

**IMPACTS OF PRESENT AND FUTURE CLIMATE VARIABILITY  
ON AGRICULTURE AND FORESTRY  
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<sub>2</sub> may enhance crop yields in northern growing areas. Major factors in these scenarios analyses 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 is also sensitive to greenhouse gases. Forests and soils are natural sinks for CO<sub>2</sub>. 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, 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.

## **I. Introduction**

The science of climate is a complex issue. While the physical aspects of this issue are most understood, the natural causes of both climate variability and climate change 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. 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 effect of changing climatic conditions. 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.

## **II. Agriculture in North America**

The United States is the world's fourth largest country. Nearly 30 percent of its territory (approximately 260 million hectares) is covered by forests. Over 25 percent (approximately 240 million hectares) is permanent grassland and other non-forested pasture and rangeland.

Approximately 20 percent 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 percent 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 percent as conservation efforts for the most environmentally-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. 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., 1999).

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 percent of the world's forests and nearly 25 percent 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 (Overview 2001).

### **III. 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 climate 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 20<sup>th</sup> century, but since the 1970's have had increasing temperatures as well. The largest observed warming across the Nation has occurred in winter (National Assessment Synthesis Team, 2000).

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. There is some discernible evidence of warming during the growing season over this period of record. However, agriculture is likely impacted by the relatively high degree of temperature variability that is 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 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 et al., 2000).

Average U.S. precipitation has increased by 5-10 percent 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 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 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<sup>0</sup>C compared to the associated global warming of 0.5<sup>0</sup>C. Figure 3 shows the annual national temperature departures and long-

term trend, 1895-1996 (CCS Executive Summary, 1999). Regional variations range from a warming of about  $1.5^{\circ}\text{C}$  in the Northwestern Territories (NWT), to a warming of less than  $1^{\circ}\text{C}$  over southern Canada, and to a cooling of  $0.8^{\circ}\text{C}$  in extreme eastern NWT (CCS Summary, 1997). 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  $0.5^{\circ}\text{C}$  over the Northeastern Forest to  $1.4^{\circ}\text{C}$  over the Northeastern Forest to  $1.7^{\circ}\text{C}$  over the Mackenzie District (Figure 5).

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

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.

Projections of future climate are generally derived from computer models 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 was developed by the National Assessment Synthesis Team 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 21<sup>st</sup> 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

precipitation models 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.

#### **IV. Agricultural Impact of Climate Variability 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 1895-2001 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-1930's 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-1990's, 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 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 3, 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, studies generally 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<sub>2</sub> 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 will 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.

In Canada, an important dimension to the relationship between climate change and agriculture is the wide range of conditions for agricultural production between different regions (CCS

Executive Summary, 1999). 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.

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 climate 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 three to five weeks. Results relating to moisture regimes show estimated precipitation changes ranging from decreases of about 30% to increases of 80 percent.

Despite favourable 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 will lead to larger seasonal moisture deficits in all 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.

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). 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 (CCS Summary, 1997).

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 percent from 1981 to 1996. 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. At the same time, increasing competition for water due to higher population in urban centers and greater demand for hydro-electric 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; waterlogging, 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.

## **V. Agriculture's Role in Greenhouse Gas Emissions**

The complex interaction becomes even more confusion 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<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). CO<sub>2</sub> 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<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O 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<sub>2</sub> to the atmosphere through the conversion of forest land to agricultural or urban use. Forests are a major terrestrial sink for CO<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub>.

The agricultural sector produces a significant amount of methane emission. Animal digestion in domestic livestock is the leading contributor to agricultural methane emission. 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. 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  $\text{N}_2\text{O}$  emissions. Bacterial action on the chemical fertilizers results in the release of  $\text{N}_2\text{O}$ . The gas is released when soil microbes digest the fertilizers. The more inorganic nitrogen-based fertilizers that are applied, the more  $\text{N}_2\text{O}$  goes into the atmosphere. This potent pollutant is detrimental to the life-preserving ozone layer (Lyman, 1990). Soil management practices, such as irrigation, tilling, or laying fallow the land can also affect  $\text{N}_2\text{O}$  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.  $\text{CO}_2$  accounts for 85 percent of net U.S. greenhouse gas emissions in 1995 (U.S. Department of State, 1997). Lower harvests in old-growth forests help prevent  $\text{CO}_2$  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 content that amounts to sequestration of atmospheric  $\text{CO}_2$ . 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 percent 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 percent. Research on ways and means of capturing methane released from manure management systems and using the captured methane as an on-farm energy resource is technologically feasible. More efficient animal production through improved grazing management, strategic feed supplementation, genetic characteristics and reproduction, and disease control contributed toward reduced methane emission. Finally, while nitrous oxide emissions account for only about 3 percent of U.S. greenhouse emission in 1995, improved management of fertilizers could reduce N<sub>2</sub>O 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., 1999), which is a companion report to "The Health of our Soils" and "The Health of our Water." 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 programme initiated by Agriculture and Agri-Food Canada in 1992.

The most important three greenhouse gases ( CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) of current concern differ in their warming effects. To compare their relative effects, therefore, their emissions are usually expressed as "CO<sub>2</sub> equivalents." One kilogram of N<sub>2</sub>O has the warming effect of about 310 kg of

CO<sub>2</sub> (when considered over 100 years), so it represents 310 CO<sub>2</sub> equivalents. Similarly, 1 kg of CH<sub>4</sub> represents 21 CO<sub>2</sub> 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 Tg (million tonnes) of CO<sub>2</sub> equivalents in 1996 (Table 1). Of this amount, about two-thirds was as N<sub>2</sub>O and about one-third as CH<sub>4</sub>. Livestock and Manure account for about 58% of these emissions, cropping practices for 37%. By comparison, net emissions as CO<sub>2</sub> were almost negligible. The estimates of CO<sub>2</sub> emission, however, exclude most of the CO<sub>2</sub> from fossil fuels used to produce inputs, power farm machinery, and transport products. These sources emitted about 25 Tg (million tonnes) of CO<sub>2</sub> in 1996. With these emissions from all other agricultural practices included, the agriculture sector's contributions were about 15% of Canada's emissions. The emission of greenhouse gases from Canadian agriculture are increasing, according to current estimates (Table 1). 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<sub>2</sub> 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<sub>2</sub>O has the highest and CO<sub>2</sub> 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., 1999).

At one time, agriculture was also an important source of CO<sub>2</sub> 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 to 2010, simulated changes in soil organic carbon (SOC) in agricultural soils of Canada. Changes in soil organic carbon (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<sub>2</sub> and will become a sink by the year 2000. Rates of carbon change for the years 1970, 1990, and 2010 were estimated to be -67, -39 and 11 kg C ha<sup>-1</sup>. 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.

## **VI. Scenarios of CO<sub>2</sub>, Climate, and Agriculture**

As the CO<sub>2</sub> 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<sub>2</sub> enrichment. Thus, from agriculture's perspective, as CO<sub>2</sub> 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 degree (C) increase in temperature with no precipitation change resulted in wheat

yield increases with the direct effect of CO<sub>2</sub> taken into account.

Elevated atmospheric CO<sub>2</sub> 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<sub>2</sub> content, given no change in precipitation trend.

The direct biological effects of atmospheric CO<sub>2</sub> 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<sub>2</sub> should also have a significant positive effect upon pasture and rangeland productivity, based on research studies. CO<sub>2</sub> enrichments appears 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<sub>2</sub> content should enable pasture and rangeland plants to better cope with water deficits.

Experiments have also shown that elevated CO<sub>2</sub> consistently enhanced rates of net photosynthesis

in upland cotton (Reddy et al., 1999). These studies indicated that although elevated CO<sub>2</sub> did not significantly impact boll size or maturation, it did increase boll numbers by about 40 percent 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<sub>2</sub> content will enhance cotton photosynthetic rates, boll production, and fiber yields without altering fiber quality.

## **VII. Vulnerability of the Agricultural Sector**

Rosenzweig (1993) presented some interesting results based on current production and change in simulated wheat yields under global circulation model (GCM) climate change scenarios. For the GCM doubled CO<sub>2</sub> climate change scenario, simulated yield increases in mid- to high latitudes were caused by the positive physiological effects of CO<sub>2</sub> 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.



MacCracken 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, to agricultural crops and livestock. 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 have also caused environmental degradation. Soil, water, and wind erosion has been significant, but largely offset by greater use of fertilizers. Further, the issue of off-farm pollution due to fertilizer runoff has increased. As a result of these issues, an alternative approach to conventional farming practices have evolved.

Erosion in the Great Plains was reduced after devastating losses of valuable topsoil during the dust bowl years of the 1930's by planting shelterbelts of trees to reduce wind erosion. 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).

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.

### **VIII. 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. The agricultural sector is highly productive, intensively managed, and market based. Further, agriculture accounts for less than 5 percent of the national gross national product (GNP), allowing considerable flexibility to adapt to changes required in the production system.

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 on 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 yield and variability under climate change (historic baseline and 2xCO<sub>2</sub> 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 and economics. Under a warmer and slightly wetter 2xCO<sub>2</sub> 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 2). Corn yields in central Canada decreased significantly by 11% , although

with increased nitrogen fertility the yield decrease was reduced to less than 5%. 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<sub>2</sub> scenario from 6% for spring wheat to 50 % for soybeans. 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 2xCO<sub>2</sub> 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 and Shepherd (personal communication) generated regional climate change scenarios for the Canadian Prairies using historic weather data and daily data from two Canadian Climate Centre Global Circulation Models (GCMII and CGCMI-A). The GCM data were combined with historic precipitation (HP) values to generate two additional scenarios (GCMII\_HP and CGCMI-A\_HP). 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 to 29 days depending on the chosen scenario - in more southern regions an additional 2 to 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). Alberta was found to benefit the greatest from warming during the growing season (seeding to harvest). 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 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 (CCS Highlights, 1997).

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 GCM 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  $\text{N}_2\text{O}$  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  $\text{CO}_2$  into soil organic matter must be evaluated relative to the impacts on  $\text{N}_2\text{O}$  emissions. For example, the portion of  $\text{N}_2\text{O}$  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  $\text{N}_2\text{O}$  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  $\text{N}_2\text{O}$  flux into the atmosphere.

A major complication to an effective strategy is the complex and rather poorly understood mechanisms that govern conditions for  $\text{N}_2\text{O}$  production and emission from agricultural soils. Seasonal distribution of  $\text{N}_2\text{O}$  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. 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., 1999). 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., 1999).

Another paper of this Workshop “Management strategies with particular emphasis on carbon sequestration to mitigate green house gas emissions from agroecosystems” by R. Desjardins, focuses on the role of management practices to store carbon in agricultural soils and at the same time minimize GHG emissions.

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<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O. 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 percent of Canada's land mass and 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 (CCS Executive Summary, 1999). Wetlands in Canada's agricultural zones are considered to be productive 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, 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 (for details see Workshop Paper by Desjardins).

Large expanses of Canada's land base is forested land. It has already been noted that trees have the potential to trap atmospheric CO<sub>2</sub> 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<sub>2</sub>O 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.

## **IX. 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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### **Figures.**

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.

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.

Figure 3. Annual national temperature departures and long-term trend: 1895-1996.

Source: Canada Country Study (CCS)) Volume VII, Executive Summary, p.3

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.

Figure 5. Temperature deviations in three regions of boreal forest: 1985-1994.

Source: Criteria and Indicators, Criterion2: Ecosystem condition and productivity, Element 2.1 Disturbance and Stress, Fig. 2.1n, p.36.

Figure 6. Iowa statewide corn yields (metric tons per hectare) for the period 1895-2001. Years of unusually extreme weather events documented.

Table 1.: Estimates of total greenhouse gas emissions from Canada's agroecosystems

	1981	1986	1991	1996	2000*	2005*	2010*
	(Tg CO <sub>2</sub> equivalents)						
CO <sub>2</sub>	9	7	5	3	1	0	0
CH <sub>4</sub>	22	20	20	23	23	24	25
N <sub>2</sub> O	32	33	34	41	43	45	48
Total	63	60	59	67	67	69	73

\* 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. 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. (R. L. Desjardins, AAFC).

Table 2: 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.

Crop	# sites	Yields (t/ha)			
		Average		Std. Dev.	
		Baseline	2xCO <sub>2</sub>	Baseline	2xCO <sub>2</sub>
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
Soybeans	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 extracted 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.

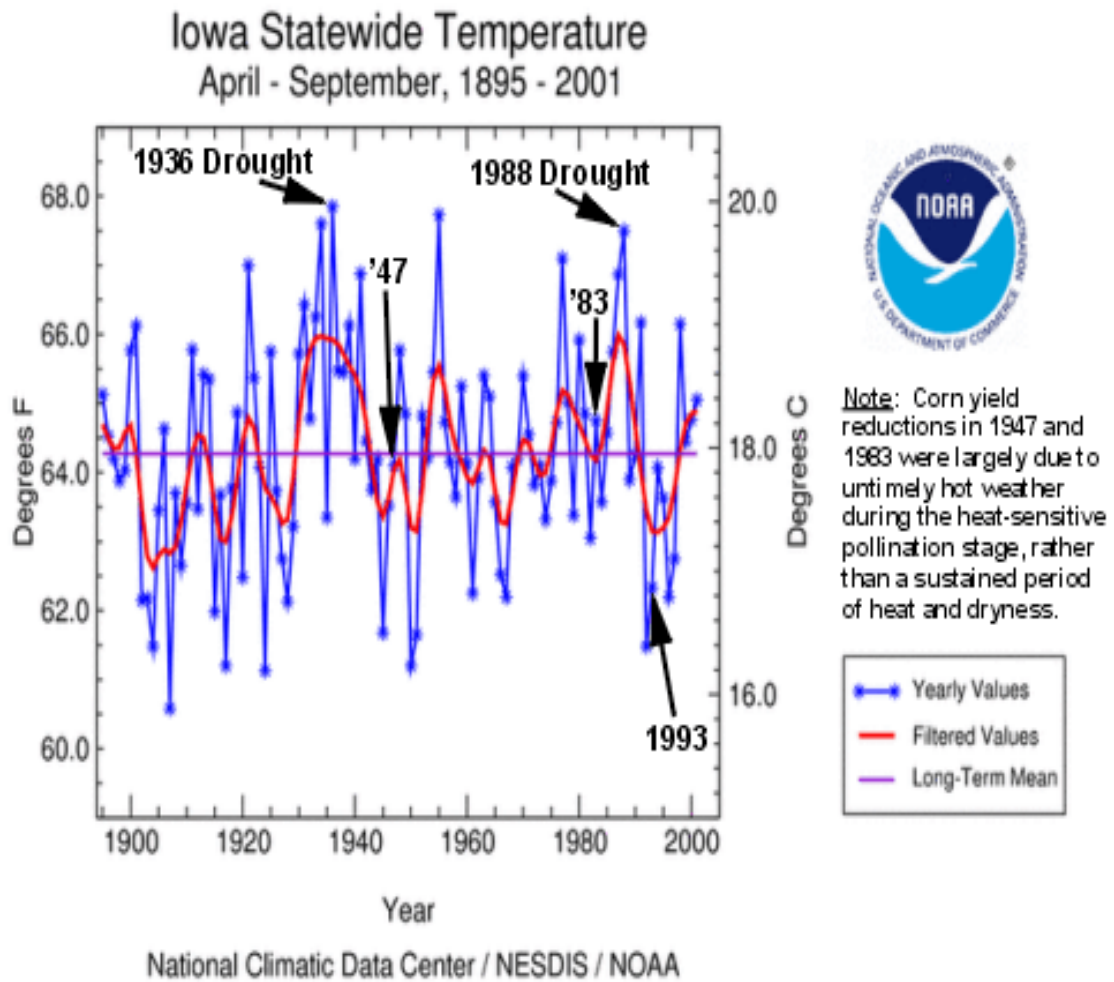


Figure 1: Iowa statewide temperatures during the growing season, April-September, for 1895-2001.

Source: National Climatic Data Center / NESDIS / NOAA.

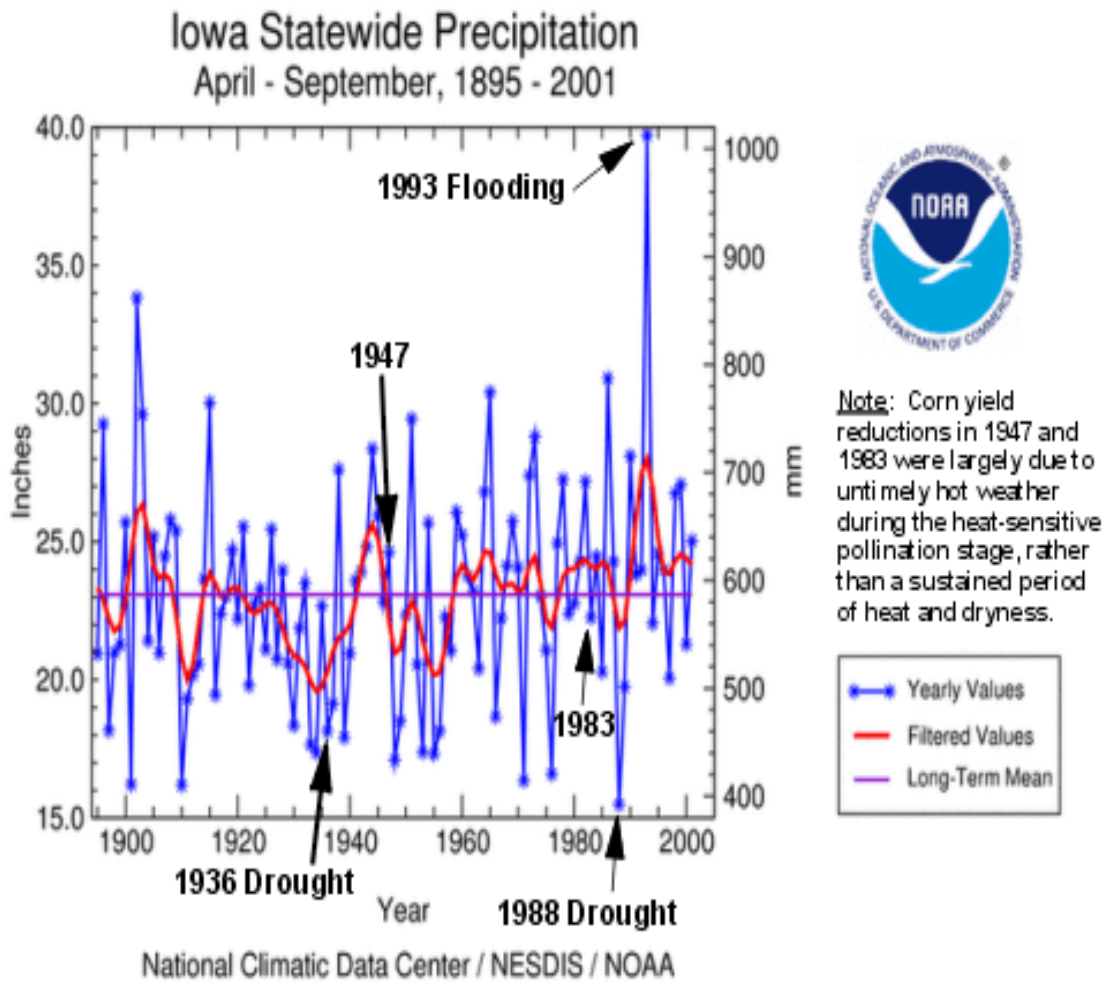


Figure 2: Iowa statewide precipitation during the growing season, April-September, for 1895-2001.

Source: National Climatic Data Center / NESDIS / NOAA.

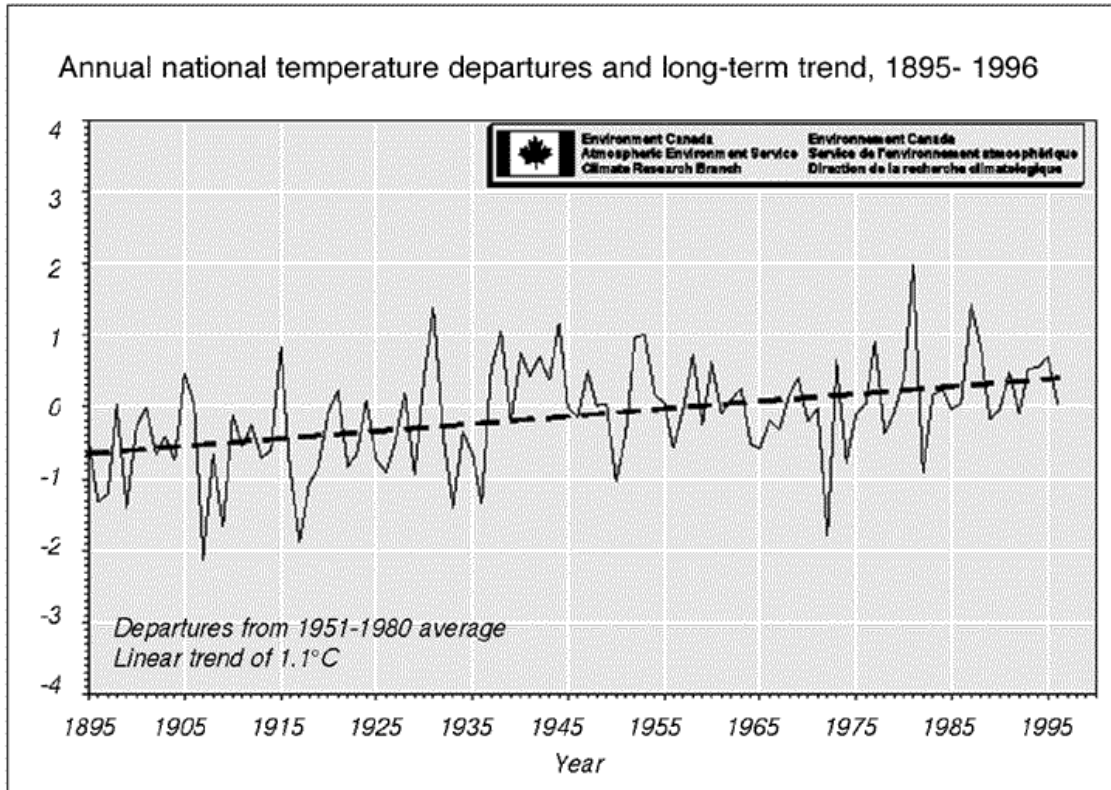


Figure 3: Annual national temperature departures and long-term trend: 1895-1996.

Source: CCS Summary 1997, p.6.

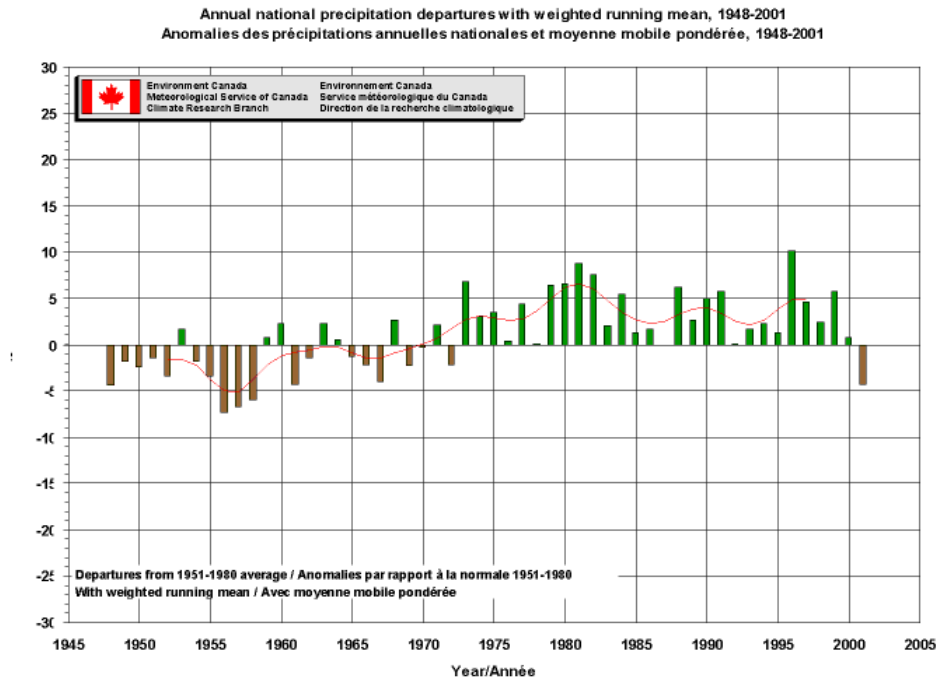
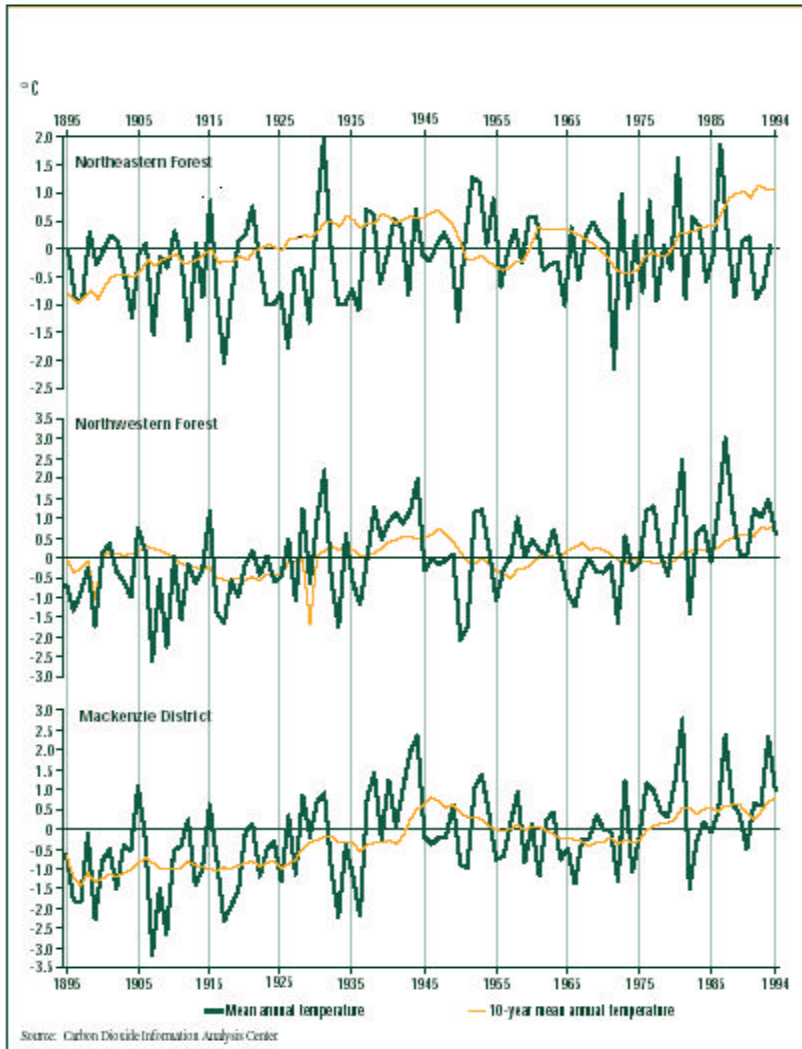


Figure 4: Annual national precipitation with weighted running mean: 1945-2001.

Source: Climate trends and variations bulletin for Canada, Annual 2001 temperature and precipitation in historical perspective, p.3. Environment Canada, Meteorological Service of Canada, Climate Research Branch.



- ◆ Disturbance and stress
- ◆ Ecosystem condition and productivity

Figure 5. Temperature deviations in three regions of the boreal forest:1985-1994

Source: Criteria and Indicators, Progress to data, Criterion 2: Ecosystem Condition and Productivity, Element 2.1:Disturbance and Stress, p. 36, Canadian Council of Forest Ministers, 2001.



## IOWA CORN YIELD, 1895-2001

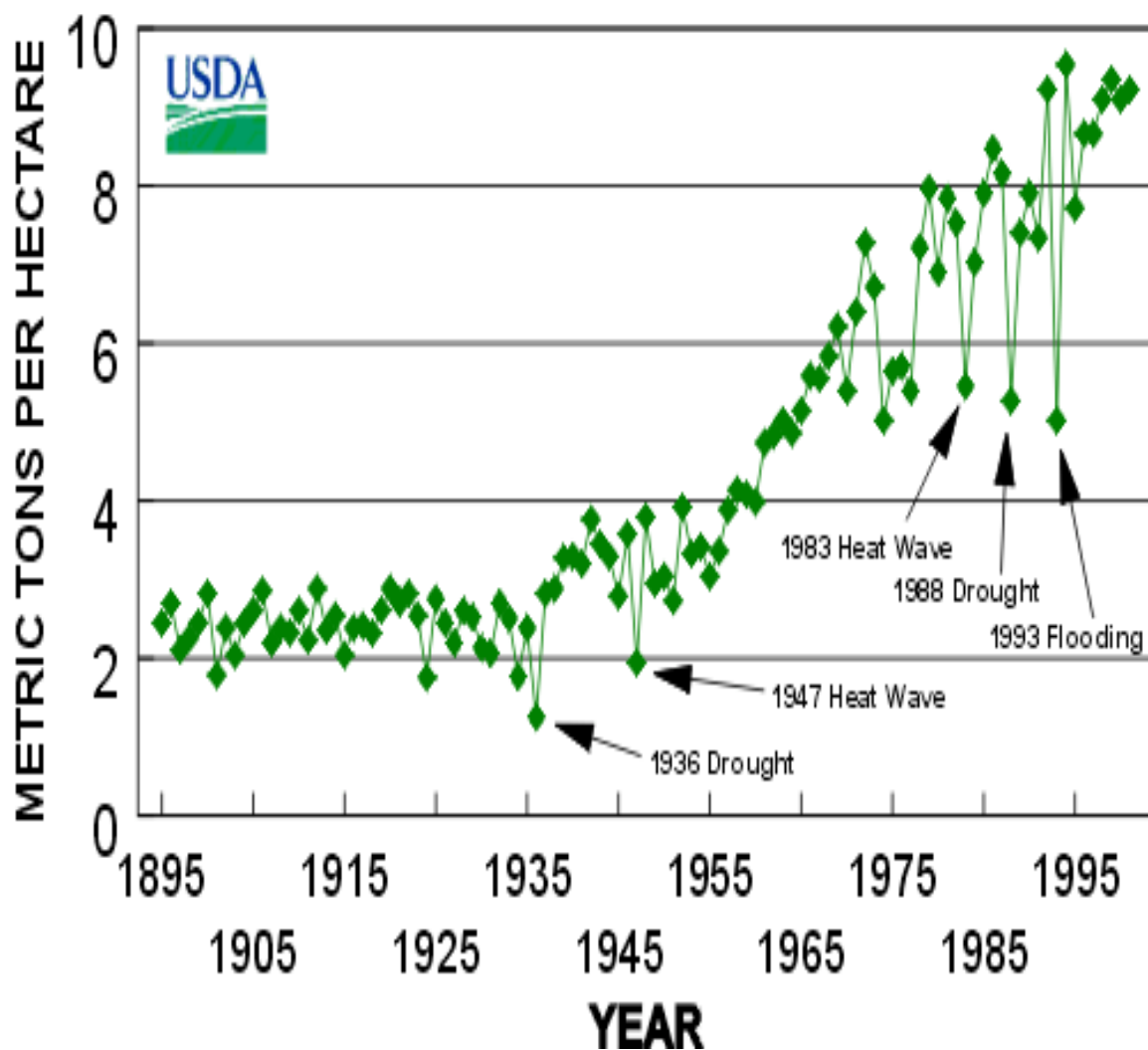


Figure 6: Iowa state corn yields (metric tons per hectare) for 1895-2001.

Source: United States Department of Agriculture.