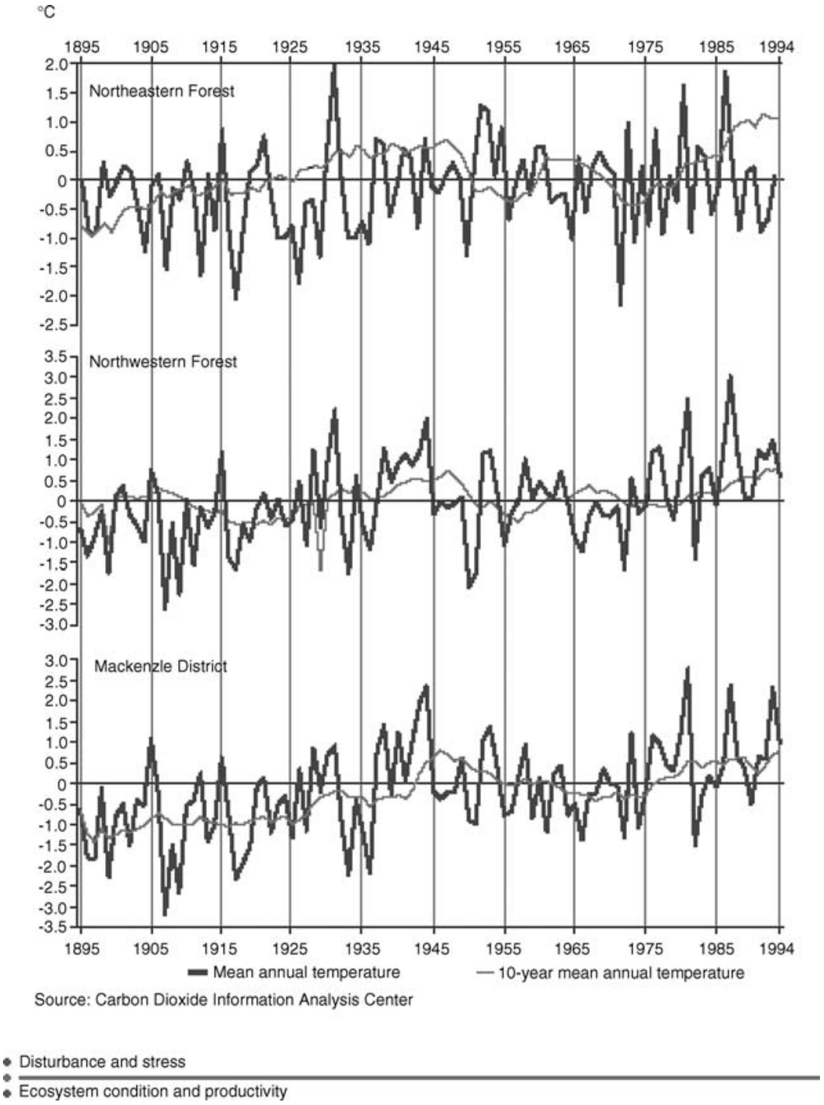

Figure 5. Temperature deviations in three regions of boreal forest: 1985–1994. *Source:* Criteria and Indicators, Criterion 2: Ecosystem condition and productivity, Element 2.1 Disturbance and Stress, Fig. 2.1n, p.36.

negative trends found in southern regions during winter. Overall, the ratio of snowfall to total precipitation has increased, with significant negative trends occurring mostly in southern Canada during spring. Zhang et al. (2000) concluded that climate has been becoming gradually wetter and warmer in southern Canada throughout the entire century, and in all of Canada during the latter half of the century.

In another study of precipitation characteristics in Canada during the past century, decadal variability was found to be a dominant feature of both the frequency and intensity of annual precipitation (Zhang et al., 2001). The observed upward trend in precipitation totals was mainly due to increases in the number of small-to-moderate rainfall and snowfall events. There appears to be upward trends over eastern Canada and in the number of heavy snowfall events for autumn and winter over northern Canada.

Similar findings were also reported by Akinremi et al. (1999) from studies on precipitation trends at 37 stations with 75 years of records across the Canadian prairies. The analysis showed that there has been an increase in rainfall amount, an increase in the number of events, and a decrease in the variance of rainfall within the last 75 years. However, snowfall has declined from 1961 to 1995. The difference in trends for snowfall between period 1 (1921–1960) and period 2 (1961–1995), combined with the inverse relationship in the rainfall-snowfall trends, suggests that these trends may be related to climate change.

Precipitation seems to have increased and become more variable over the past 100 years (Bootsma, 1994, 1997). This may have impacted agriculture through reduced drought stress but may have increased problems in coping with excess moisture. Increased variability may have resulted in greater fluctuations in crop yields in recent decades. While long-term changes in precipitation are statistically significant, they are still relatively small in comparison to the year to year variability that growers must contend with (Bootsma, 1997). Soil moisture is critical for both agriculture and natural ecosystems. While observations of soil moisture are wholly inadequate for analysis, there is a good understanding of its relationship to climate. Soil moisture levels are determined by an intricate interaction between precipitation, evaporation, run-off, and soil drainage. Precipitation is the source for soil moisture. However, higher air temperatures increase the rate of evaporation and may remove moisture from the soil faster than it can be added by precipitation. Under this scenario, a region would become drier even though rainfall increases. These conditions have been observed in portions of the Great Plains and eastern seaboard, where precipitation has increased and air temperature has risen. Bootsma's conclusions are substantiated by the trends computed for 1900–1998 for southern Canada reported by Zhang et al. (2000) viz. an annual mean temperature increase between 0.5 °C and 1.5 °C and an annual precipitation increase from 5% to 35%.

Projections of future climate are generally derived from Global Circulation Models (GCMs) which depict scenarios of what is expected under particular assumptions. Scenarios provide a realistic framework to help identify vulnerabilities and plan adaptation strategies. The following scenario analysis of future U.S. climate, discussed in the next several paragraphs, was developed by the National Assessment Synthesis Team (2000) for the United States Global Change Research Program. Average warming in the U.S. is projected to be somewhat greater than for the world as a whole over the 21st century. Seasonal patterns indicate that projected changes will be particularly large in winter, especially at night. In summer, temperature increases in the South will raise the heat index, a measure of discomfort based on temperature and humidity, significantly.

Model projections of precipitation change are in less agreement. Generally, western and northern portions of the nation are projected to receive increased precipitation mainly in the winter. There is divergence of expectation for southern and eastern areas of the nation, however, with some GCMs projecting increases and other indicating decreases. The largest projected decreases are most evident during summer. One very interesting observation can be made from these model projections. There is general agreement that most regions are expected to experience an increase in the frequency of heavy precipitation events. This model projection raises concern over the impact that these extreme precipitation events would have on flooding and erosion which are key issues for agriculture.

In the West, the models generally concur that a warmer Pacific Ocean would pump moisture into the region and cause a southward shift in Pacific Coast storm activity. With projected temperature increases, much of the increased precipitation in winter would fall as rain rather than snow, causing a reduction in mountain snowpacks. Winter snowpack is a major source of water in the West for both summer agriculture and hydroelectric power generation. Thus, while wintertime river flows would tend to increase, diminishing snowpacks would reduce summertime flows creating potentially dangerous water shortages in the heat of summer.

Projections of soil moisture are even more diverse because any differences in change in precipitation and temperature are accentuated in the soil moisture projections. Model projections generally agree that soil moisture increases are likely in the U.S. Southwest. In the models that project both significant increases in temperatures and decreases in precipitation, substantial soil moisture decreases are common, most notably from the central Great Plains to the East. However, models that project more modest warming and precipitation increases generally result in soil moisture increases over these same areas.

Another interesting and important feature of this scenario analysis for agriculture is drought tendencies. Models generally indicate increased incidence of drought, especially east of the Rocky Mountains from the Great Plains to the East. Intense drought tendencies are projected to increase in many agricultural areas of the nation. Both soil moisture availability and drought tendencies will have a significant impact on water supply, the vigor of agriculture, and the health of forests. In Canada, the climate is expected to change with significant regional variations. Long-term (100 years) climatic trends for agriculture were studied for five locations in Canada: Agassiz, B.C., Indian Head, Saskatchewan; Brandon, Manitoba; Ottawa, Ontario; Charlottetown, Prince Edward Island (Bootsma, 1994). A total of 17 agroclimatic parameters were computed on a yearly basis from daily climatic data. The parameters included climatic characteristics of importance to agriculture such as frost dates, growing degree days, temperature, precipitation, potential evapotranspiration and forage aridity index. The climatic attributes were extremely variable, such that detection of warming (greenhouse induced or otherwise) was difficult. Most of the evidence of climatic warming comes from stations located in western Canada. This warming is mainly confined to the growing season and is not apparent in mean temperatures during winter. The temporal variations are not uniform over space. Stations in western Canada indicated trends of increased frost-free periods, growing degree-days and corn heat units. Stations in eastern Canada did not exhibit the same warming trend.

4. Impacts of Climate Variability and Change on Agriculture in North America

Before discussing future projections, let's return to the state of Iowa and look at agricultural trends over the past century. Figures 1 and 2 presented time series of seasonal growing season temperatures and precipitation during the past century for the state of Iowa. How do they compare with corn yields for Iowa during the same period? Figure 6 presents the time series for corn yields during 1895–2002 for the state of Iowa, revealing some interesting comparisons. First, there are three relatively stable trends in this time series. During the 1895–1940 period, there is no upward trend revealed in the data, with relatively low variability, except in the mid-1930s associated with a prolonged drought. From 1940 to 1970, generally low variability is evident but a substantial increase in trend yields is associated with the introduction of fertilizers, seed hybrids, and better farm management practices. From 1970 to the mid-1990s, the upward trend in yields continues but this period is marked with high variability around the trend yields.

Ironically, the greatest departures from trend yields occur within 5 years of each other due to extreme but contrasting weather events. In 1988, one of the worst droughts in modern history during the growing season (see Figure 2) caused significant agricultural losses. In 1993, even greater yield losses were caused by

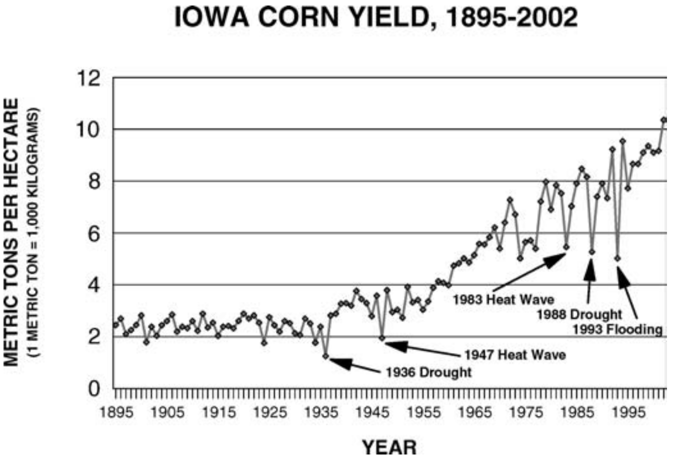

Figure 6. Iowa statewide corn yields (metric tons per hectare) for the period 1895–2002. Years of unusually extreme weather events documented. *Source:* United States Department of Agriculture.

severe and prolonged flooding in the U.S. Midwest. This represents a period of extreme weather variability over a relatively short climatic period.

While drought and flooding cause significant yield losses as illustrated in Figure 6, untimely heat during critical growth phases can also have a significant negative impact on yields. Corn development is especially sensitive to the weather during the crucial reproductive phase of development. Hot, dry weather during silking can inhibit grain development, reducing the yield potential. The large negative departures from trend noted in 1947 and 1983 were caused by untimely heat waves during the crucial reproductive phase. The impact of these extreme weather events are demonstrated in these charts and illustrate how weather and climate variability are major factors affecting the success or failure of crops in the U.S. Midwest.

The potential impact of climate change on agricultural production in the United States and Canada varies mostly by latitude. In the United States, projections based on scenarios from GCM outputs indicate a decrease in yields of all major unirrigated crops based on the premise of increased temperature and reduced crop-water availability. The largest reductions are projected for the South and Southeast. In northern areas, however, where temperature is currently a constraint on growth, yields of unirrigated corn and soybeans could increase as higher temperatures increase the length of the available growing season. When the direct effects of increased CO_2 are considered, yields may increase further in northern areas. Some recent climate models are projecting higher expected precipitation due to feedback mechanisms. However, higher air temperatures will increase the rate of evaporation. In some areas, moisture loss may still be greater than the increased projected precipitation. With the relative increase in productivity in northern areas and decrease in southern areas, a major northward shift in land use is implied for the United States.

The comprehensive Canada Country Study (CCS), Climate Impacts and Adaptation provides a state-of-the-art assessment based on a range of scenarios from five GCMs developed in Canada, United States and United Kingdom (Environment Canada, 1999). The assessment indicates that an important dimension to the relationship between climate change and agriculture is the wide range of conditions for agricultural production between different regions in Canada. There has been considerable research into the possible implications of climate change scenarios for agro-climatic conditions in all regions of Canada. These studies have considered several climatic change scenarios and have examined the implications of altered climates for wide range agro-climatic properties, including the growing and frost free seasons, and seasonal values for temperature, growing degree days, corn heat units, precipitation and moisture deficits. The implications for thermal regimes have been investigated more thoroughly than the implications for moisture regimes.

According to the CCS, all of the global climatic change scenarios and studies suggest warming for most of Canada. Impacts of climate change on agriculture will be most directly reflected through the response of crops, livestock, soils, weeds, and insects and diseases to the elements of climate for which they are most sensitive. Soil moisture and temperature are the climatic factors likely to be most sensitive to change across large agricultural areas of Canada. Longer frost free seasons more conducive for commercial agriculture are expected under climate change. For the Prairies, Ontario and Quebec, most estimates suggest an extension of 3 to 5 weeks. Results relating to moisture regimes show estimated precipitation changes ranging from decreases of about 30% to increases of 80%.

The CCS further concludes that despite favorable potential impacts in terms of longer and warmer frost-free seasons and of greater precipitation, most climate change scenarios also imply important increases in potential evapotranspiration. This may lead to larger seasonal moisture deficits in many regions of Canada, with the severest situations anticipated for Ontario. Impacts on agricultural land potential north of 60° are generally considered to be insubstantial in nature. However, the Peace River region and northern agricultural areas in Ontario and Québec are expected to see some expansion of the land area suitable for commercial crop production. The physical potential for fruit and vegetables could expand beyond current southern locations in Québec, Ontario and British Columbia, but may be very much limited by lack of suitable soils for agriculture in these regions.

Other results suggest largest changes in soil moisture deficits will likely be in the southern prairie regions of Saskatchewan and Manitoba, but results vary somewhat depending on which GCM is used and how deficits are determined. See for example, the soil moisture maps available on the web site of the Canadian Climate Impact Scenario project (CCIS) at: http://www.cics.uvic.ca/scenarios/index.cgi.

Computer simulation models have been extensively used for analysis of the complex climate-crop interactions and the assessments of climate change on agroclimate, agricultural resources and crop production. Such studies are important for national and international resource planning because Canada is identified to become even more prominent as a supplier of food with projected climate change (IIASA, 2001). While the agricultural sector of the economy is highly vulnerable to climate change, it is generally felt that agriculture can readily adapt to the kinds of changes that have occurred over the past 100 years or so (Bootsma, 1997). However, projected changes for the next 100 years by the GCMs are substantially larger by at least an order of magnitude than changes that have occurred over the past 100 years. If these projections are accurate, agriculture may experience increased difficulty in adapting to any negative impacts. On the other hand, projected changes in climate could result in longer and warmer frost-free periods across Canada and, thereby, generally enhance thermal regimes for commercial agriculture. The extent to which these changes might benefit Canada, however, will in all likelihood be diminished by less soil moisture in all regions and under all climate change projections (Environment Canada, 1997b).

Climate variability raises another major concern in Canada. Large tracts of land in the prairies lie unprotected from the wind (McRae et al., 2000). In fact, about two-thirds of the prairie region would be under a moderate to severe risk of wind erosion if soil conservation measures were not taken. Improved tillage practice has reduced the risk of wind erosion in the Prairies by about 30% from 1981 to 1996

(McRae et al., 2000, p. 72). However, higher temperatures, lower precipitation, and higher wind speeds, associated with climate extremes, would have a negative impact on crop productivity potential.

Another important point for consideration of agricultural impacts related to climate variability is the difference between primarily rainfed agriculture and irrigation agriculture. Gadgil et al. (2000) notes that, in rainfed agriculture, yields tend to be lower and there are large fluctuations in yield induced by variations of the environment. In this agricultural system, available resources for input to the system are typically low. In the more mechanized irrigation-based agricultural system, higher-yielding varieties involve large inputs from the farmers in terms of fertilizers and pesticides and from the farmers/government in irrigation of the lands. Consequently, the impact of climate variability typically was reduced by adopting measures such as irrigation.

Irrigated agriculture is common in the western United States, relying heavily on winter snowpack in the Rocky Mountains as the principal source of irrigation supplies. Intensive agriculture has been highly successful but heavily dependent on these irrigation reserves. Extreme climate variability and changing climatic trends may have a profound effect in this production system for two reasons. First, if the tendency is for winter precipitation to diminish during this scenario of more extreme variability or climate change, the available supply of water for agriculture will be reduced. However, some GCMs show increased precipitation over winter in the western U.S. for future climate (see, for example, maps available on the CCIS web site: http://www.cics.uvic.ca/scenarios/index.cgi). It is more likely that the winter snow pack may be reduced due to increased melt during winter and more precipitation in the form of rain rather than snow.

At the same time, increasing competition for water due to higher population in urban centers and greater demand for hydroelectric power generation compounds the issue of agricultural water supplies. In the long-term, policymakers need to focus attention on these water management issues as they affect all segments of the economy.

The environmental consequences of agriculture are strongly influenced by climate. Significant problems other than highly variable crop production include substantial loss of fertile topsoil to erosion; spread of desert-like conditions; water logging, salinization, and alkalization of formerly productive areas; and, flooding and silting due to deforestation. Climate variability and associated extreme weather events contribute substantially to agricultural losses caused by these problems. Thus, agriculture is highly vulnerable to the vagaries of climate.

5. Agriculture's Role in Greenhouse Gas Emissions

The complex interactions become even more confusing as noted earlier by the growing concern over greenhouse gases. Warming from the natural phenomenon, characterized by warming from the atmospheric greenhouse effect, is highly beneficial to life as it exists on earth. The gases causing the warming of the atmosphere are known as greenhouse gases, including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 is released to the atmosphere when solid waste, fossil fuels, and wood are burned. Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from the decomposition of organic wastes in municipal solid waste landfills, and the raising of livestock. Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of solid waste and fossil fuels.

There is growing evidence that the concentrations of CO_2, CH_4, and N_2O have been increasing steadily since the Industrial Revolution, associated with more intense human activity. Greenhouse gases may have the desired effect of warming the atmosphere sufficiently to create favorable conditions for biological activity in some areas. Enhanced greenhouse warming due to human activity may, however, lead to uncertain, disruptive consequences to the natural ecosystems.

Agriculture is a relatively minor source of gases that contribute directly to changing climate conditions. However, agriculture is especially sensitive to climate and atmospheric composition. Agriculture can play a contributing role in slowing the buildup of greenhouse gases. Changes in land use and forestry activities can emit CO_2 to the atmosphere through the conversion of forest land to agricultural or urban use. Forests are a major terrestrial sink for CO_2. Approximately half the dry weight of wood is carbon and, as trees add mass to trunks, limbs, and roots, carbon is stored in relatively long-lived biomass instead of being released to the atmosphere. Soils and vegetative cover also provide potential sinks for carbon emission. Soils and trees act as natural sinks for carbon, with hundreds of billions of tons of carbon in the form of CO_2 absorbed by oceans, soils, and trees each year. Thus, removal of forests and changes in land use, associated with the conversion from rural to urban domains, alters this natural sink for carbon and increases the potential for atmospheric CO_2.

The agricultural sector produces a significant amount of methane emission (Desjardins et al., 2001). Animal digestion in domestic livestock is the leading contributor to agricultural methane emission (McRae et al., 2000). Enteric fermentation, the process in which microbes that reside in animal digestive systems, breaks down the feed consumed by the animal and releases methane. The decomposition of organic animal waste in an anaerobic environment also produces methane. Rice cultivation is another source of methane emission (Lal et al., 1998; Wang et al., 1996). The soil's organic matter decomposes under the anaerobic conditions created by flooded fields, releasing methane to the atmosphere through the rice plants. These are considered major sources of methane in the atmosphere.

The application of synthetic nitrogen and organic fertilizers is a leading contributor to N_2O emissions. Bacterial action on the chemical fertilizers results in the release of N_2O. The gas is released when soil microbes digest the fertilizers. The more inorganic nitrogen-based fertilizers that are applied, the more N_2O goes into the atmosphere. This potent pollutant is detrimental to the life-preserving ozone layer (Lyman et al., 1990). Soil management practices, such as irrigation, tilling, or laying fallow the land can also affect N_2O fluxes to and from the soil.

Thus, agriculture has a significant role in the inventory of atmospheric greenhouse gases and in mitigation measures to reduce greenhouse gases. CO_2 accounts for 85% of net U.S. greenhouse gas emissions in 1995 (U.S. Department of State, 1997). Lower harvests in old-growth forests help prevent CO_2 emissions. A shift toward ecosystem management also favors timber harvest methods that inflict less damage, and helps retain carbon in forest lands. The conversion from conventional tillage to reduced-tillage systems increases soil organic carbon (SOC) content that amounts to sequestration of atmospheric CO_2. Removal of erosion-prone land from cropping, and seeding it in perennial grasses, also allows soils to sequester carbon.

Rosenzweig and Hillel (2000) noted that proper land management aimed at enhancing soil organic matter improves soil fertility and soil structure, reduces soil erosion, and helps to mitigate the greenhouse effect. It is estimated that methane comprised about 11% of U.S. greenhouse gas emission in 1995. The improvement in animal breeding and husbandry, the adoption of biotechnology, and the current declining trend in the consumption of milk and red meat could cut methane emission by 20%. Research on ways and means of capturing methane released from manure management systems and using the captured methane as an on-farm energy resource showed that it is technologically feasible (Janzen et al., 1998., p. 55). More efficient animal production through improved grazing management, strategic feed supplementation, genetic characteristics and reproduction, and disease control contributed toward reduced methane emission (U.S. Department of State, 1997). Finally, while nitrous oxide emissions account for only about 3% of U.S. greenhouse emission in 1995, improved management of fertilizers could reduce N_2O emissions from the soil.

In Canada, the effect of agriculture on the atmosphere has been documented in a national report entitled: *The Health of Our Air* (Janzen et al., 1998), which is a companion report to *The Health of Our Soils* and *The Health of Our Water*. *The Health of Our Air* provides first comprehensive estimates of GHG emissions from Canadian agriculture with reference to the global concepts. It addresses in detail the amounts of the various greenhouse gas emissions and possible ways of reducing them. Many of the findings presented were obtained from a national research program initiated by Agriculture and Agri-Food Canada in 1992.

The three most important three greenhouse gases (CO_2, CH_4, and N_2O) of current concern differ in their warming effects. To compare their relative effects, therefore, their emissions are usually expressed as "CO_2 equivalents." One kilogram of N_2O has the warming effect of about 310 kg of CO_2 (when considered over 100 years), so it represents 310 CO_2 equivalents. Similarly, 1 kg of CH_4 represents 21 CO_2 equivalents. According to best estimates, using the approaches described for each gas, farm management practices contributed about 10% of Canada's GHG emissions or 67 T.g. (million tonnes) of CO_2 equivalents in 1996 (Table I). Of this

TABLE I
Estimates of total greenhouse gas emissions from Canada's agroecosystems

	(T.g. CO_2 equivalents)						
	1981	1986	1991	1996	2000[a]	2005[a]	2010[a]
CO_2	9	7	5	3	1	0	0
CH_4	22	20	20	23	23	24	25
N_2O	32	33	34	41	43	45	48
Total	63	60	59	67	67	69	73

[a] Predicted using a scenario of medium growth from Canadian Regional Agricultural Model (CRAM) to 2007. All 2010 data follow a best-fit trend using data from 1993 to 2007 from the CRAM (Kulshreshtha et al., 2000). All fertilizer data were predicted using a best-fit trend from 1981, 1986, 1991, and 1996 Census data. All sheep, chicken, and turkey populations were predicted using a best-fit trend from Census data. (From: Janzen et al., 1998, Table 14.)

amount, about two-thirds was as N_2O and about one-third as CH_4. Livestock and Manure account for about 58% of these emissions, cropping practices for 37%. By comparison, net emissions as CO_2 were almost negligible. The estimates of CO_2 emission, however, exclude most of the CO_2 from fossil fuels used to produce inputs, power farm machinery, and transport products. These sources emitted about 25 T.g. (million tonnes) of CO_2 in 1996. With these emissions from all other agricultural practices included, the agriculture sector's contributions were about 15% of Canada's emissions.

The emissions of greenhouse gases from Canadian agriculture are increasing, according to current estimates (Table I). By 2010, emissions may be about 9% higher than those in 1996, unless producers adopt better management practices. These projected increases stem largely from predicted increases in livestock numbers and N inputs as fertilizer and manure. Emissions of CO_2 are expected to decline, but not nearly fast enough to compensate for predicted increases in the other gases.

The above Canadian statistics are not without uncertainties, N_2O has the highest and CO2 lowest uncertainty. Nevertheless they serve as a reference point for showing trends. Future emissions will depend on changes in farming practices that are hard to predict. Livestock numbers, crops that are grown, fertilization patterns, and manure management techniques can all change quickly, throwing off the current best projections (Janzen et al., 1998).

At one time, agriculture was also an important source of CO_2 because of the substantial loss in soil carbon that has occurred since cultivation began through conversion of forest and rangeland to arable land, fertilizer manufacture, and fossil fuel use. However, these emissions have decreased to almost negligible levels. Smith et al. (2000), using the Century model for the period 1970–2010, simulated changes in SOC in agricultural soils of Canada. Changes in SOC in agricultural soils influence soil quality and greenhouse gas concentrations in the atmosphere. The simulation changes indicate that the agricultural soils in Canada, whose SOC are currently very close to equilibrium, may stop being a net source of CO_2 and will become a sink by the year 2000. The rates of carbon change for the years 1970, 1990, and 2010 were estimated to be -67, -39 and 11 kg C ha^{-1}. These changes are the result of an increase in the adoption of no-tillage management, a reduction in the use of summer fallowing, and an increase in fertilizer application.

6. Scenarios of CO_2, Climate, and Agriculture

As the CO_2 content of air rises, many plants exhibit increased rates of net photosynthesis and biomass production. Plant water use efficiency is defined as the amount of carbon gained per unit water lost per unit leaf area. Plant water use efficiency among many field crops and grasses is directly related with atmospheric CO_2 enrichment. Thus, from agriculture's perspective, as CO_2 content of air continues to rise, plant life in general should exhibit increases in water use efficiency and biomass production. In Canada, Rosenzweig et al. (1993) analyzed model scenarios and found that a 2 °C increase in temperature with no precipitation change resulted in wheat yield increases with the direct effect of CO_2 taken into account.

The productive capacity of a plant is the net resultant of two processes, photosynthetic fixation of carbon dioxide and its release by respiration (Rosenberg, 1974). Crop species vary in their response to $CO_{2.}$Wheat, rice, soybeans, cotton, oats, barley, and alfalfa belong to a physiological class called C3 plants that respond readily to increased CO_2 levels. Corn, sorghum, sugarcane, millet, and other tropical grasses are C4 plants, though more efficient photosynthetically than C3 plants at present levels of CO_2, tend to be less responsive to enriched concentrations. C3 crops show an average increase in et primary production of approximately 33% for a doubling of atmospheric CO_2 (Koch and Mooney, 1996). Some field studies show C4 plants responded to elevated CO_2 due to increased water use efficiency (Owensby et al., 1993).

Elevated atmospheric CO_2 concentrations tend to reduce the size of open stomatal pore space on leaf surfaces. Thus, plants tend to display lower stomatal conductances which effectively reduces the amount of water lost to the atmosphere via transpiration. As a result, the soil moisture content would likely rise with increased atmospheric CO_2 content, given no change in precipitation trend.

However, the reduced transpiration may be offset by higher evaporation at higher temperatures. While water use efficiency may increase under this scenario, the effects of higher temperatures may negate any beneficial effects. For example, increased temperatures may accelerate the rate at which plants release CO_2 through respiration, resulting in less tan optimal conditions for net growth (Rosenzweig and Hillel, 1995).

Highly productive forest ecosystems have the greatest potential for absolute increases in productivity due to CO_2 effects. Studies have shown a stimulation of photosynthesis of about 60% for a doubling of CO_2 (Saxe et al., 1998; Norby et al., 1999). A fast growing young pine forest showed an increase in 25% in net primary production for an increase in atmospheric CO_2 to 560 ppm (DeLucia et al., 1999). Slowing deforestation and promoting natural forest regeneration and afforestation could increase CO_2 storage.

The direct biological effects of atmospheric CO_2 enrichment tend to mimic a warming and moistening of the environment. This is expected because plant optimum temperatures and water use efficiencies both rise. Studies have shown that woody species, such as oak trees, will gradually expand onto arid and semi-arid grasslands due to increased precipitation patterns, especially during the summer growing season. This is a likely scenario in the southwestern United States where climate models generally predict a tendency toward increasing precipitation.

The rise in atmospheric CO_2 should also have a significant positive effect upon pasture and rangeland productivity, based on research studies. CO_2 enrichments appear to slightly augment the legume content of grasslands, providing more nitrogen to the ecosystem which promotes the nutritive quality of the forage. Increases in the air's CO_2 content should enable pasture and rangeland plants to better cope with water deficits.

Experiments have also shown that elevated CO_2 consistently enhanced rates of net photosynthesis in upland cotton (Ready et al., 1999). These studies indicated that although elevated CO_2 did not significantly impact boll size or maturation, it did increase boll numbers by about 40% regardless of temperatures, without changing fiber properties. The results infer that if air temperatures in cotton-growing areas of the United States increase in future years, the predicted rise in the air's CO_2 content will enhance cotton photosynthesis rates, boll production, and fiber yields without altering fiber quality. It remains unclear, however, if the enhanced photosynthesis due to the direct effect of higher CO_2 will be offset at least partially by projected higher moisture stress in some areas.

7. Vulnerability of the Agricultural Sector

Rosenzweig et al. (1993) presented some interesting results based on current production and change in simulated wheat yields under GCM climate change scenarios. For the GCM doubled CO_2 climate change scenario, simulated yield increases in mid- to high-latitudes were caused by the positive physiological effects of CO_2 and the lengthened growing season. In contrast, decreases in simulated yields were caused by shortening of optimum growth periods due to higher temperatures, decreases moisture availability and poor vernalization.

As mentioned earlier, increased concentrations of greenhouse gases in the atmosphere are a major factor in contributing to enhanced natural climate variability. Climate extremes are becoming more pronounced and the impact on agriculture can be catastrophic in terms of productivity declines and economic losses. Rapid geographical shifts in the agricultural land base, brought about by very rapid climate changes, could disrupt rural communities and associated infrastructures.

McCracken et al. (1990) reviewed the critical issues in agricultural impact assessment. Agricultural crops and livestock are extremely vulnerable to extreme events, such as droughts, heat waves, and severe storms. The frequency, intensity, and duration of extreme climatic events can be more consequential to crop yields than changes in mean values. Another important aspect of this analysis is that next to climate, technology is the most critical factor affecting agricultural productivity. Projecting the impact of future climate change requires a projection of future technological improvements.

Even in the highly industrialized United States, agriculture is highly vulnerable to the vagaries of climate and the complex interactions between farming and the environment. Farming has successfully produced food and fiber but it also caused environmental degradation. Worldwide degradation of agricultural land causing irreversible loss of productivity is estimated to be 6 million hectares per year (Lal et al., 1998). Soil erosion by wind and water has been significant, but any decline in yields has been largely offset by greater use of fertilizers. However, off-farm pollution due to runoff of fertilizer and agrichemicals has increased. As a result of these issues, an alternative approach to conventional farming practices has evolved. This approach focuses on the reduction of environmentally damaging use of fertilizers and chemical pesticides through processes that directly or indirectly (by reducing waste) affect fertilizer and pesticide consumption. These processes include improved efficiency of fertilizer uptake by a plant; biological pest control practices; production of plants more resistant to stress; and reduction of post-harvest losses through better storage, handling, and distribution (Bugliarello, 1989).

8. Adaptation Strategies

Agriculture in the United States and Canada has many strong points in its favor to permit successful adaptation to climate variability and climate change. The overall production system is technically advanced and can adopt new technology rather quickly. It is regionally diverse, making adaptation to a wide range of conditions quite feasible (IPCC, 2001). The agricultural sector is highly productive, intensively managed, and market based. Further, agriculture accounts for less than 5% of the national gross national product (GNP), allowing considerable flexibility to adapt to changes required in the production system. At the same time, it would be prudent for agriculture to take advantage of any positive opportunities offered by climate change in order to maximize production efficiency and remain competitive in the international marketplace.

U.S. agriculture is vulnerable to rapidly changing climate conditions. The range over which major crops are planted could eventually shift hundreds of kilometers to the north. The availability of fresh water and the distribution of pests and diseases may have significant impacts on production potential. The goals of adaptation strategies are to improve the knowledge and skills of farmers, to encourage adoption of new technologies, and to expand the array of options available to farmers.

One option of the research community is to continue to develop new ways for certain crops to adapt to climatic constraints, such as warmer or colder temperatures, and drier conditions. More recent innovations in biotechnology offer promising new techniques. New tissue-culturing and genetic-engineering tools, combined with traditional agricultural breeding methods, alter plants to incorporate greater disease, insect, and weed resistance, and to better withstand environmental stresses such as drought, heat, and frost. Efficient water resource planning is also an essential aspect of adaptation strategies for agriculture.

Erosion in the Great Plains was reduced after devastating losses of valuable topsoil during the dust bowl years of the 1930s by planting shelterbelts of trees to reduce wind erosion. Reduction of summer fallow practice and move to minimum or zero tillage are management practices which have reduced erosion and promoted higher soil organic matter (McRay et al., 2000, Chapter 7). Other means of alternative agriculture included systematically incorporating natural processes, such as nutrient cycles, nitrogen fixation, and pest-predator relationships into the agricultural production process; reducing the use of chemicals and fertilizers; making greater use of the biological and genetic potential of plant and animal species; improving the match between cropping patterns and the productive potential and physical limitations of agricultural lands in order to ensure the long-term sustainability of the land; and, emphasizing improved farm management and conservation of the soil, water, and biological resources (World Resources, 1992).

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Having noted this, however, it must also be said that given the uncertainties and serious consequences of potentially inaccurate assessments, a prudent course of action is to aggressively study and research how best to limit and mitigate the impacts of climate change or agriculture. Complacency poses great risk. A vigorous effort is needed to understand and prepare for potentially serious impacts on agriculture by developing strategic adaptation strategies.

Crop yields and variability under climate change (historic baseline and $2 \times CO_2$ scenario) and adaptive crop management scenarios (planting dates; harvest dates; fertilizer applications; tillage practices) were assessed for the major agricultural regions across Canada, using the EPIC simulation model (De Jong et al., 2001). EPIC (version 5300) integrates the major processes that occur in the soil-crop-atmosphere management system, including hydrology, weather, wind and water erosion, nutrient cycling, plant growth, soil temperature, tillage, plant environmental control

TABLE II

Summary of crop yields and standard deviations as simulated by EPIC for baseline (1966–1995 period) and a future climate scenario (2041–2060 period) for selected locations in Canada

		Yields (Mg/ha)			
		Average		Std. Dev.	
Crop	# sites	Baseline	$2 \times CO_2$	Baseline	$2 \times CO_2$
Barley	29	3.5	3.5	0.77	0.94
Spring wheat	25	2.8	2.7	0.85	0.91
Canola	12	2.5	2.6	0.89	1.03
Corn	6	5.7	5.0	1.73	1.99
Soyabeans	6	2.0	2.2	0.56	0.83
Potatoes	5	6.7	7.9	0.81	1.01
Winter wheat	3	3.5	4.2	0.67	0.77

Source: Results were taken by A. Bootsma from: De Jong, R., Li, K. Y., Bootsma, A., Huffman, T., Roloff, G., and Gameda, S. 2001. Crop yield and variability under climate change and adaptive crop management scenarios. Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre, Ottawa, Ontario, Climate Change Action Fund Project A080, Final Report. 49 pp.

and economics. Under a warmer and slightly wetter $2 \times CO_2$ climate scenario, the planting dates advanced 1 to 2 weeks in eastern and central Canada and by approximately 3 weeks in western Canada. Yields of spring planted barley, wheat and canola (prairie region only) did not change significantly (Table II). Corn yields in central Canada decreased significantly by 11%, although with increased nitrogen fertility the yield decrease was reduced to less than 5%. With the projected longer growing season, higher yielding corn hybrids with higher heat unit regimes may also negate the projected yield declines. Soybean, potato and winter wheat yields increased by approximately 12%, 16% and 18% respectively. The temporal yield variability of all crops increased under the $2CO_2$ scenario from 6% for spring wheat to 50% for soybeans. The reduction in corn yields predicted by the EPIC model is probably the result of water stress, as other studies have suggested that even many areas in central Canada (Ontario/Quebec) may, like soybeans, have increased corn yields as a result of being able to grow longer season, higher yielding hybrids with the higher heat units regimes.

Based on the assumption that at least 2400–2500 crop heat units must be available for the crop to mature, corn and soybeans could be grown under the $2 \times CO_2$ climate scenario at all locations (29 climate stations in 17 ecoregions selected across Canada) – except some of the most northern ones. When water stress was not a limiting factor, corn and soybean yields were comparable to those simulated in central Canada where these crops are currently grown.

McGinn et al. (2001) generated regional climate change scenarios for the Canadian Prairies using historic weather data and daily data from two Canadian Climate Centre Global Circulation Models. The climate change scenario data included daily maximum and minimum air temperature and precipitation data generated using the Canadian Centre for Climate Modelling and Analysis second generation Global Circulation Model (GCMII) and their newer coupled (linking ocean and atmospheric processes) GCM with atmospheric aerosols (CGCMI-A). In addition, a combination of each GCM temperature and the historic precipitation (HP) amount and frequency were used to generate a third (GCMII_HP) and fourth (CGCMI-A_HP) climate change scenario.

All scenarios were used to drive the modified Versatile Soil Moisture Budget model that assesses soil moisture, aridity and other agroclimatic indices. The results from the four climate change scenarios were compared to those using the historic climate data. With spring warming occurring earlier the provincially averaged advancement of seeding dates varied between 16 and 29 days depending on the chosen scenario – in more southern regions an additional 2–3 days compared to the provincial averages. All four climate change scenarios predicted increases in the number of degree-days between 3% and 22% (provincial averages). Greatest warming during the growing season was anticipated in Alberta. Soil moisture was predicted to increase between 22% and 34% using GCMII scenario, coinciding with the large predicted increase in precipitation. However, little change in soil moisture was predicted under a CGCM1-A scenario.

Climate change with warming but no change in precipitation (GCMII_HP and CGCM1-A_HP) resulted in a 10% decrease in soil moisture in Alberta and no change in Saskatchewan and Manitoba. Aridity during the growing season was predicted to decrease dramatically under a GCMII scenario (wetter conditions) to only slight changes with the remaining scenarios. Both GCM output data resulted in a shift to earlier seeding dates and an improvement in soil moisture status on the Canadian Prairies. Even under the worst-case scenario (no change in annual precipitation amount or pattern), the shift in seeding dates compensated for increased evaporation during the summer – only. Alberta was predicted to experience a decrease in soil moisture. It should be noted that these projected changes in soil moisture are based on the advancement in the growing season dates and decreased maturity period. The adoption of earlier seeding dates with conventional short-season crops was an adaptive strategy that resulted in water savings.

Without this adaptive strategy, production of cereal crops in the Prairies is expected to drop by up to a third in western areas and increase by up to two-thirds in eastern areas due to changes in available soil moisture. Ontario and Quebec will experience similarly variable results. In both the Atlantic Region and British Columbia increased grain yield potential is foreseen but realization of this potential is likely dependent on the amount of water available for irrigation (Environment Canada, 1997b).

Agroclimatic indices (heat units and water deficits) were determined for the Atlantic region of Canada for the present day climate (1961–1990) and for two future periods (2010–2039 and 2040–2069) using the output from the Canadian GCM (Bootsma et al., 2001). The climatic changes expected to occur within the next 50 years, based on the Canadian GCMI model and a "business as usual" scenario for Green House Gases emissions, are likely to have significant impacts on crop production. Crop (Corn) Heat Units (CHU) would increase by 300–500 CHU for 2010–2039 and between 500–700 CHU for 2040–2069 in the main agricultural areas of the Atlantic region. Anticipated changes in water deficits, defined as the amount by which evapotranspiration exceeded precipitation over the growing season, were generally less than 50 mm for both periods, increasing in some areas and decreasing in others. Statistical comparisons of crop yields with climate indices suggest that yields of grain corn and soybeans could increase as much as 3.8 and 1.0 tonnes per hectare, respectively, by the year 2055, mostly as a result of increased availability of heat units. Changes in water deficit are not expected to have a significant impact on crop yields. Yields of barley are likely to change only slightly but the competitive advantage in relation to corn and soybeans will be significantly reduced and likely lead to major shifts in areas seeded to these crops.

Grasslands are an important carbon and methane sink. Mitigation strategies for grasslands focus on small to moderate improvements in soil carbon levels, primarily through the prevention of overgrazing which leads to dramatic changes in plant species, decreased plant growth, and potential desertification. Improved management of grasslands can result in small increases of carbon sequestration per unit of land. In contrast, the biological process of denitrification releases nitrous oxide and enteric fermentation by cattle grazing the forage on grassland releasing methane. The complexity of issues involved can be illustrated by the following interaction. Some of the mitigation strategies that have the potential to increase soil carbon sequestration could result in increased nitrous oxide and methane emissions due to improved soil fertility and increased cattle numbers on the land. For cultivated land, soil carbon sequestration is dependent upon three key factors: land tillage practices, plant species selected, and soil nutrient and water inputs. Minimum or zero tillage initially was recognized as an important tool for reducing soil erosion and improving water conservation. However, low-tillage soil management has also been recognized as an effective means of soil carbon sequestration. There is increasing consensus that summer fallow acreage will also reduce N_2O emissions.

As noted earlier, nitrous oxide occurs as a result of the denitrification processes in the soil. Soil carbon and nitrogen cycles are linked. Therefore, land management strategies directed toward the incorporation of atmospheric CO_2 into soil organic matter must be evaluated relative to the impacts on N_2O emissions. For example, the portion of N_2O that is produced near the soil surface or that is not able to be absorbed at deeper levels through downward diffusion due to an inhibiting layer will result as N_2O flux into the atmosphere. An inhibiting layer is, for example, a frozen ground layer in the spring. Thus, a greenhouse gas mitigation strategy relative to soil nutrient management is to reduce this soil N_2O flux into the atmosphere.

A major complication to an effective strategy is the complex and rather poorly understood mechanisms that govern conditions for N_2O production and emission from agricultural soils. Seasonal distribution of N_2O emissions have been well characterized; however, the ability to quantify these emissions has been difficult. A number of factors influence nitrification and denitrification processes, the time lag between production and emission of soil N_2O, and the relationship between production and emission rates of N_2O. These include rainfall, snowmelt, temperature, freezing and thawing, fertilizer and manure applications, and tillage.

Although agriculture is a net emitter of green house gases, farmers can adopt several measures to reduce emissions (Desjardins et al., 2001). Some of these are expensive, but some can be used with little cost or even at higher profit. Widespread use of such practices could reduce emissions of all three green house gases, and for CO_2, even make farms net absorbers (Janzen et al., 1998). Practices that are relevant to GHG emission reduction and sustainable development include: reduced tillage intensity; reduced summer fallow area; improved manure management; improved feeding rations; improved drainage/irrigation. Other considerations that come into play include their practical feasibility, economic cost, effect on soil quality, and influence on the whole environment. The projected effects of the above selected practices on GHG emissions and on other considerations are illustrated in Table 16 of *The Health of Our Air* (Janzen et al., 1998).

Water management practices and trends have a direct impact on greenhouse gases. Soil water content influences the timing, nature, and magnitude of soil microbial processes which are responsible for the production and consumption of CO_2, CH_4, and N_2O. Further, wetlands and bogs represent areas of significant carbon accumulation due to high plant productivity, coupled with the inhibition of organic matter oxidation.

Wetlands currently cover 14% of Canada's land mass ands are a critical resource providing habitat for species (including some of Canada's rare, threatened, or endangered ones), storage for atmospheric carbon, nutrient and mineral cycling, water purification, and natural flood control. Climate change could result in the conversion of semi-permanent wetlands from open-water dominated basins to vegetated areas (Environment Canada, 1999). Wetlands in Canada's agricultural zones are considered to be product ecosystems and are a net sink for greenhouse gases. In some areas, a promising mitigation strategy would be to return those lands that are marginally producing or that are increasingly subject to salinization to either permanent grass cover or to wetlands.

Opportunities for reducing emissions through increasing C sequestration exist by using improved farming practices and thereby modifying the soil climate and other physical soil properties, but the net effect is complicated. For example, the increase in soil moisture associated with no-till or reduced tillage leads to more soil decomposition, whereas the cooler temperatures and less soil aeration lead to less soil composition. But no-till has also other benefits such as minimizing C loss associated with soil erosion and savings in fossil fuel emissions because of reduced machinery use. In fact, no-till is the most efficient management practice for sequestering C in cropland, when compared to cover crops, crop rotation, fertilizer strategies and manure applications (Desjardins et al., 2001).

Large expanses of Canada's land base is forested land. It has already been noted that trees have the potential to trap atmospheric CO_2 and sequester carbon. Planting shelterbelts have traditionally been an effective means of protecting agricultural or grazing land from strong winds. Plants and livestock can be subjected to severe stresses associated with excessive chilling, high temperatures, dessication, or direct wind injury. Windbreaks can, by reducing these stresses, be profoundly beneficial to the growth of plants and health of livestock. Thus, an effective mitigation strategy is the planting of trees on the landscape that is normally devoted exclusively to agricultural production. In addition to sequestering carbon, shelterbelts have the potential to reduce N_2O emissions. There would be less fertilizer nitrogen applied to the land. More trees would mean less nitrogen moving out from the root zone to surface or groundwater resources (i.e., less denitrification). Finally, nitrogen would be recycled from the tree leaves that fall to the ground, reducing the need for nitrogen application to the soil.

9. Summary and Conclusion

Increased weather variability likely resulted in greater fluctuations in crop yields in recent decades. Key issues for agriculture are extreme weather events, such as drought, flooding, and heat waves. Changes in drought tendencies, soil moisture availability, and frost-free growing seasons are also factors that influence agricultural and forest productivity. Agriculture plays a role in the inventory of greenhouse gases and in mitigation measures to reduce these gases.

Rapid shifts in the agricultural land base brought about by extreme climatic variability can have a major disruptive effect on rural communities and associated infrastructures. It is essential that proactive mitigation measures be developed to cope with these changes and preserve the all-important agricultural and forest systems.

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