CHAPTER 5

THE WILDCARD OF CLIMATE CHANGE

1. INTRODUCTION

To this point we have examined the natural resources of the NAGP, its economy and the nature of current land use in the region. As explained in foregoing sections, land use on the Plains has evolved as the result of historical forces in response to changing demographics, economic conditions, and public policy. But until now public policy, rules for managing the Missouri River dams, drought mitigation programs, etc., as well as general and public expectations, continue to rest on the assumption that the climate of the region, while encompassing large and sometimes dramatic day-to-day and year-to-year variability, is essentially stable and fundamentally unchanging.

Yet all of us have memories that lead to such thoughts as …"winters sure ain't what they used to be"…or…."spring doesn't last as long as it used to"…or…"the rains are getting heavier and heavier"…, and so on. Such musings imply that the climate is changing. However, until the last decade or so there was little evidence that what some perceive as "change" actually lies outside the range of normal climate variability. But an emerging body of evidence that squares well with this theory indicates that climate is, indeed, now changing—globally, not only in the Plains. And at least one driver of climate change, perhaps the preeminent cause, is "anthropogenic", i.e., the result of human activity.

We know that the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other radiatively active trace gases are rising due to the combustion of fossil fuels, cement manufacture, and changes in land use and management, and that these gases strengthen the Earth's natural "greenhouse effect". This process can only lead to a warming of the lower atmosphere, the land and its water surfaces and, more slowly, the oceans. Global warming is, itself, a climate change but other aspects of climate—precipitation, winds, and currents must also change as the Earth warms.

What is the extent of the warming so far? For more than a century, maximum and minimum air temperatures have been measured daily at about 1.8–2.0 m above ground surface at many thousands of sites around the world. Records compiled from these stations and from lake and sea observations mostly in the Northern Hemisphere show that the globe has, in fact, warmed to the extent of

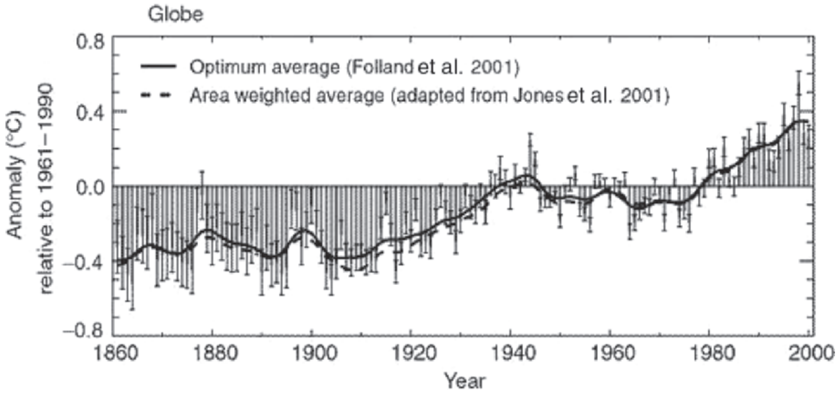

Figure 5-1. Combined annual land-surface air and sea-surface temperature anomalies (°C) 1861–2000, relative to 1961–1990. Two standard error uncertainties are shown as bars on the annual number (IPCC Third Assessment Report 2001)

0.6°C during the last 140 years. The warming trend is shown in Figure 5-1 taken from a report of the Intergovernmental Panel on Climate Change (IPCC) (2001a). This figure shows a long upward trend in temperature interrupted by a decrease between 1940 and 1975. Thereafter, a warming trend has dominated the record. Climatologists at NASA's Goddard Institute for Space Studies (GISS) have noted that the highest global annual average surface temperature in more than a century was recorded in their analysis for the 2005 calendar year. The records show that the warmest 5 years since the 1890 have been, in order of descending temperature, 2005, 1998, 2002, 2003, and 2004.[1] It has also been observed (e.g., Karl et al. 1993, 1996) that daily minimum temperatures have risen more than maximum temperatures. Nights are warming more than days, which is consistent with the theory of "greenhouse warming" described below.

Indicators of change documented by the IPCC (2001b) include shrinkage of the area of sea ice in the Arctic, increasing depth of the active layer of soil and organic materials overlying permafrost in Alaska, and lengthened agricultural growing seasons in North America and Europe in the latter half of the 20th century. Two seminal papers on the ecological effects of warming appeared in *Nature* in 2003 (Root et al. 2003; Parmesan and Yohe 2003). Root et al. selected 143 studies from thousands examined that met certain criteria and found a consistent temperature-related shift "….in species from mollusks to mammals." Parmesan and Yohe documented significant range shift averaging 6.1 km

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[1] http://www.nasa.gov/vision/earth/environment/2005_warmest.html

poleward per decade and a significant mean advancement of spring events of 2.3 days per decade in 279 species.

The temperature decrease between 1940 and 1975 seen in Figure 5-1 provides an easy way to emphasize the notion that climate is always changing and has always done so because of natural phenomena uncontrollable by man, but a growing body of evidence points to significant anthropogenic changes now occurring in climate that are likely to become increasingly evident during the course of this century. Among these are a warming of the lower layers of the atmosphere, particularly in the higher latitudes; an intensification of the hydrologic cycle leading to more evaporation and precipitation but with a geographical distribution different from today's; a year-round decrease in the average extent of the arctic ice cap and its possible disappearance in summer; and a rise in sea level that may be great enough to force abandonment of many low-lying areas or necessitate the construction of expensive protective systems. Why might all this happen?

The following sections of this chapter briefly examine the mechanisms of climate change, projections of how, given varying severities of global warming, the climate of the NAGP could change over the course of this century and what the impacts of such changes might be for important sectors of the region's economy.

2. THE GREENHOUSE EFFECT AND GLOBAL WARMING

2.1. The energy balance

Figure 5-2 from Kiehl and Trenberth (1997) is a schematic description of the Earth's annual and global mean energy balance. Mean flux density of incoming solar radiation at the top of the atmosphere is 342 W m^{-2}. Of the incoming solar radiation, which is primarily in the visible waveband, the atmosphere absorbs 67 W m^{-2}. Clouds, aerosols and atmospheric gases reflect 77 W m^{-2} to space and the Earth's surfaces reflect another 30 W m^{-2}. The surface absorbs 168 W m^{-2} of the incoming solar radiation. The Earth-atmosphere system must dispose of the incoming energy or the planet would warm uncontrollably. The surface disposes of energy by a number of mechanisms: warming the air coming in contact with it (24 W m^{-2}) and by evapotranspiration (ET)—direct evaporation of water from the soil and free-water surfaces and by transpiration—evaporation at the leaf-surface of water drawn through plants (78 W m^{-2}). The surface also emits (on average) 390 W m^{-2} by thermal infrared radiation of which 40 W m^{-2} passes through what is called the "atmospheric window"—a portion of the spectrum from about 8 to 12 microns in which water vapor is not a strong absorber of longwave radiation. Back radiation to the surface from the atmosphere in the thermal waveband is 324 W m^{-2}. The outcome of the exchanges of thermal radiation is an outgoing flux density of longwave radiation at the top of the atmosphere of 235 W m^{-2} which, together with the reflected radiation of 107 W m^{-2}, balances the incoming solar radiation.

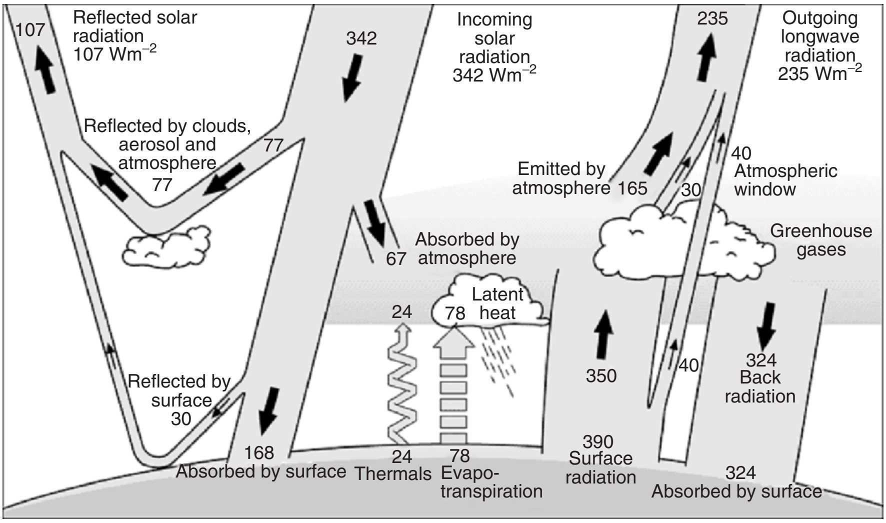

Figure 5-2. The Earth's annual and global mean energy balance (Kiehl and Trenberth 1997; Reprinted from IPCC Third Assessment Report 2001a)

2.2. The greenhouse gases

Our particular concern here is with the radiation passing through the atmospheric window. Natural constituents of the atmosphere—water vapor, CO_2, CH_4, N_2O, and ozone (O_3) and some manufactured substances such as the chlorofluorocarbons (CFCs) are partially opaque to the longer wavelength thermal radiation and trap a portion of it. These gases, except for water vapor, have strong absorption peaks in the "atmospheric window."

A portion of the energy absorbed by these "greenhouse gases" is retained in the lower layers of the atmosphere, raising its temperature. Since the late 19th century, scientists have speculated that because of their strong absorption of infrared radiation, especially in the atmospheric window, the rising concentrations of CO_2 and the other radiatively active trace gases cause a warming of the lower layers of the atmosphere. Warming caused by these gases also increases the atmosphere's capacity to retain water vapor, a positive feedback toward warming. This phenomenon has been likened to the process that occurs in greenhouses: the glass permits solar radiation to penetrate, but it absorbs infrared radiation emitted by the soil and plants within. Although the analogy is defective, the process of warming in the lower layers of the atmosphere caused by the infrared absorptive behavior of CO_2 and the other radiatively active trace gases mentioned above has come to be known as the "greenhouse effect."

Carbon dioxide: It is not known for certain what the concentration of CO_2 was before the industrial revolution, although the record of sporadic air analyses from

1870 on and samples of air trapped in glacial ice suggest a value of ~280 parts per million by volume (ppmv). From that time on, as coal became increasingly important as the source of energy to power the industrializing society, CO_2 concentration began to increase. As a graduate student in meteorology and soil science in the late 1950s, I learned that the concentration had already risen to 315 ppmv. As this book is written (2006) atmospheric CO_2 concentration is approaching 380 ppm (Blasing and Jones 2005). Thus, the atmospheric loading of this important greenhouse gas has increased by more than a third since the beginning of the industrial revolution. The emissions of CO_2 in 2002 from fossil fuel combustion, cement manufacture, and land use change injected ~6.975 Gt carbon[2] into the atmosphere, up 2% from the previous year (Marland et al. 2005).

Methane: Methane (CH_4) is the greenhouse gas next in importance to CO_2 in radiative forcing. Although emitted in much smaller quantities than CO_2 (millions rather than billions of metric tonnes per annum),[3] the CH_4 molecule has a greenhouse warming potential 23 times greater than that of CO_2. CH_4 concentration had more than doubled from a preindustrial (before 1750) concentration of ~0.7–1.73 ppmv and 1.85 ppmv in 2003. CH_4 is a fossil fuel and can leak from oil wells and natural gas processing and transport facilities. It is also emitted under anaerobic conditions from swamps, rice paddies, landfills, and by ruminant animals and termites. Emissions were in the range of 600 Tg of CH_4 in the late 1990s (IPCC 2001a).

Nitrous oxide: Nitrous oxide (N_2O) is released from soil to the atmosphere during the nitrification process that occurs in soil under aerobic conditions. The use of nitrogenous fertilizers increased greatly after World War II, and is primarily responsible for the increase from its preindustrial atmospheric concentration of 270–318 parts per billion (ppb) in about 2003. However, N_2O is also emitted as the result of denitrification—a process that occurs in waterlogged soils. It has been suggested that the drainage of such soils and alterations in their acidity may have reduced this source of natural nitrogenous emissions to some degree. N_2O is also a more effective greenhouse gas than CO_2. In 1990 N_2O was increasing at the rate of 0.25% per annum. Its warming potential per molecule is ~296 times that of CO_2. Emissions in the late 1990s were in the order of 16.4 Tg (IPCC 2001a).

Clorofluoromethanes: The clorofluoromethanes or "Freons" (CFCs 11 and 12), used as refrigerants, propellants, and for cleaning electronic components are human-made, having no natural sources. Although better known for their role in erosion of stratospheric ozone layer to which they deliver chlorine atoms that catalyze the photolytic destruction of O_3, the Freons are also extremely strong infrared absorbers. In the late 1990s concentrations of CFCs 11 and 12 were 253 – 256 and 542 – 546 parts per trillion (ppt), respectively (Blasing and Jones 2005). Molecules of these gases have greenhouse warming potentials 4,600 and

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[2] Billions of metric tonnes = Gt = gigatonne = petagram = 10^{15} g.

[3] Millions of metric tonnes = Tg = terragram = 10^{12} g.

10,600 greater than that of CO_2. Production of CFC 11 and 12 was banned by the Montreal Protocol,[4] and its concentration is no longer rising; indeed it has begun to fall. However, some of the chemicals that are intended to replace the Freons, while nonthreatening to the ozone layer, are even stronger as greenhouse gases.

2.3. The CO_2-fertilization effect

Although CO_2 is the greenhouse gas of the greatest immediate concern with regard to global warming because of the immense quantities being emitted, the increase in its atmospheric concentration can have a potentially positive effect as well. CO_2 is the substance from which plants synthesize the basic sugars, building blocks of all plant products, through the process of photosynthesis. The increase in its atmospheric concentration affects plants in two ways. Photosynthesis is increased in the C-3 plants, those having a 3-carbon intermediate molecule in the photosynthetic pathway. The C-3 plants include the legumes, small grains, cool-season grasses, most root crops and trees. Photosynthesis is only slightly affected in the C-4 plants, tropical grasses such as corn, sorghum, millet, sugarcane, and some warm-season grasses, which have a more efficient photosynthetic mechanism than the C-3 group. But elevated CO_2 concentration has the effect of partially closing the stomates (pores) of plant leaves and stems in both C-3 and C-4 plants, making the diffusion of water vapor into the air more difficult. This results in decreased transpiration and conservation of soil moisture. Both groups of plants experience an improvement in their water-use efficiency (WUE, the ratio of photosynthetic production and water consumption). The degree to which this “CO_2-fertilization effect” might offset stresses on crops caused by climatic change or might augment beneficial effects of climate change, should such occur, is evaluated in subsequent portions of this chapter.

3. CLIMATE CHANGE SCENARIOS

Understanding of how climate change might affect natural processes such as plant growth, ET, and ecological functioning in general, requires models that can mimic the processes involved. A few such physical and biological process models are described below. But before these models can be employed, information must first be provided on how the climate might actually change in the future. A number of techniques are used to generate “scenarios” of climate change. Among these are: climatic analogues, statistical regressions, and general circulation models.

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[4] Montreal Protocol (Protocol on substances that deplete the ozone layer) is a treaty signed by 25 nations in 1987. The protocol set limits on the production of the CFCs, halons, and other substances that release chlorine or bromine into the upper atmosphere where ozone is concentrated. The protocol has been amended several times and 168 nations are now signatories (source: http://www.factmonster.com/ce6/sci/A0833884.html).

3.1. Climate analogues

Climatic phenomena of the past provide a basis for formulating scenarios of future climate change. The actual climate record of the drought era of the 1930s in a portion of the Great Plains and adjacent states (Missouri, Iowa, Nebraska, and Kansas) was used, in a study reported by Rosenberg (1993), to create scenarios of climate change for the region to the year 2030. These scenarios, essentially a replay of the drought of the 1930s (the "dirty-thirties") climate, were used to evaluate potential impacts on agriculture, forestry, water resources, energy supply, and demand in the region as it was in 1990 and as it might be in 2030. The climate analogue records were applied to process models and other tools in order to accomplish this.

Glantz and Ausubel (1984) posed another sort of climate analogue for the Great Plains, using known and anticipated impacts of the depletion of the Ogallala aquifer (Chapter 2) as a guide to what might happen in the region if, as anticipated, climate change depletes water resources in the region.

A general weakness of the analogue approach is, of course, that the climate events or deviations from normal in the past may be quite different from what might occur under greenhouse-forced climate change. For instance, the hot, dry conditions of the Dust Bowl days may not be repeated under climate change; a hot, wet future for the Dust Bowl region is not out of the question.

3.2. Statistical regression

The climate record has also been used to establish sensitivity of various crops to temperature and precipitation fluctuations by means of statistical regression. Agronomists (e.g., Thompson 1986) have established how, over a long period of time, the final yield of corn and soybeans in Iowa is affected, say, by a 1 – 3°C warmer than usual May, June, July mean temperature, or by a 10 – 20% wetter or drier conditions in these months. The relationships established are then used in regression equations to project the effects of such changes should they become the long-term means in the future. Newman (1980) and Blasing and Solomon (1983) were among the first to use the regression approach. While the regression approach provided useful insights about climate change impacts on crop production, projecting statistical relationships developed under a limited range of current conditions far out of that range is an uncertain practice.

3.3. General circulation models

The general circulation model (GCM) is a global, three-dimensional computer model of the climate system which can be used to simulate human-induced climate change. It has become the primary tool used by climatologists to analyze the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures, and ice boundaries.[5]

Essentially, the GCM divides the surface of the globe into a two-dimensional grid, typically several hundreds of kilometers on a side. The atmosphere above each two-dimensional grid box is divided into 10–20 layers reaching to about 35 km, effectively the top of the atmosphere. In coupled ocean-atmosphere models, the oceans are similarly subdivided into grids and layers. The equations of motion, the radiation balance and the properties of the atmosphere determine the dynamics of the atmosphere or ocean within each three-dimensional cell. Each cell exchanges momentum, heat, and water vapor with its neighbors. It is no wonder, then, that the computational requirements of GCMs, with their tens of thousands of cells and the complex physical phenomena they simulate, have been a major factor leading to development of super-computers.

The GCM can be applied in the short-term (years) to explore, for example, the effects of volcanic eruptions; the relatively long-term (decades to centuries) to explore the potential effects of the increasing atmospheric burden of aerosols, greenhouse gases, and other substances; or the truly long-term (millennia) to explore the effects of changes in solar luminosity and/or variations in the Earth's orbit around the sun. There are perhaps two dozen GCMs presently being used to project the timing and geographic distribution of greenhouse-forced climate change.

Although simpler models have been used to provide globally or regionally averaged estimates of the climate response to greenhouse warming, the scientific consensus is that only GCMs, possibly in conjunction with regional models nested within them (see below), have the potential to provide the geographically and physically consistent estimates of regional climate change that are required in impact analysis.[6]

The scale of the grid box in a GCM is usually too large to provide information that can be directly applied to a farm or even a county or watershed. In regions of complex topography—say Washington State—a single grid box may encompass range, or wheat land, mountains, and ocean, so that the average temperature or precipitation change projected has little value for impacts assessments. Some researchers (e.g., Georgi and Mearns 1991; Georgi et al. 1998; Brown et al. 2000) use smaller, more geographically detailed models "nested" within the larger grid cell and driven by its projected climate changes to provide information at a more usable scale.

What do the GCMs predict for the Plains region? There is no definitive answer to this question since, as mentioned above, there are many GCMs in current use. Because of differences in the ways that physical processes are parameterized and because of differences in computational strategies employed, agreement among the

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[5] eobglossary.gsfc.nasa.gov/Library/glossary.php3

[6] IPCC Data Centre, ipcc-ddc.cru.uea.ac.uk/ddc_gcm_guide.html

GCMs is not always gratifying. For example, among six of the most widely used GCMs (BMRCD2, CCC1D2, ECH4D2, GFDLD2, GISSD2, and HAD3D2)[7] correlation coefficients with respect to their projections for normalized annual temperature change range from a low of 39 to a high of 83 where 100 would represent perfect agreement. The situation with respect to normalized annual precipitation change is considerably worse with a low value of 3 to a high of 39.[8]

Nonetheless, it is possible to see in Figures 5.3a and b the broad outlines of the climate futures projected for the Great Plains by a number of the better-known and accepted GCMs. These figures have been assembled by means of a computer model SCENGEN (scenario generator) developed by the Climate Research Unit of the University of East Anglia (Hulme et al. 1995) in cooperation with National Center for Atmospheric Research in Boulder, Colorado.[9]

3.3.1. The US National Assessment

GCMs have been used in some recent assessments of climate change impacts on the USA. A major assessment organized by agencies of the US government reported its findings in the "National Assessment" (USGCRP 2002). This report was organized to deal with "mega-regions" of which the Great Plains was one. Two GCMs—the Canadian Global Coupled Model (CGCM, Flato et al. 2000; Canadian model hereafter) and the Hadley Centre model (HadCM3, Johns et al. 1997; Hadley model hereafter)—were used to project climate change in the 21st century. The models were also used to retrospectively project the climate changes of the 20th century.

The Plains region as a whole warmed by 0.5 to 1.0°C during the 20th century. The Canadian model shows warming in the order of 5.5°C and the Hadley model shows warming of about 2.3°C in the 21st century. During the 20th century, precipitation decreased by 10% in eastern Montana, North Dakota, eastern Wyoming, and Colorado, and increased by more than 10% in the eastern portion of the Great Plains. Also the snow season ended earlier in spring because of greater seasonal warming in winter and spring. The Canadian model projects decreases in the 21st century of as much as 30 – 40% in precipitation in the southern Plains, and increases of 20% in the northern Plains. The Hadley model, on the other hand, projects increases in the range of 20% in almost all of the US Plains with some modest decreases east of the Rockies.

3.3.2. GCMs in the JGCRI study

Another assessment aiming to derive impacts of projected climate changes on agriculture, water resources and irrigation in the conterminous USA was recently

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[7] Bureau of Meteorology Research Centre (Australia); Canadian Centre for Climate Modeling and Analysis; Max Planck Institute (Germany); Geophysical Fluid Dynamics Institute (USA); Goddard Institute for Space Studies (USA); and Hadley Centre (Gt. Britain).

[8] SCENGEN website http://www-pcmdi.llnl.gov/projects/cmip/cmip_abstracts/wigley03.pd

[9] Latest updated versions at http://www.cru.uea.ac.uk/~mikeh/software/scengen.htm

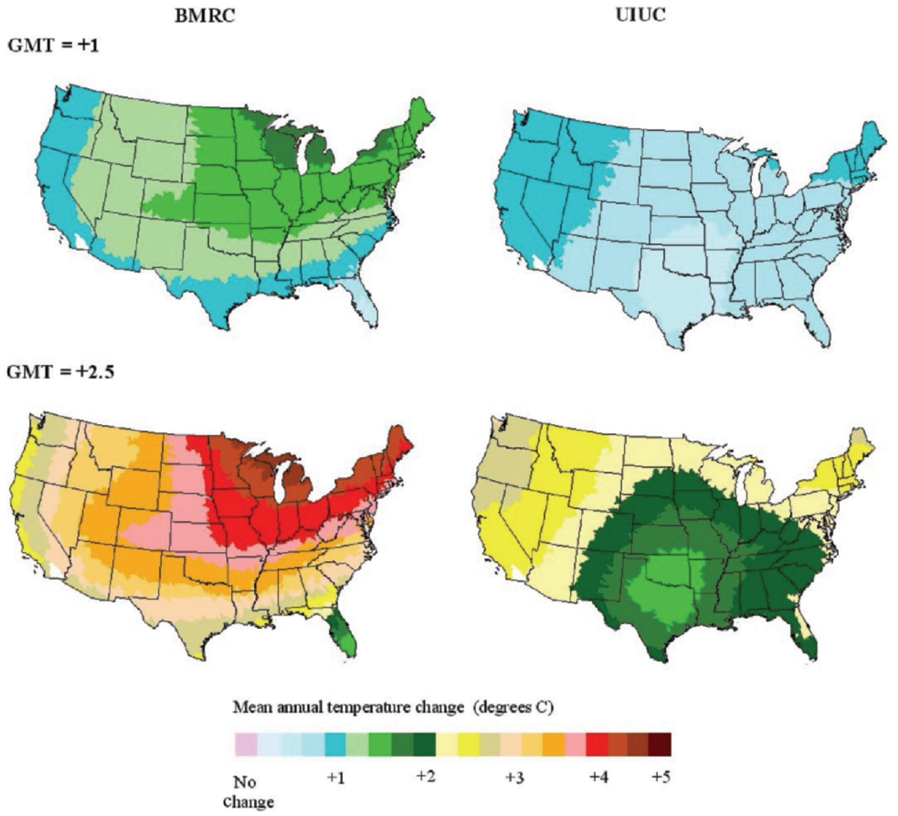

Figure 5-3a. Mean annual temperature change from baseline for the BMRC and UIUC GCMs used in the JGCRI study (Source: Smith et al. 2005) (*See Color Plates*)

reported in Rosenberg and Edmonds (2005). This study was conducted by scientists at the Joint Global Change Research Institute (JGCRI)[10] and made use of two other GCMs—the Australian Bureau of Meteorology Research Centre (BMRC) model (McAveney et al. 1991), and the University of Illinois, Urbana–Champagne (UIUC) model (Schlesinger 1997). These models illustrate the range of differences in climate change projections that can be found among GCMs (Figures 5-3a and b).

Virtually all GCMs indicate some degree of warming, but the range of change in monthly, seasonal, and annual temperatures can be considerable. The UIUC and BMRC models used by Thomson et al. (2005a) in the JGCRI study project

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[10] A collaboration of the Pacific Northwest National Laboratory and the University of Maryland–College Park, USA.

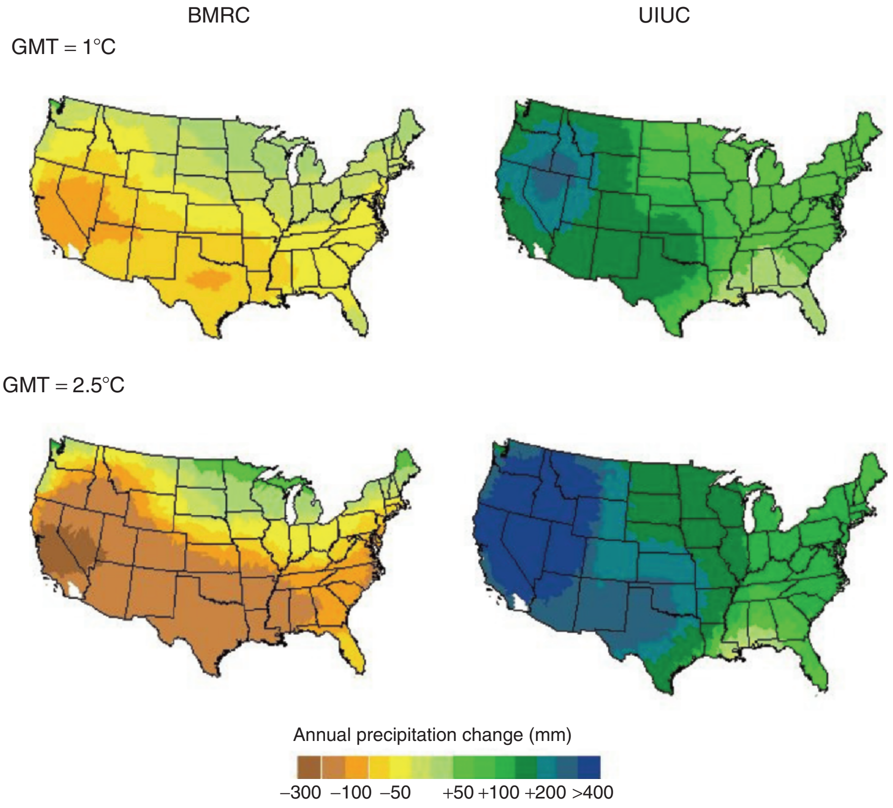

Figure 5-3b. Mean annual precipitation change from baseline for the BMRC and UIUC GCMs used in the JGCRI study (Source: Smith et al. 2005) (*See Color Plates*)

annual mean temperature change in eastern Nebraska to range from <1°C to ~2°C, respectively, when global mean temperature has risen by 1°C. With global mean warming of 2.5°C, these same models project mean annual temperature at the same location to range from slightly under 2°C to 4°C.

Differences in precipitation projected by the GCMs can be considerably greater, and ultimately of greater importance. In the Thomson et al. (2005a) study the UIUC and BMRC models project, respectively, a 50% increase and a 50% decrease in precipitation in eastern Nebraska with global mean temperature change of 1°C. With GMT of 2.5°C UIUC projects a 100% increase; BMRC continues to project a 50% decrease.

Seasonal differences can be even more significant. BMRC projects temperatures higher than UIUC by 2.09°C, 1.60°C, 1.05°C, and 1.35°C for winter, spring, summer, and fall in the Missouri River Basin at GMT = 2.5°C. In the Arkansas Basin these differences are 2.02°C, 2.58°C, 1.06°C, and 1.04°C for the same seasons. Differences in seasonal precipitation projected by UIUC and BMRC are 28%, 33%, 164%, and 113% for winter, spring, summer, and fall, respectively in the Missouri River basin and 91%, 22%, 184%, and 138% in the Arkansas.

The uncertainties inherent in using general circulation models for climate change impact study should evoke a sense of humility in those who use them for that purpose. Keeping those uncertainties and limitations in mind, and for lack of a better alternative, we proceed to examine what those impacts might be for the NAGP.

4. IMPACTS OF PROJECTED CLIMATE CHANGES ON PLAINS AGRICULTURE AND WATER RESOURCES

4.1. Introduction

Many researchers who have dealt with climate change impacts conclude that agriculture is one—perhaps the major—economic sector likely to be affected in the USA by climatic change (e.g., Rosenberg 1982; National Academy of Sciences 1992; IPCC 2001b; Reilly et al. 2003). There are many possible modes of agricultural adaptation to climatic change if it cannot be avoided (Rosenberg 1992). These include introduction of new, better-adapted crops, development of new cultivars for current crops, changes in tillage practices to optimize management in response to changes in season length and other fairly obvious adjustments. Irrigation would be the most effective way to compensate for rising temperatures, greater ET and, in some regions, reduced precipitation. This assumes, of course, availablity of water to irrigate where dryland yields fall below profitable levels. But will the water actually be there?

Studies based on the use of process models have been conducted for agricultural systems throughout the world and for most of its crops. Summaries of such studies are to be found in the first three IPCC Assessment Reports (1991, 1996, 2001)[11] and in many national assessments—the most relevant of which for this book are the US National Assessment (USGCRP 2001) and the JGCRI study (Rosenberg and Edmonds 2005) cited above, each of which used a different pair of GCMs to drive process models of crop growth and yield and regional water supply.

4.2. Results of the National Assessment

Assessments of climate change impacts are developed using process models driven by GCM projections. In the National Assessment which involved analysts from a number of research centers, a range of process models were used for

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[11] Accessible through http://www.ipcc.ch/pub/reports.htm

this purpose. The general outcome of their model runs with respect to the Great Plains is as follows: applying the climate scenarios stemming from the Canadian and Hadley GCMs to process models for major crops and considering crop and livestock production weighted by prices, the National Assessment found that regional production changes in 2030 and 2090 relative to current production differed greatly by region and by GCM. Under the Canadian model the northern Plains showed a small loss in 2030 where no adaptation was attempted and a small gain with adaptation. Loss was in the order of 20% with no adaptation in 2090 but adaptation increased production by 20%. For the southern Plains under the Canadian Climate model, regional production suffered losses in 2030 or 2090, only partially alleviated by adaptation.

Under the Hadley model of climate change both the northern and southern Plains show increased regional production. In the northern Plains the increases are roughly 10% and 40% without adaptation in 2030 and 2090, and 22% and 60% with adaptation. In the southern Plains the gains are more modest, about 2% and 20% without adaptation in 2030 and 2090, and 5% and 35% with adaptation.

4.3. Results of the JGCRI Assessment

4.3.1. Agricultural production

The JGCRI study was an "integrated assessment" considering climate-change effects on crop production, water resources, unmanaged ecosystems, and irrigation. For crop-production effects this study relied on the EPIC model (version 7270) of Williams (1995) to simulate climate change impacts on agricultural production on the field scale for the entire conterminous USA. A more detailed explanation of the EPIC model is given here to foster understanding of the level of detail used in current agricultural assessments.

The EPIC model simulates climate change impacts on agricultural production on the field scale by calculating the maximum daily increase in plant biomass allowed by solar radiation incident on the field. The algorithms used to model potential plant growth are driven in EPIC by photosynthetically active radiation (PAR), the 0.4 – 0.7 micron portion of the solar spectrum. The amount of solar radiation captured by the crop is a function of leaf area index (LAI) and the amount converted into plant biomass is a function of the radiation use efficiency (RUE) which is crop-specific. Solar radiation also provides the energy that drives ET.

In EPIC the potential daily photosynthetic production of biomass is decreased by stresses caused by shortages of radiation, water and nutrients, by temperature extremes and by inadequate soil aeration. Each day's potential photosynthesis is decreased in proportion to the severity of the most severe stress of the day. As pointed out above, elevated atmospheric CO_2 concentration increases photosynthesis in C-3 plants and reduces ET in both C-3 and C-4 plants. Stockle et al.

(1992a, b) adapted EPIC to simulate the CO_2-fertilization effect on radiation use efficiency RUE and ET.[12]

Planting and harvesting dates in EPIC are based on accumulated heat units during the growing season and therefore, vary with different climate scenarios. Crop yields are estimated by multiplying aboveground biomass at maturity by a harvest index (proportion of the total biomass in the harvested organ).

The land areas used for the EPIC modeling in the JGCRI study were the 204 "4-digit" hydrologic unit areas of the lower 48 states (USGS 1987) shown in Figure 5-4. The GCM projections were downscaled by SCENGEN (see above) to fit these basins. BMRC and UIUC projections of climate change were made at global mean temperature increases of 1°C and 2.5°C. Crop behavior with and without the CO_2-fertilization effect (represented by CO_2 concentrations of 365 and 560 ppm) was also modeled. Model fields of corn, soybeans, and winter wheat were simulated for a representative farm in each of the 4-digit basins. Not all of these crops grow in all of these basins today, but climate change could conceivably alter the boundaries of the most productive regions of the country

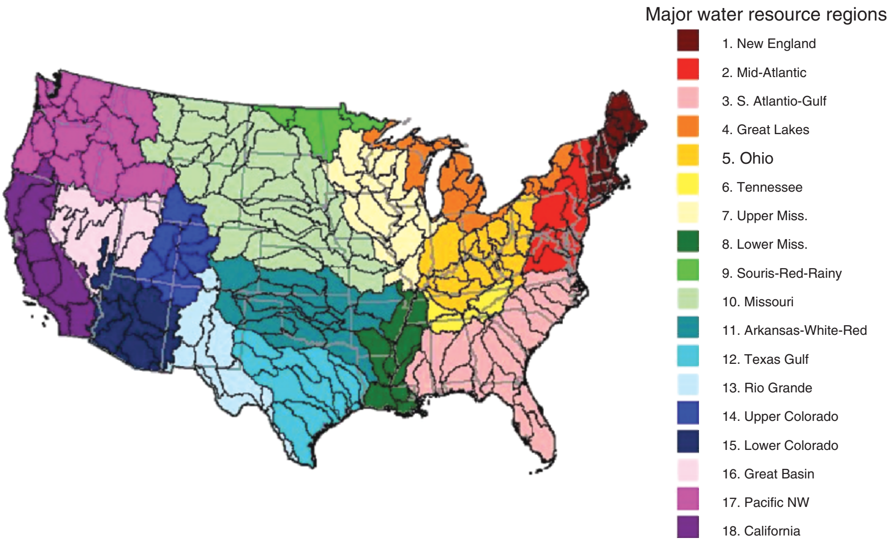

Figure 5-4. Major Water Resource Regions of the conterminous USA as defined by US Geological Survey (1987). The 204 modeling regions used in the JGCRI study are shown (*See Color Plates*)

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[12] A recent review of studies conducted with Free Air Carbon Dioxide Enrichment (FACE) technology (Long et al. 2006) indicates that the CO_2-fertilization effect on both photosynthesis and evapotranspiration is less than had previously been estimated from the results of greenhouse, growth chamber and open-topped field chambers, the basis for the Stockle et al. (and many other) model algorithms. (*See Color Plates*)

for each crop. A "yield threshold" for change was defined for each crop by reference to their known core production areas (CPAs). The lowest EPIC simulated baseline (current climate) yield within the CPA was chosen as the yield threshold. These are: 2.5 Mg ha^{-1} for corn; 1 Mg ha^{-1} for soybean, and 1 Mg ha^{-1} for winter wheat. Yields lower than these identify areas where profitable production of these crops is unlikely under current or changed climates.

Figure 5-5 from Thomson et al. (2005a) shows results of these calculations for the conterminous USA. The brown colored areas are those in which production of the indicated crop is possible; the yellow hatching over brown demarcates the current core production areas. Green shows areas into which production may expand under the BMRC and UIUC GCM scenarios at GMT of 2.5°C. The ameliorating effects of CO_2-fertilization are not considered in this figure. Red indicates areas lost to production of the particular crop under these conditions. We focus here on results for the Great Plains. Under BMRC corn production becomes unprofitable in western portion of South Dakota, Nebraska, and eastern Wyoming. Under the UIUC scenarios, on the other hand, corn production becomes economically possible in northeastern Colorado, parts of Wyoming,

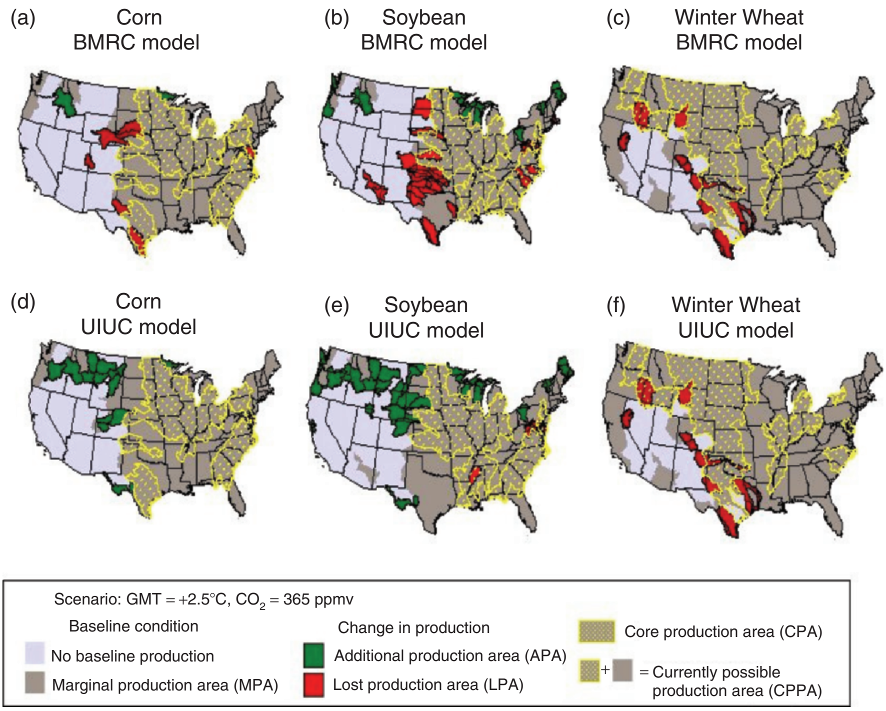

Figure 5-5. Regions projected to enter or leave production for three grain crops with the BMRC and UIUC GCMs at a global mean temperature increase of +2.5°C and CO_2 concentration of 365 ppmv (Source: Thomson et al. 2005a) (*See Color Plates*)

and much of Montana. While changes in the geography of corn production occur mostly on the western margins of the Plains, impacts on soybean production are more widespread. Under the dry BMRC scenario, potential production area is lost in the western corner of the North Dakota and South Dakota boundary, in southern South Dakota, central Kansas, Oklahoma, Texas, New Mexico, and southeast Colorado. New soybean areas appear in Montana, Wyoming, North Dakota, South Dakota, and Colorado under the moist UIUC scenario. The core production area for wheat also loses area to climate change at the western edge of the Plains under BMRC, but gains area under UIUC. Not surprisingly, the regions most affected by climate change, regardless of GMC scenario, are those on the margins of the regions in which they are currently grown.

4.3.2. Water resources

The hydrologic unit model of the USA (HUMUS) (Srinivasan et al. 1993) a geographic information system (GIS)-based modeling system, was used to simulate climate change effects on hydrology in the JGCRI study. HUMUS can be applied to a wide range of basin sizes depending on the availability of input data and the study objectives. In this study, the hydrologic cycle was simulated at the scale of the 8-digit USGS Hydrologic Unit Areas (USGS 1987), of which there are 2,101 in the conterminous US. In the modeling work climate, land use, and soil type are treated as uniform within each of these basins.

Water yield, a measure of net water flow out of each watershed, is calculated as the sum of surface and lateral flow from the soil profile and groundwater flow from the shallow aquifer. HUMUS and Soil and Water Assessment Tool (SWAT) runs on a daily time step with the same weather data inputs as described above for the EPIC model. The same algorithms are also used to account for the CO_2-fertilization effects on ET.

The HUMUS model was run for the BMRC and UIUC GCM projections scaled to each basin. Results were summed for each of the 18 major water resource regions of the USA shown in Figure 5-4. The Great Plains lie primarily within the Missouri, Arkansas-White-Red, and Rio Grande basins. Results for these basins in terms of water yield (most closely representing stream flows) are summarized in Table 5-1 (from Thomson et al. 2005b). This table shows that flows are reduced under BMRC in all three river basins at both levels of global warming (GMT=1.0°C and 2.5°C) and regardless of CO_2-fertilization. Under UIUC, on the other hand, flows increase in all three river basins. These results are consistent with the drying and wetting of these regions according to the BMRC and UIUC projections. Higher GMT worsens water yields still more under BMRC because of intensified drying and, conversely, increases water yields under UIUC wherein the greater global warming results in more precipitation for the Great Plains region. The higher CO_2 moderates losses under BMRC and increases water yields still further under UIUC.

Figure 5-6 shows the geographic distribution of the change in water yields. The general drying and wetting under BMRC and UIUC are evident. The southeastern corner of the Plains region shows the most severe drying under BMRC.

Table 5-1. Water yield at baseline climate and change from baseline (mm) for three Major Water Resource Regions under the BMRC and UIUC climate change scenarios (Thomson et al. 2005b, Table 1)

Scenario	GMT (°C)	CO_2 (ppm)	Missouri	Arkansas-White-Red	Rio Grande
Baseline	0	365	107	235	40
BMRC	1.0	365	−16	−31	−10
		560	−11	−19	−8
	2.5	365	−35	−73	−21
		560	−31	−62	−21
UIUC	1.0	365	20	50	15
		560	26	65	18
	2.5	365	55	139	46
		560	63	157	51

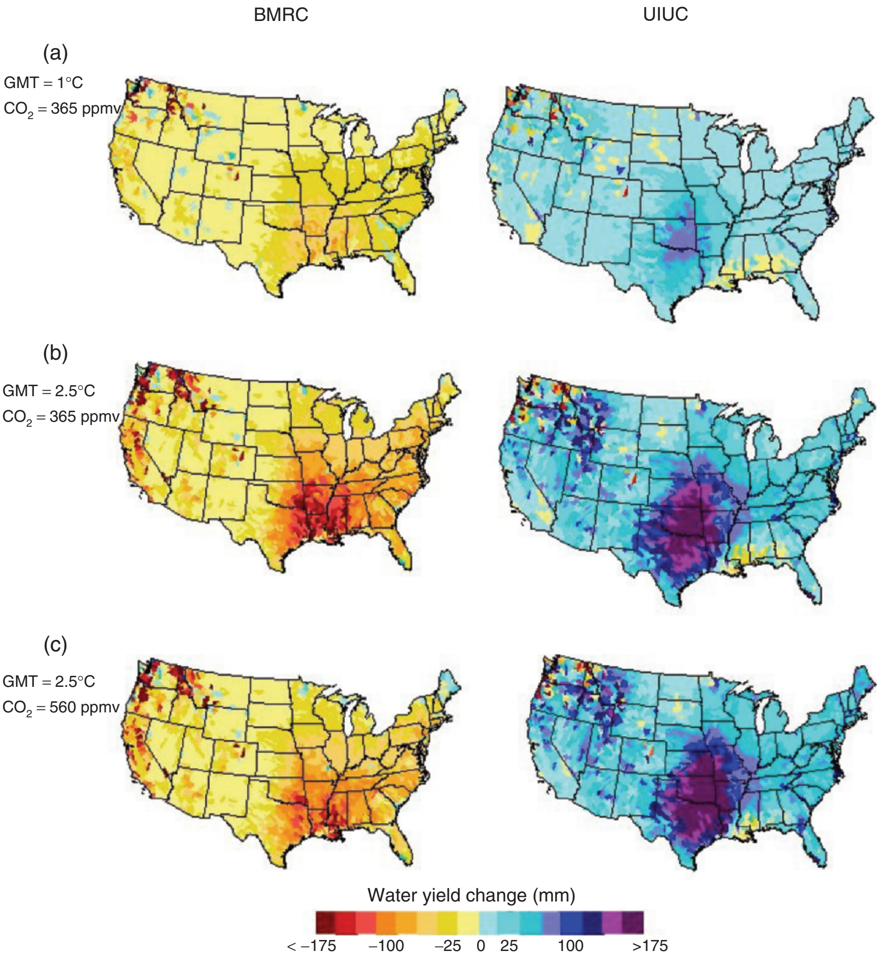

Figure 5-6. Water yield change from baseline (mm) for two GCMs with increasing global mean temperature (GMT) with and without the CO_2-fertilization effect (Thomson et al. 2005b)(*See Color Plates*)

Almost all of the USA shows increased water yields under UIUC, but increases are greatest in the southern Plains. Notable increases in water yield of 75% or more extend into eastern Kansas and Nebraska as well.

4.3.3. Implications for irrigation

Under the bountiful (indeed, in some regions excessive) precipitation of the UIUC scenario, the need for irrigation in the Great Plains is diminished, as it is in the country as a whole (Thomson et al 2005c). Under the BMRC scenarios, on the other hand, irrigation declines because of lost water yields. In such a case agriculture may be doubly disadvantaged as sectors other than agriculture will compete for shares of the diminished water supplies. Conflicts among competing users of water, already a fact of life on the Plains, would surely intensify.

If the past is any guide to the future, we can expect that farmers on the Plains will find ways, if not to fully adapt to a worsened climate, at least to partially offset its impacts in ways that reduce the need for irrigation of water. These include development of drought resistant or tolerant cultivars of the current crops, and the introduction of less water intensive new crops. Efforts will be made to increase irrigation efficiency through increased use of water conserving application methods such as are described in Chapter 4, and through the use of monitoring devices that determine optimum timing and application rates. Nonetheless, should warming and drying occur in the Plains region—more likely, most specialists agree, than wetting—reliance on irrigation to maintain its productive capacity will be more difficult.

5. SUMMARY: POSSIBLE IMPACTS OF CLIMATE CHANGE ON GREAT PLAINS AGRICULTURE

From studies such as those described above and from other major information assembly efforts such as IPCC, a generally good understanding has emerged of what the impacts of climate change could be for agriculture. The IPCC process turns out comprehensive reports on climate change science, impacts and mitigation strategies every 5 years. The IPCC Third Assessment Report (TAR) covered the period 1995 – 2000 and was published in 2001. The Fourth Assessment Report is to be published in 2007. The TAR sections on agriculture and water resources and its report on North America provide useful, but very general, assessments of how its agriculture may be affected by climate change. A review of all these sources leads this writer to conclude that:

- The CO_2-fertilization effect should raise crop yields, but not by the amount demonstrated in controlled experimental environments, because in the field the effects of variable climate, soil fertility, and tilth are not always optimum and crops face competition from weeds, some of which may benefit as much or more from elevated CO_2, and from stress due to insects and diseases. The benefits of CO_2-enrichment in increased water use efficiency may be offset by higher temperatures and increased evaporative demand (see footnote 12).

- In some regions (the Great Plains is a candidate) climatic changes may lead to increased leaching of nutrients, loss of soil organic matter, and increased soil erosion, but such effects can be combated or alleviated by crop rotations, conservation tillage and improved nutrient management.
- Livestock can also be affected both directly and indirectly. Livestock are stressed by warmer, drier conditions although warmer winters may improve survival rates on the open range. Warmer, drier conditions—more likely than not on the Plains according to the majority of GCMs—may reduce forage quality and water availability for the livestock. Since livestock can be moved if necessary and feed can be imported, impacts on the livestock sector may be delayed or offset, but ultimately livestock production would become untenable where producers cannot count on reliable feed supplies.
- Modest improvements in crop growing conditions are projected by several GCMs for the northern tier of the American states and for the Canadian Prairie Provinces. Warming and a consequent lengthening of the growing season could encourage corn production in North Dakota and a further northward advance of winter wheat in Canada.
- Whether small or large, and whether accompanied by precipitation change or not, temperature increases have certain consistent effects on crop growth and yield. Annual crops can be planted sooner in northern climes with earlier thawing of the ground in spring. As they are for the most part driven by thermal-time (i.e., heat units), the passage of the plant's phenological (developmental) stages is accelerated and all occur earlier in the growing season.
- Two disadvantages accompany warming. During the reproductive phase, certain crops (notably corn) are very sensitive to high temperatures. Pollination can be unsuccessful in such a case with the result of deep reductions in yield. Another disadvantage is the earlier achievement of crop maturity. With a shortened growing season, there is less time for the plants to synthesize and store starch or other products in the seed or tuber. So, without development of new cultivars better suited to the greater warmth, crop yields could suffer from a warmer climate.
- On the other hand, frosts are likely to be less frequent and severe as the climate warms, so the risk of early-season and late-season damage is decreased. This truism may not be totally reliable, however, especially in spring. Neild et al. (1979) have shown that as a warmer spring advances the development of newly planted crops, they may actually be at a more vulnerable phenological stage when frosts do occur. On the other hand, perennial crops, especially those grown for forage, hay, or biomass should benefit from warming because of a lengthened growing season. General warming will also permit the growth of major crops such as corn in higher latitude locations than at present. But the importation of cultivars from lower latitudes is not always simple because they are generally adapted to the length of day where they are grown.
- Higher temperature has another important influence on crop growth through its effects on water use. Evapotranspiration is a function of leaf and air temperatures.

Warm air provides energy to evaporate water. The dryness of the air in contact with the crop's leaves is also a function of air temperature. The drying power of the air (its vapor pressure deficit) increases exponentially with temperature. Relative humidity (the ratio of actual water vapor pressure to the saturation vapor pressure at the ambient air temperature) falls rapidly with rising temperature. So, whether there is more precipitation or less, the actual crop water use (if water is present) increases with warming.

- The impacts of change in precipitation are intuitive: too much rain leads to flooding or at least to saturated soil, anaerobic conditions, and leaching of nutrients; too little rain leads to moisture stress on plants, wilting, closure of the leaf stomata (pores) so that photosynthesis is shut down. If severe and protracted, lack of precipitation means drought and, ultimately, crop failure.

With these general concepts in mind and recognizing that, however uncertain the specific climatic changes awaiting the Great Plains, profound impacts are possible in the region's agriculture as this century progresses. We next explore the possibility that the Great Plains region may have a role to play in mitigating or at least slowing the progress of global climate change, perhaps to its own long-term benefit.

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