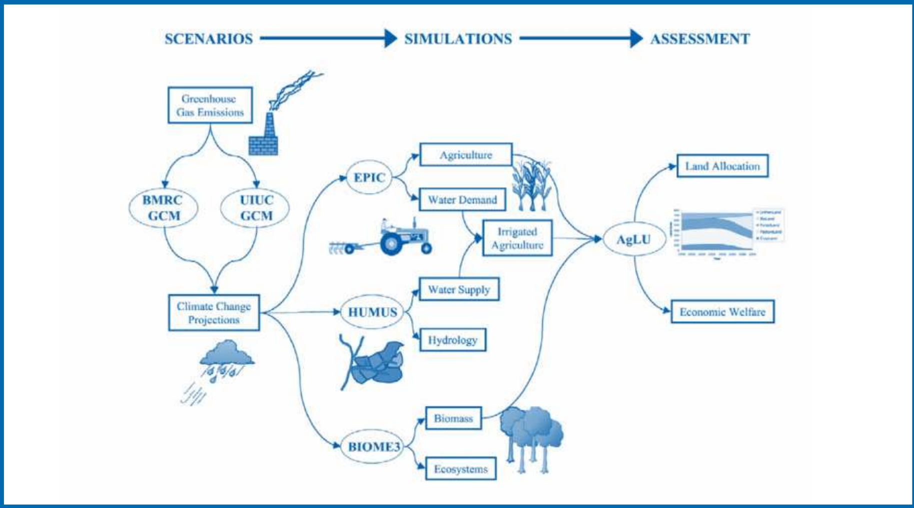
Climate Change Impacts for the Conterminous USA

An Integrated Assessment

Edited by
Norman J. Rosenberg and James A. Edmonds



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EDITOR'S NOTE

Climatic Change is pleased to acknowledge that this Special Issue is the fifth such effort by guest editor Norman Rosenberg, who has recently "retired" (at least officially). On behalf of the Climatic Change production team and readers, I wish to thank Norm for his yeoman service to the scientific community in general and to this journal in particular. However, Norm, don't think that retirement will exempt you from more refereeing and editing for the journal!

STEPHEN H. SCHNEIDER
Editor

CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT: FROM MINK TO THE 'LOWER 48'

An Introductory Editorial

A decade ago this journal published a special issue "Towards an Integrated Impact Assessment of Climate Change: The MINK Study" (Rosenberg, ed., 1993), an early attempt to explore the possible impacts of climate change on the resources, resource-based industries and economy of a distinct and important agricultural region of the United States (Missouri–Iowa–Nebraska–Kansas or simply MINK). The title was in fact suggested by Stephen H. Schneider, then and now Editor of this journal. An integrated assessment is, indeed, what the scholars involved in the MINK study had done, but none of us were familiar with the term at that time. Integrated Assessment (IA) came to be recognized in the 1990s as an important unifying tool, almost a sub-discipline of climate change research, even to the extent of generating new journals to cover the intellectual gap left by the multiplicity of disciplinary publications. Two, for example, that have joined this journal in encouraging IA research are *Integrated Assessment – An International Journal* and *Environmental Modeling & Assessment*.

Integrated Assessment is an analytical approach that knits together knowledge derived from a variety of disciplinary sources to gain insights from the analysis of interactions. It is being increasingly applied to complex environmental issues having natural science, social science and economic dimensions. As applied to the climate change problem, IA provides a framework for examination of how derivative changes in climate that result from greenhouse warming might affect natural and unmanaged ecosystems, and how these effects might ramify to the economic sector. The application of IA approaches can aid in understanding the complexities and inter-relatedness of anthropogenic forcing of climatic change, changes in the natural environment brought about by human appropriation and manipulation of water and land resources and the changing sensitivity of managed and unmanaged ecosystems to extremes of weather and climate.

Progress has been made during the past decade in developing IA frameworks and tools for application to environmental problems, viz. MERGE (Manne et al., 1995), IMAGE 1.0 (Rotmans et al., 1990), IMAGE 2.0 (Alcamo et al., 1994a, b), RICE and DICE (Nordhaus, 1996; Nordhaus and Boyer, 1994), ICAM (Dowlatabadi and Morgan, 1993; Morgan and Dowlatabadi, 1996; Dowlatabadi and Ball, 1994), MIT Integrated Global System Model (Prinn et al., 1999), AIM (Morita et al., 1994), MARIA (Mori and Takahashi, 1999; Mori, 2000), ASF (Sankovski et al., 2000), TARGETS (Rotmans and de Vries, 1997), GCAM (Edmonds et al., 1994). With greater or lesser detail each of these frameworks attempt to describe and

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quantify the impacts of human activity on land, ocean, atmosphere, and managed and unmanaged ecosystems. The natural and social sciences describe the causes and effects and the linkages, interactions and feedbacks that characterize the dynamics of human/environmental interactions. Simulation models of various kinds are used to quantify the relevant phenomena.

The problems to which IA is currently applied are of such complexity that comprehensive modeling dealing with all (to the extent that they are known), or even most of the relevant phenomena and processes in a meaningful way is as yet impossible. For example, demographics and economic conditions determine the rates of fossil fuel emissions to the atmosphere; these emissions affect chemistry of the atmosphere as it is currently constituted; changing atmospheric chemistry causes deviations from current climate; these climate changes affect current agriculture, forestry, water resources and unmanaged ecosystems. At the same time, of course, changes in the human condition, such as numbers of people and their economic well-being, are changing the use of natural resources (e.g., the allocation of land between agriculture, urban, and unmanaged states). Changes in land use, whatever their cause, also affect natural emissions of radiatively active trace gasses, changes in surface properties such as reflectivity, and changes in the hydrological cycle.

With these challenges in mind a group of natural scientists and economists in the Joint Global Change Research Institute (JGCRI; a cooperative endeavor of the Pacific Northwest National Laboratory and the University of Maryland at College Park) has undertaken to extend and improve IA methodology to facilitate understanding of the complex problems described above. As a demonstration of the use of IA, we apply this methodology to the scale of the conterminous United States or the 'Lower 48'.

We have developed a set of climate change scenarios and used them to drive process models of crop production, water resource and unmanaged ecosystem dynamics. The results have been integrated into an economic model of global agriculture, forestry, and land use developed at Pacific Northwest National Laboratory that simulates world demand and supply of agricultural, energy and forest products over one century and allocates land between competing uses. Results across climate scenarios on crop yield, irrigation demand, water supply, and productivity of unmanaged ecosystems are combined to alter simulated agricultural productivity in the United States.

First a set of 12 climate change scenarios were developed based on three General Circulation Models (GCMs), the Australian Bureau of Meteorology Research Centre (BMRC), the University of Illinois Urbana-Champagne (UIUC) and a version of UIUC that considers the effects of sulfate aerosols (UIUC + Sulfates). Two relatively conservative climate sensitivities were assumed for each GCM – global mean temperature (GMT) change of +1.0 and +2.5 °C. Two levels of atmospheric CO_2 concentration ($[CO_2]$) to represent the absence and presence of a "CO_2-fertilization effect" were also used (365 and 560 ppmv). In Part 1 of this series, the resulting set of 12 scenarios are placed in the context of recent work on climate-change scenarios developed by the IPCC for the whole of the 21st century (Cubasch et al., 2002). Scenario development is described in Part 1.

The regionalized climate change scenarios and their spatial variations are described in Part 2, as are two of the ecosystem process models. These are the Erosion Productivity Impact Calculator (EPIC) crop growth and yield model and the Hydrologic Unit Model of the United States (HUMUS) hydrology model. Comparisons with historical crop yields and streamflow data were made to establish the utility of these models for application to the conterminous U.S. The 12 climate change scenarios (plus a baseline scenario) are used in Part 3 to drive the EPIC model in order to simulate climate change impacts on yields of dryland crops. These were done for 204 ‘representative farms’ distributed one to each of the USGS 4-digit hydrologic unit areas (HUAs) in the conterminous U.S. Three major grain crops (corn, soybean, winter wheat) and two forage crops (alfalfa and clover hay) were modeled and the results reported in terms of total national production. The regions most likely to experience significant change in yield, positive or negative, and in which production of the individual crops studied would likely be lost or gained are identified. The amounts of water needed for irrigation of each crop on each farm are also simulated in this exercise, but are reported in a subsequent paper (Part 5).

In Part 4, we apply the HUMUS model to examine the sufficiency of water supply to meet changing demands in the face of climate change as represented by the 12 scenarios (3 GCM $\times$ 2 GMT $\times$ 2 [CO_2]). The HUMUS model simulates hydrologic processes including evapotranspiration, runoff, soil profile recharge, and lateral flow to streams. In this case the simulations are made on the scale of the 2,101 8-digit (USGS classification) HUAs in the country. Results are aggregated for various calculations and consistency with the EPIC modeling to the scale of the 204 4-digit HUAs. The primary purpose of Part 4 is to provide information bearing on the sufficiency of future water resources to meet changing demands of irrigated agriculture under climate change.

Many researchers who have dealt with this question conclude that agriculture is one (perhaps the major) economic sector in the U.S. likely to be affected by climatic change (e.g., Rosenberg, 1982; National Academy of Sciences, 1992; IPCC, 2001; 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 changes in season length and other fairly obvious adjustments. Irrigation would be the most effective way to compensate for rising temperatures, greater evapotranspiration and, in some regions, reduced precipitation. This assumes, of course, that there will be water available to irrigate where dryland yields fall below standards of economic viability. But will the water actually be there?

In Part 5 we draw information on climate change impacts on dryland agriculture and on the water resources necessary for crop production from the prior papers to assess the overall impacts of changes in water supply on national grain production. We calculate national production in current crop growing regions by applying irrigation where it is needed and where water is available. One interesting finding: irrigation on a national level (under the assumptions and constraints applied) declines under all of the climate change scenarios. In certain regions and scenarios, precipitation declines so much that water supplies are too limited; in other regions precipitation is so plentiful that little value is derived from irrigation. The foregoing analyses provide information on areas in the country where dryland and irrigated crop production might be abandoned (for lack of profitability) and on areas into which production might expand. But if the former, what types of unmanaged vegetation would encroach? And if the latter, what types of unmanaged vegetation would be displaced? These questions are addressed in Part 6.

The biogeography and productivity of terrestrial ecosystems has changed over time as the result of normal climatic variability and change and also because of human activity. They are likely to change still more with greenhouse warming and its attendant climatic changes. Part 6 reports the results of an analysis in which the ecological model BIOME3 was used to characterize the range in response of unmanaged ecosystems to the 12 climate change scenarios. The BIOME3 model provides information on net primary productivity (NPP) and geographical distribution of major biomes of the conterminous U.S. The model provides information, then, on the vegetation that exists where the land is not farmed and, by inference, what kinds of vegetation would colonize agricultural lands that are abandoned. This analysis also provides surrogate information on forest productivity and the potential for biomass production to offset some portion of current and future fossil fuel use. Validations show that under the current (baseline) climate, BIOME3 captures the potential distribution of major biomes across the U.S. and reproduces the general trends of observed NPP acceptably.

Changes in crop productivities, water availability, and the natural ecosystem will affect human activities and welfare over time and space. Additional tools are needed to assess some of the implications of such changes and the adaptations that markets could engender. Information provided in the previous papers is incorporated into JGCRI's Agriculture and Land Use Model (AgLU) in Part 7. AgLU is an economic model with 14 world regions and a century time scale and is used to simulate the supply of and demand for four aggregate crop types, three aggregate animal products, and one aggregate forest product. Key drivers include food demand, trends in regional population, and trends in income. At low per capita income levels increasing wealth increases the demand for both animal products for grains consumed directly. As per capita incomes increase that pattern changes to one in which the demand for animal products increases, but the demand for grains to be consumed directly by humans saturates and even declines. Agricultural and forest production are constrained by land productivity in each region, while international trade allows agricultural production to shift among world regions according to their comparative advantage. Data from the preceding papers in this series provide information on potential changes in agricultural yield due to climate change in the United States. This data is aggregated to a national index and then applied to an autonomous baseline trend of increasing yield in AgLU. In the absence of climate change, agricultural yields are anticipated to continue to increase with time. Land is allocated among competing uses in AgLU in response to changes in the expected economic performance of each hectare in its alternative uses. Implications of all the changes documented in these papers for global food supply, land rents and the economic well-being of farmers and land owners in the U.S. are analyzed in this final paper of the series.

And so, with this roadmap to guide us, we proceed to the details, considering a future touched by both human development and climate change. On to the Lower 48!!

Acknowledgements

The research reported in these papers was supported by a grant from the National Science Foundation (Project DEB-9634290), by core support from the U.S. Department of Energy's Integrated Assessment Program and with additional support from the Electric Power Research Institute.

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 1. SCENARIOS AND CONTEXT

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Abstract. As carbon dioxide and other greenhouse gases accumulate in the atmosphere and contribute to rising global temperatures, it is important to examine how derivative changes in climate may affect natural and managed ecosystems. In this series of papers, we study the impacts of climate change on agriculture, water resources and natural ecosystems in the conterminous United States using twelve scenarios derived from General Circulation Model (GCM) projections to drive biophysical impact models. These scenarios are described in this paper. The scenarios are first put into the context of recent work on climate-change by the IPCC for the 21st century and span two levels of global-mean temperature change and three sets of spatial patterns of change derived from GCM results. In addition, the effect of either the presence or absence of a CO_2 "fertilization effect" on vegetation is examined by using two levels of atmospheric CO_2 concentration as a proxy variable. Results from three GCM experiments were used to produce different regional patterns of climate change. The three regional patterns for the conterminous United States range from: an increase in temperature above the global-mean level along with a significant decline in precipitation; temperature increases in line with the global-mean with an average increase in precipitation; and, with a sulfate aerosol effect added to in the same model, temperature increases that are lower than the global-mean. The resulting set of scenarios span a wide range of potential climate changes and allows examination of the relative importance of global-mean temperature change, regional climate patterns, aerosol cooling, and CO_2 fertilization effects.

1. Introduction

Atmospheric concentrations of carbon dioxide and other heat-trapping gases have been increasing over the past century, enhancing the atmosphere's natural greenhouse effect. This increase is thought to be the major cause of the measured increase in surface temperatures over the last 50 yr (Mitchell et al., 2002). Further climate changes over this century are nearly certain, although of uncertain magnitude.

While global-mean temperatures are a useful measure of the overall magnitude of possible anthropogenic influence, it is regional climate changes that will produce

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impacts on both human and natural systems. Further, it is not necessarily average changes but changes in seasonality, variability and extremes that will be more disruptive. Changes in climate will translate to changes in other important natural processes, notably the hydrologic cycle. In addition to climate changes, increasing atmospheric carbon dioxide concentrations ([CO_2]) will likely affect plant growth and water balance.

This series of papers presents a coordinated set of climate impact studies that examine the responses of agriculture, water resources, and natural ecosystems to a set of climate change scenarios. The biophysical models used are the EPIC model for agriculture (Williams, 1995), the HUMUS model for water resources (Arnold et al., 1999), and the BIOME3 model for natural ecosystems (Haxeltine and Prentice, 1996). These are fully described and validated in Parts 2 and 6.

Using a range of future climate scenarios, we simulated the impacts on dryland agriculture (Part 3) and on water resources (Part 4). Next, we examined the degree of change of water demand by irrigated crops, the amount of water available to meet that demand, and how total potential crop production in the United States might be affected (Part 5). We then assessed, under the same climate scenarios, the possible magnitude of changes in natural ecosystems (Part 6). The series ends with an economic analysis of the impacts of the various climate change scenarios on agriculture and water resources (Part 7). In this, the first of the papers, we present the climate change scenarios used for these analyses, discuss the changes projected over the United States and provide some context for the sectoral impact studies.

2. Climate Change Scenario Descriptions

A set of climate scenarios projecting how temperature and precipitation will change due to anthropogenic influences is one of the fundamental inputs needed for biophysical impact models. These models also require future CO_2 concentrations to evaluate the impact of CO_2-fertilization on vegetation. The magnitude of these changes is not known, however, due to uncertainties in both the climate response to anthropogenic influences and the extent of future emissions of greenhouse gases. Thus, we conduct our analyses over a matrix of scenarios that covers a wide range of possible future climatic conditions in order to examine the range of possible impacts.

The impact models used in this study require inputs of climate parameters such as temperature and precipitation; for this reason the scenario descriptions also focus on physical rather than socio-economic parameters. This is not to say that socio-economic factors are irrelevant to impacts analysis. Different assumptions for driving forces such as population levels and income, for example, can lead to drastically different demands for agricultural goods, which would imply quite different implications for climate impacts on agriculture. In this analysis socio-economic effects and physical changes are separated. We first calculate impacts such as agricultural productivity changes for a matrix of physical climate change scenarios. The last paper (Sands and Edmonds, 2004) in this series then conducts an analysis that examines the impact of these physical changes in a larger socio-economic context using an integrated assessment model.

Ideally, an end-to-end analysis would include all of these factors simultaneously, considering a self-consistent set of impact inputs from global-mean-climate changes, rates of climate change, carbon dioxide concentrations, regional climate changes, and regional (and global) socio-economic factors. Developing such a study would likely require a spatially disaggregated representation of driving forces such as population, income, and other social-economic indicators. Just as the uncertainty in climate changes increases with decreasing spatial scale the same is also true for socio-economic driving forces, even if larger-scale values are taken as given. Such an end-to-end analysis would provide useful insights and self-consistent results, but would be one of a wide range of possible results given the uncertainty in each of the factors in the causal chain.

The present study is, instead, structured to examine a range of possible outcomes in a conceptually (and computationally) straightforward framework. We, therefore, will proceed below to examine the variables that define the inputs needed for each of these analyses. Each scenario consists of the following three sets of input data: (1) a specification the magnitude of future anthropogenic climate change in terms of global-mean temperature change, (2) the strength of the effect of increasing CO_2 concentrations on plant processes, and (3) the spatial pattern of these changes in temperature and precipitation as simulated by GCM models. No changes in climate variability are considered: the absolute values of inter-annual changes are assumed to be identical to those in the 30-yr reference period (see below). Each of these variables is discussed below. The result is a grid of twelve climate change scenarios along with a baseline case of no further climate changes (Table I).

2.1. GLOBAL-MEAN TEMPERATURE CHANGE

The global-mean temperature change due to anthropogenic influences is the most widely used measure of the magnitude of future climate change. There are two primary determinants of the overall level of future climate changes, the level of greenhouse gas emissions, including the influence of aerosols, and the *climate sensitivity* (see below). Neither the future emission levels nor the climate sensitivity are known, which means that there is a wide range of possible changes in global-mean temperature.

For this study two values of global-mean temperature (GMT) change are used: $+1\,^{\circ}$C and $+2.5\,^{\circ}$C . The temperature changes here, and henceforth, are relative to a 1990 base year.[1] As with most climate impact analyses, this one was done with a discrete set of input parameters. In all likelihood, future climate changes will not

TABLE I

Scenario matrix: A baseline climate plus 12 combinations of climate model, global-mean temperature projection, sulfate aerosols and CO_2 fertilization effects

GCM	GMT (°C)	CO_2 concentration (ppmv)
Baseline		365
BMRC	1	365
		560
	2.5	365
		560
UIUC	1	365
		560
	2.5	365
		560
UIUC + Sulfates	1	365
		560
	2.5	365
		560

Note. The CO_2 concentration levels are meant as proxies for the strength of the fertilization effect and not as specific concentration levels associated with the given temperature change values (Section 6).

be stationary but will change over time, so that any specific set of parameters will occur only once (or perhaps not at all).

2.1.1. *SRES Context*

To put these changes into context, first consider the simplified range of future changes given in Figure 1, which shows the global-mean changes projected for six illustrative emission scenarios from the IPCC Special Report on Emission Scenarios (SRES) using a central value for the climate sensitivity (Cubasch et al., 2002). The SRES scenarios cover a wide range of driving forces, which result in a range of emissions. As demonstrated in Figure 1, these emissions result in a range of future climate changes (although note that different sets of driving forces can result in similar emissions; Nakicenovic and Swart, 2000). We see that a global-mean temperature change of 1 °C occurs in these scenarios as a transient point, which is exceeded in all of these cases. The case for a 2.5 °C change is less certain. Both in scenarios with high emissions or with elevated climate sensitivity (not shown), this level of climate change can be exceeded. There are also scenarios in which this level of climate change is not reached.

The picture given in Figure 1 is, however, incomplete. The range of future climate changes is determined by emissions, the behavior of the climate system, and the behavior of gas cycles. Uncertainty in all of these contributes to the spread in

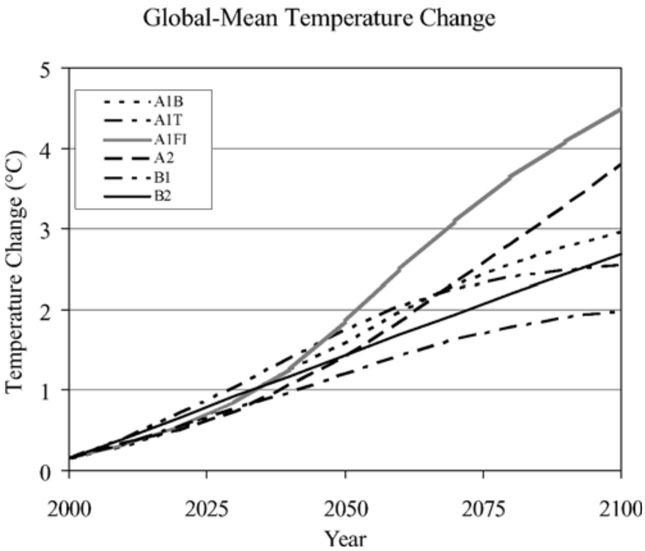

Figure 1. Global-mean temperature change, relative to 1990, under six different scenarios for future emissions under the assumption of a climate sensitivity of 2.5 °C. These six emissions scenarios span a range of future assumptions for global socio-economic development in the absence of climate policy (Nakicenovic and Swart, 2000). See Cubasch et al. (2002) for details of the temperature change calculations.

possible future climate change (Wigley and Raper, 2001). A particularly important parameter is the climate sensitivity, which is an aggregate measure of how much the climate will respond to changes in radiative balance, such as those caused by changes in greenhouse gas concentrations. The climate sensitivity is conventionally given as the equilibrium global-mean warming associated with a doubling of carbon dioxide concentrations.

2.1.2. *Probabilities and Scenarios*

In order to present a fuller picture considering variation in multiple parameters we will turn to probabilistic estimates of future temperature change, using the results from the analysis of Wigley and Raper (2001). In using these results we wish to put the discrete scenarios used in this study into some context. Any probabilistic calculation is, however, itself subject to uncertainty and we will discuss below how the uncertainties in these calculations affect our interpretation in the context of the present work.

Figure 2 shows one estimate of the probability of exceeding a 1 °C and 2.5 °C increase in global-mean temperature over the next 100-yr assuming that no climate mitigation policies are implemented (Wigley and Raper; 2001). Intermediate date and probability figures are purposely not given in this figure to emphasize that we are not attempting to assign a specific probability to our impacts scenarios but to provide context to the scenarios.

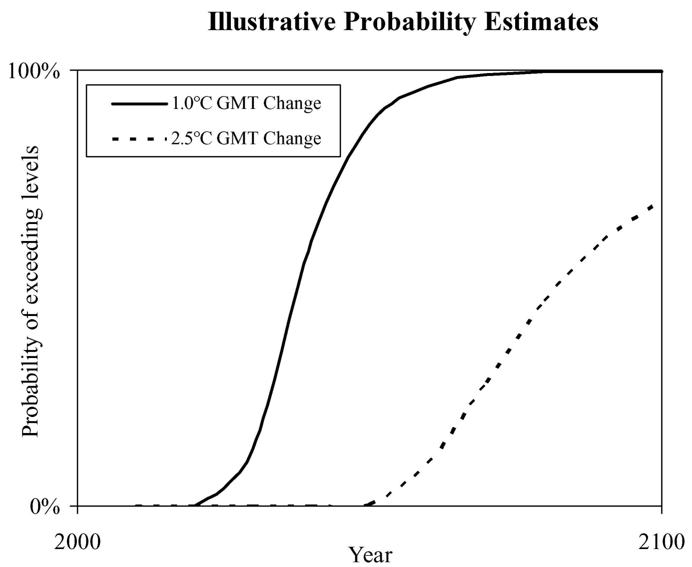

Figure 2. Estimates of the probability of exceeding two specified levels of global-mean temperature change, relative to 1990, as calculated by Wigley and Raper (2001). These estimates take into account range of possible future emissions and climate parameters.

The probabilistic calculations presented here are based on two sets of assumptions. The primary set of assumptions is about the distribution of input parameter values. The second set of assumptions concern the behavior of the climate system. The latter are embodied in the simple climate model used to translate input parameter values into climate outputs. The model used (MAGICC) has been shown capable of re-producing the global-mean outputs of most general circulation models. With the exception of possible discontinuities in the behavior of the climate system, we conclude that the uncertainties in this calculation lie primarily with the assumptions about the distribution of input parameter values.[2]

The principal input parameters that determine future climate change are emissions of greenhouse gases and aerosols and the value of the climate sensitivity. Here, we assume that each of the emissions scenarios are equally likely and that all values of the climate sensitivity over the range of 1.5–4.5 °C per CO_2 doubling, as assumed by the IPCC, are equally likely as well (a range in gas-cycle parameters is also considered). The shape of the distribution for climate sensitivity does not have a large effect on the outcome since most realizations will use values near the center of the distribution (Wigley and Raper, 2001).

The range of parameters used is based largely on results from both physical-science models (for values of the climate sensitivity) and socio-economic models (for emissions scenarios). While model results are often constrained by observational or historical data, it is clear that there is much about both the climate system and socio-economic systems that is not well understood. While we believe the parameter ranges are a reasonable representation of our current understanding of these systems, future estimates could turn out to be significantly different than those estimated here. This is an important, and almost impossible to quantify, source of uncertainty, as has been recognized for other systems where modeling has been used to predict the future of poorly understood systems (Sarewitz et al., 2000).

A particular point of contention exists regarding the assignment of probabilities to emissions scenarios. While the properties of a physical systems can be subject to a formal statistical analysis, projections of the state of socio-economic systems 100 years in the future is arguably more problematic. Many of the critical links between socio-economic systems are not understood well enough to allow straightforward incorporation into a quantitative model. Furthermore, future socio-economic developments are not independent variables, but are subject to policy decisions made today and in the future. Recognizing these difficulties, Wigley and Raper (2001) choose to make all of the SRES scenarios equally likely. In constructing these scenarios, the SRES writing team did not assign a probability to any of the scenarios or scenario families, stating that "the distribution of the scenarios provides a useful context for understanding the relative position of a scenario but does not represent the likelihood of its occurrence." These considerations will be noted as we proceed with interpretation of probabilistic results.

2.1.3. *Probabilistic Context*

With these points on the probabilistic interpretation of scenarios in mind, we now turn to the specific scenarios used in this study. Consider now the probability of exceeding a 1 °C increase in global-mean temperature relative to 1990 as shown in Figure 2. The probability of exceeding a 1 °C global-mean temperature change by the middle of the century is very high. At this point the influence of the emissions scenario of global-mean temperature change is relatively small (Figure 1). Therefore, the probabilities up to mid-century are influenced largely by the values of climate parameters, in particular the climate sensitivity. We conclude that, given our current understanding of the climate system, that a 1 °C change in global-mean temperature is nearly certain to occur by the end of the century and probably will occur by mid-century. While policy scenarios may reduce emissions, such reductions will have limited impact on climate change for some time due to both the thermal inertia in the climate system (Dai et al., 2000) and interactions between greenhouse gas and sulfur dioxide emissions (Smith et al, 2004). Note also that the lower range of the SRES emissions scenarios result in carbon dioxide concentrations by 2100 that are nearly stable at around 550 ppmv, a commonly analyzed policy target. Therefore, even under many climate change mitigation policy scenarios, global-mean temperature is likely to exceed 1 °C by 2050. In the long term, the impacts under this scenario are likely to be underestimates of eventual climate impacts by the end of the century.

For the 2.5 °C set of impacts scenarios, we can conclude that there is low chance of a 2.5 °C increase in global-mean temperature, relative to 1990, by 2050.[3] Again, by 2050, the influence of the emissions scenario assumptions is relatively small and the results are primarily driven by climate system and aerosol forcing assumptions. Therefore, the 2.5 °C set of impact scenarios are focused on the second half of the century if not later. After 2050 the conclusions that can be drawn from the probabilistic analysis are less well defined. Due to the longer time horizon, most of the assumptions made for this calculation have a larger impact on results in 2100 as compared to 2050 including issues of how to probabilistically represent emissions scenarios. The calculation of Wigley and Raper (2001) results in a 70% probability of a global-mean temperature change that exceeds 2.5 °C by 2100 with no climate policies in place. Therefore, we can conclude that a level of climate change of 2.5 °C is feasible, but that this is by no means certain to occur nor is this an upper bound to possible changes by 2100.

In summary, the 1 °C impact scenarios provide a conservative lower bound for the future impacts of climate change. Impacts at this level are likely to be exceeded by the middle of the century. The 2.5 °C impact scenarios simulate a level of climate impacts that may be felt at some point in the latter half of this century. Global temperatures might not reach this level, or could exceed this level, depending on climate sensitivity, future socio-economic developments, and the presence of climate policy actions.

2.2. CARBON DIOXIDE FERTILIZATION EFFECT

The primary driving force of the climate changes presented above is the increasing concentration of carbon dioxide in the atmosphere. In addition to the effect of any changes in climate on plant growth, changes in the atmospheric concentration of CO_2 ([CO_2]) will also affect plants directly. In experiments in controlled environments (Kimball, 1983; Rogers et al., 1996) and in field studies using free-air carbon dioxide enrichment (FACE) facilities (Mauney et al., 1994; Kimball et al., 1995), a CO_2 'fertilization effect' has been observed; agricultural crops grown at higher [CO_2] experience increased growth rates, improved water use efficiency, and higher yields (Makino and Mae, 1999; Allen et al., 1998; Maroco et al., 1999). Plants respond to increasing CO_2 concentrations with increased rates of photosynthesis and with increased stomatal resistance that reduces transpiration, hence conserving water and reducing water stress.

While the presence of these CO_2 "fertilization" effects are well documented, there is considerable uncertainty regarding how accurately and consistently these effects can be applied to long-term simulations of crop growth over large areas (Bowes, 1993; Makino and Mae, 1999) and how these effects extend to unmanaged ecosystems (Drake et al., 1996; Oechel et al., 1994; Oren et al., 2001). These uncertainties are discussed in detail in the subsequent papers on the EPIC model. We consider these uncertainties by reporting results for the two levels of CO_2 concentration used in the impact studies reported here. The first, a level of 365 ppmv, essentially the current concentration,[4] is used to represent the notion that the direct effects of 'fertilization' do not manifest themselves or are insignificant. This is, therefore, a lower bound case for CO_2 fertilization effects. A higher [CO_2] – 560 ppmv – was also used in the analysis. Given that CO_2 fertilization effects tend to saturate with increases in concentration, the use of this concentration level, along with central assumptions about the physiological response of plants to [CO_2] represent a reasonably strong CO_2 fertilization effect. Under a wide range of assumptions about the carbon cycle, a [CO_2] level of 500 ppmv is reached or exceeded by most of the SRES scenarios by the end of the century (Prentice et al., 2002). A number of scenarios, depending again on carbon-cycle assumptions, can exceed this level by 2050.

The uncertainty in the climate sensitivity, in particular, means that there is no unique figure for the amount of temperature change that could be considered consistent with a specific CO_2 concentration level. The matrix of climate scenarios considered for the impact analyses thus is not intended to literally pair a specific CO_2 concentration level with specific levels of climate change. Instead, we are considering two simplified cases: no CO_2 fertilization effect and a moderate to strong CO_2 fertilization effect as bounding cases.

In summary, combining the two climate change (temperature change) levels and the two chosen CO_2 concentration levels gives four scenarios. While we do not expect there to be no effects due to CO_2 fertilization, these effects may be significantly limited in the real world as compared to an idealized model. The 365 ppmv – "no fertilization effect" – scenarios provide a certain lower bound for fertilization effects.

The combination of 1 °C and 560 ppmv is unlikely in the 'real-world'. Temperature changes that would accompany this concentration level are likely to be significantly higher that 1 °C . This scenario represents, then, a modest amount of climate change coupled with a strong CO_2 fertilization effect and sets a lower bound for the transient effects that could occur between about 2030 and 2050 (Figures 1 and 2).

The fourth combination of 2.5 °C and 560 ppmv is physically realizable and not improbable. It is possible that CO_2 fertilization effects could exceed the level assumed here. It is also probable that saturation effects and other limiting factors will be important given both the significant levels of CO_2 fertilization and climate change assumed. We consider this combination to be a reasonable point estimate of climate change with possible ameliorating effects of CO_2 fertilization, as could occur towards the end of this century.

2.3. THE SPATIAL PATTERN OF CLIMATE CHANGE

Global-mean temperature change, while useful as a measure of overall strength of greenhouse warming, is not the most relevant measure for impact analysis, which requires information on regional and local changes in climate. Relevant variables include precipitation, temperature, and changes in the variability and extremes in these quantities. Regional climate changes are estimated by a variety of methods including historical analogy, general circulation models (GCMs), and GCMs coupled with various downscaling techniques.

Our method here is to use historical climate data, coupled with GCM results. Rather than using GCM results directly, we use the pattern scaling method embodied in the SCENGEN system of Hulme et al. (1995) to produce regional climate change patterns. In this method, each GCM is considered to have a characteristic climate sensitivity and climate response pattern, although the latter can change with different assumptions about aerosol effects. Since neither the true response pattern nor the climate sensitivity are known, this method allows a wide range of possible climate responses to be generated.

A historical climate data series from 1960 to 1989 was used to establish a baseline climate data set for the EPIC, HUMUS and BIOME3 simulations (Arnold et al., 1999). The GCMs provided data on the monthly change in daily mean temperature and precipitation. Baseline daily climate data were then adjusted with the GCM-generated changes.

To provide the widest range of possible future climate scenarios, two GCMs were chosen for their divergent projections of future climate over the continental United States. This allows the analysis to consider the widest range of potential future conditions and place theoretical bounds on the degree and direction of change most likely to occur. The models are from the Australian Bureau of Meteorology Research Center (BMRC) (McAveney et al., 1991) and the University of Illinois at Urbana Champagne (UIUC) (Schlesinger, 1997). The UIUC GCM was also run with the inclusion of sulfate aerosol effects (UIUC + Sulfate), providing a third set of climate change projections. The pattern of climate change from these three models, each at two levels of global-mean temperature and two levels of [CO_2] gives 12 climate change scenarios to be evaluated, as shown in Table I.

The spatial patterns of temperature and precipitation change for the BMRC scenarios are identical for the 1 °C and 2.5 °C scenarios; only the magnitudes of the changes are different. The same is true for the UIUC scenarios (without sulfate aerosols). This is because, for forcing components where the pattern of forcing remains constant over time, the climate change response pattern is assumed also to remain constant with time. The situation is different for the UIUC + Sulfate aerosol scenarios. Since the pattern of forcing from sulfate aerosols varies with time, the resulting pattern of climate change will also vary with time. For this scenario a SCENGEN run with IS92a forcing assumptions was used to derive the climate change patterns. The 1 °C and 2.5 °C scenarios were produced when the global-mean temperature change in the IS92a scenario reached these points. This results in climate change patterns that are different for the 1 °C and 2.5 °C scenarios. A quantitative discussion of the climate change patterns as given by the three GCM results follows.

3. Geographic Patterns of Climate Change

3.1. ANNUAL TEMPERATURE AND PRECIPITATION CHANGES

The annual temperature and precipitation change, averaged over the conterminous United States, is given in Table II. All three model results project an increase in the annual-mean temperature of the conterminous United States, although the magnitude of the increase (relative to the global-mean) differs with each model.

Temperature change in the United States is greater than the global average value for the BMRC model, about equal to the global average in the UIUC model, and less than the global average in the UIUC + Sulfates model run.

The simulation results for precipitation also differ, with the UIUC model showing increasing precipitation over most of the conterminous United States and the BMRC showing substantial drying. Precipitation decreases in BMRC, increases in the UIUC model run and increases even more in the UIUC + Sulfates model run.

The average results given in Table II are only a general indication of the regional effect of climate change. Regional patterns in these changes over the U.S. drive the ecosystem models used in this analysis. The pattern of changes for each of these three models is discussed below.

3.1.1. *BMRC*

Temperature increase under BMRC is moderate in the southern states, along the West Coast and in the more northerly portions of the Great Plains and Northeast (Figure 3). The Great Lakes region shows the greatest increase in temperature. The range of increase here for a global-mean temperature (GMT) = +1 °C is from 1 to 2 °C and for GMT = +2.5 °C the range is from 2.5 °C to 5 °C above baseline. In the BMRC scenarios precipitation declined nationwide under GMT of +1 °C and +2.5 °C (Figure 4). Drying is most extreme in the south and southwestern parts of the country and up the West Coast. The exception is the northern part of the country

TABLE II
Average annual change in temperature and precipitation over the conterminous United States given by the GCM climate change scenarios, as scaled for use in this study

GCM	GMT (°C)	Temperature change(°C)	Precipitation change (mm)
BMRC	1	1.5	−39
	2.5	3.6	−98
UIUC	1	0.9	98
	2.5	2.3	245
UIUC + Sulfates	1	0.4	132
	2.5	1.6	287

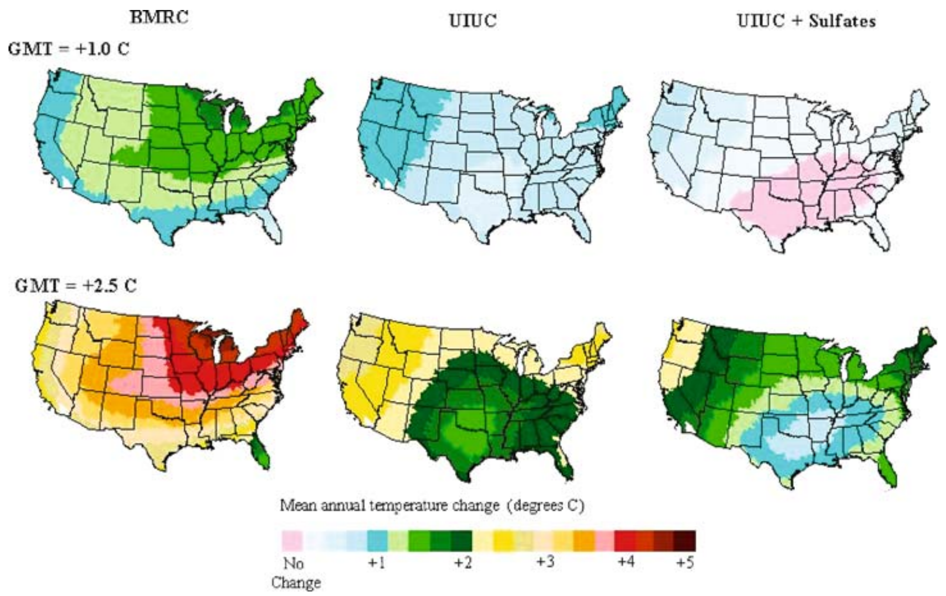

Figure 3. Mean annual temperature change from baseline for the three GCMs at two global-mean temperature change levels.

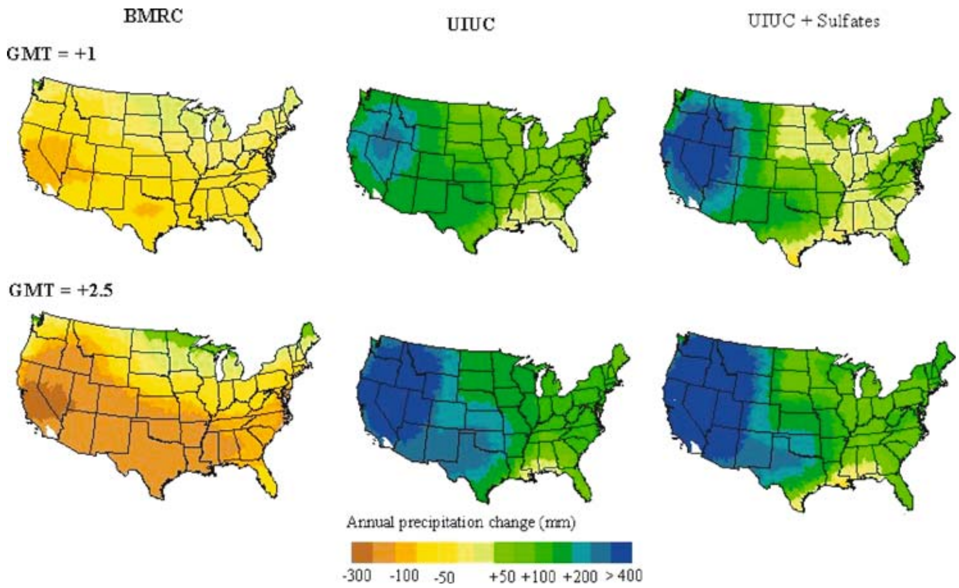

Figure 4. Annual precipitation change from baseline for the 3 GCMs at two levels of global-mean temperature change.

where drying is moderate. Some precipitation increases are projected, notably in the Great Lakes region and the Northeast. The increase of GMT to $+2.5\,^{\circ}$C intensifies both the drying in the Southwest and West Coast and the increase in precipitation in the Northeast and Great Lakes states.

3.1.2. *UIUC*

Warming under UIUC is moderate, ranging from 0.5 °C to 1.5 °C above baseline when GMT = +1 °C and from 1.5 °C to 3 °C when GMT= +2.5 °C (Figure 3). Warming is weakest in the south central part of the country and strongest in the Northeast and Northwest. UIUC projects increased precipitation across most of the country (Figure 4). Some slight drying is shown on the Gulf Coast, but moderate to large increases in precipitation occur over the rest of the country. The Western half of the country receives more of an increase than the East. At GMT = +2.5 °C, precipitation increases further across the country, and the drying along the Gulf Coast is moderated.

3.1.3. *UIUC + Sulfates*

Temperature and precipitation changes are affected by the inclusion of the sulfate aerosol effect in the UIUC model (Figure 3). Temperature increases are least under this scenario, ranging from 0 °C to 1 °C with GMT = +1 °C and from 1 °C to 3 °C when GMT = +2.5 °C . The regional distribution of temperature change is similar to that under UIUC without sulfate. Precipitation declines in some regions with the addition of sulfates to the UIUC model, but increases in others (Figure 4). Precipitation increases were least in the southern Gulf Coast states and through the Ohio Valley and parts of the Midwest. Precipitation increases in the Northeast, unchanged from UIUC, and increases to a greater extent over much of the western half of the country.

3.2. SEASONAL CHANGE IN TEMPERATURE AND PRECIPITATION

Projected climate changes will not be uniform throughout the year. How air temperature increases seasonally will determine crop growth and hydrologic response. Higher summer temperatures could induce more severe and protracted temperature stress in crops as well as increased rates of evapotranspiration, reducing crop water use efficiency[5] and runoff. Temperature increases in the spring and fall would lengthen the crop growing season but also shorten the time to maturity, thereby lowering yields. A longer growing season may also favor introduction of new species or cultivars and enable use of management practices not previously possible.

Seasonal differences in the patterns of temperature change are reported for seven of the eighteen major U.S. water resource regions in Table III. Under BMRC, the temperature increase is greatest in winter for the Ohio, Upper Mississippi, Arkansas and Texas Gulf regions and least in the spring. For the Missouri, South Atlantic, and Pacific Northwest regions, the increase is greatest in the summer and the least in fall. Temperature change under UIUC is greatest in summer and least in winter in these regions. The temperature increase in summer is 0.5 °C greater than the average annual increase. Under UIUC + Sulfate, a distinct change occurs where the Ohio, Upper Mississippi and Arkansas-White-Red regions register a slight cooling in

TABLE III
Mean daily temperature change (°C) in 7 major water resource regions

Scenario	3. S. Atl.-Gulf	5. Ohio	7. U. Miss	10. Missouri	11. Arkansas	12. TX Gulf	17. Pacific NW
				Winter			
BMRC +1	1.14	1.94	2.10	1.63	1.59	1.24	1.33
BMRC +2.5	2.87	4.83	5.22	4.08	3.95	3.09	3.32
UIUC +1	0.66	0.55	0.69	0.80	0.38	0.49	1.08
UIUC +2.5	1.64	1.34	1.68	1.99	0.93	1.24	2.71
UIUC Sulfate +1	−0.06	−0.52	−0.56	−0.10	−0.48	−0.21	0.63
UIUC Sulfate +2.5	0.59	−0.14	−0.05	0.76	−0.26	0.25	2.11
				Spring			
BMRC +1	1.21	1.44	1.56	1.38	1.61	1.52	1.10
BMRC +2.5	3.03	3.62	3.90	3.43	4.01	3.80	2.74
UIUC +1	0.83	0.80	0.69	0.73	0.57	0.53	1.08
UIUC +2.5	2.09	2.02	1.72	1.83	1.43	1.35	2.71
UIUC Sulfate +1	0.19	0.16	0.08	0.21	−0.16	−0.21	0.86
UIUC Sulfate +2.5	1.17	1.12	0.91	1.10	0.42	0.29	2.41
				Summer			
BMRC +1	1.21	1.58	1.59	1.70	1.47	1.05	1.46
BMRC +2.5	3.03	3.94	3.95	4.24	3.68	2.64	3.65
UIUC +1	0.95	1.04	1.20	1.28	1.06	0.95	1.40
UIUC +2.5	2.37	2.61	2.99	3.19	2.62	2.37	3.48
UIUC Sulfate +1	0.40	0.63	1.10	1.19	0.65	0.54	1.33
UIUC Sulfate +2.5	1.57	2.09	2.96	3.17	2.10	1.80	3.46
				Fall			
BMRC +1	1.05	1.47	1.58	1.33	1.30	1.14	1.05
BMRC +2.5	2.64	3.67	3.95	3.34	3.26	2.85	2.62
UIUC +1	1.04	1.04	0.89	0.79	0.89	0.85	0.89
UIUC +2.5	2.58	2.60	2.19	1.99	2.22	2.11	2.26
UIUC Sulfate +1	0.59	0.68	0.69	0.43	0.77	0.62	0.25
UIUC Sulfate +2.5	1.94	2.11	1.97	1.49	2.06	1.79	1.33

winter and spring. The greatest increases in temperature occur in the summer and fall in these regions.

The seasonal distribution of precipitation is also very important in the growth and management of crops. Higher spring and summer precipitation would lower demand for irrigation. In many regions, reduced fall and winter precipitation would reduce the reserves of water in snowpack and, ultimately, the water level in reservoirs, diminishing the supplies for irrigation, navigation, hydropower, fisheries and wildlife. A large increase in the winter and spring could increase the frequency of damaging floods and lower crop production because of water-logging, impediments to tillage, soil erosion, loss of nutrients by leaching and so on.

The seasonal distribution of precipitation is also different from the annual change in the seven regions represented in Table IV. Under BMRC, the largest percentage

TABLE IV
Seasonal precipitation (mm) at baseline and percentage change in precipitation under the climate change scenarios in 7 major water resource regions (MWRR)

Scenario	3. S. Atl.-Gulf	5. Ohio	7. U. Miss	10. Missouri	11. Arkansas	12. TX Gulf	17. Pacific NW
				Winter			
Baseline (mm)	321	236	106	51	125	155	320
BMRC +1 (%)	−10	5	7	2	−13	−23	1
BMRC +2.5 (%)	−25	12	18	4	−32	−57	3
UIUC +1 (%)	0	11	18	13	24	22	4
UIUC +2.5 (%)	0	29	44	32	59	56	9
UIUC Sul +1 (%)	−3	25	24	11	15	5	13
UIUC Sul +2.5 (%)	−8	45	51	26	43	28	24
				Spring			
Baseline (mm)	335	310	230	161	241	226	188
BMRC +1 (%)	−6	−7	5	6	−7	−10	−5
BMRC +2.5 (%)	−15	−16	13	14	−17	−24	−13
UIUC +1 (%)	−14	3	10	7	−2	−4	9
UIUC +2.5 (%)	−35	8	24	19	−5	−9	23
UIUC Sul +1 (%)	−32	0	6	1	−26	−30	8
UIUC Sul +2.5 (%)	−62	3	19	8	−43	−51	20
				Summer			
Baseline (mm)	413	313	301	192	237	224	93
BMRC +1 (%)	−18	−12	−14	−20	−22	−20	−30
BMRC +2.5 (%)	−45	−30	−34	−50	−56	−51	−74
UIUC +1 (%)	7	0	7	46	51	36	150
UIUC +2.5 (%)	18	0	17	114	128	91	375
UIUC Sul +1 (%)	22	−9	−5	63	64	45	260
UIUC Sul +2.5 (%)	41	−15	−4	134	144	101	534
				Fall			
Baseline (mm)	282	265	219	116	208	250	210
BMRC +1 (%)	−4	−7	−5	−8	−18	−18	5
BMRC +2.5 (%)	−11	−18	−14	−21	−46	−45	14
UIUC +1 (%)	28	20	18	37	37	34	53
UIUC +2.5 (%)	71	51	46	92	92	86	133
UIUC Sul +1 (%)	29	9	−4	23	25	29	91
UIUC Sul +2.5 (%)	71	32	8	66	72	76	184

declines in precipitation occur during summer in most regions. The Upper Mississippi and Missouri regions show increased precipitation during the winter and spring months. The Pacific Northwest and Ohio regions also show small increases in winter precipitation. Percentage precipitation increases are greatest in the summer and fall under the UIUC scenarios. Precipitation is decreased in the South Atlantic, Arkansas and Texas Gulf regions during the spring. Under UIUC + Sulfate, the decrease in spring precipitation in these regions is intensified. The South Atlantic region also shows a decline in winter precipitation. Summer precipitation declines slightly in the Ohio and Upper Mississippi regions, while the remaining regions experience their greatest increases in this season. Increases in the Ohio and the Upper Mississippi are greatest in winter.

4. Summary and Conclusions

Here we have presented the general methodology used in this study and the motivation behind it. In the papers that follow we first analyze the validity of the impact assessment models, EPIC and HUMUS, and conclude that they can reproduce historical conditions of crop yield and streamflow with a level of confidence sufficient for the geographical coverage and scale of this study. We then present the results of these model simulations for a wide range of possible climate changes. Using two GCMs, we explore a range of possible changes in climate that could occur based on differences in the degree of warming, the influence of sulfates, and the potency of the CO_2-fertilization effect.

Climate change over the conterminous United States, as given by the GCM results, are scaled to match two levels of global-mean temperature increase: 1 °C and 2.5 °C . By this procedure we span a range in uncertainty of the overall magnitude of future climate change. While the uncertainty in future climate change is difficult to access quantitatively, analysis indicates that the 1 °C increase in global-mean temperature is nearly certain to be exceeded within the next half century (Figure 2). Therefore, the range of impacts found for this set of scenarios (see Table I) are those likely to occur, even in the event that policies to control climate change are implemented. The likelihood of our scenarios that assume a 2.5 °C global-mean temperature change is more difficult to assess. This level of climate change could well be exceeded within this century, particularly in the case with no policy actions. It is also possible that this level might not be reached, but the impacts on crops, water resources and unmanaged ecosystems identified under these scenarios certainly cannot be considered as upper bounds on the possible impacts of climate change.

The different climate change models used to represent a range in how global changes would be translated into regional changes that affect agricultural and natural systems. The BMRC and UIUC projections of climate change over the United States differ both with respect to the degree of warming and the sign and amount of precipitation change. We will show that the choice of regional climate pattern has a substantial effect on impacts.

Simulations in the papers that follow consider two levels of atmospheric [CO_2]. We note that the impact of CO_2 on ecosystem function, especially on the water use efficiency and carbon uptake of plants, is not yet fully understood at the landscape scale. Therefore, the simulations are run both assuming that the effect of CO_2 will not change ($CO_2 = 365$ ppmv) and that CO_2 will influence ecosystems based on the parameters in the impact models ($CO_2 = 560$ ppmv) at double the pre-industrial concentration. Thus, the results presented represent a range of global and regional climate change plus a range in CO_2 fertilization effects.

The impacts calculations presented in the following paper concentrate on what can be termed physical impacts – changes in crop productivity and ecosystem composition for example. The combination of a range in assumptions (Table I) for global climate change, regional changes, and CO_2 fertilization effects results in a wide range in physical impacts. The actual range of possible impacts, however, is likely even larger. The calculations here, for example, assume that the absolute value of climate variability over a 30-yr time period is scaled simply from that in the base year. Changes in climate variability in the future could have significant impacts and this adds additional uncertainty to impacts results. Finally, changes in socio-economic driving forces such as population, technology and income levels are co-determinants of impacts. Here, we have concentrated on the physical impacts, where we demonstrate a very large uncertainty range. Inclusion of socio-economic interactions would be particularly challenging in a factorial design as presented here, but would add further to the range in impact outcomes.

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Notes

[1]The impact analyses were performed relative to a baseline climatology for 1960–1989. To be fully consistent, a small additional increment of anthropogenic temperature should be added to the SRES temperature change values presented here. For simplicity, since these calculations are used only for context, this has not been done.

[2]The probabilistic calculations did not include the possibility of some large, non-linear change in the climate system. The probability of such a change is difficult to estimate, since this may be

caused by behavior that is currently not well understood or modeled. It is generally thought that the probability of such a "state change" would increase with increasing global-mean temperature change.

[3]Even given the previous caveat about "state changes" in the climate system, the basic physics of the ocean's thermal inertia is robust and will not significantly change this conclusion. At later times, however, such state changes could significantly change the results.

[4]The atmospheric concentration of CO_2 in 2000 was 371 ppmv.

[5]Total biomass (or harvested) yield per unit of water consumed.

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 2: MODELS AND VALIDATION

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Abstract. As carbon dioxide and other greenhouse gasses accumulate in the atmosphere and contribute to rising global temperatures, it is important to examine how a changing climate may affect natural and managed ecosystems. In this series of papers, we study the impacts of climate change on agriculture, water resources and natural ecosystems in the General Circulation Model (GCM)-derived climate change projections, described in Part 1, to drive the crop production and water resource models EPIC (Erosion Productivity Impact Calculator) and HUMUS (Hydrologic Unit Model of the United States). These models are described and validated in this paper using historical crop yields and streamflow data in the conterminous United States in order to establish their ability to accurately simulate historical crop and water conditions and their capability to simulate crop and water response to the extreme climate conditions predicted by GCMs. EPIC simulated grain and forage crop yields are compared with historical crop yields from the US Department of Agriculture (USDA) and with yields from agricultural experiments. EPIC crop yields correspond more closely with USDA historical county yields than with the higher yields from intensively managed agricultural experiments. The HUMUS model was validated by comparing the simulated water yield from each hydrologic basin with estimates of natural streamflow made by the US Geological Survey. This comparison shows that the model is able to reproduce significant observed relationships and capture major trends in water resources timing and distribution across the country.

1. Introduction

Atmospheric concentrations of carbon dioxide ([CO_2]) and other heat-trapping gasses have been increasing over the past century, enhancing the atmosphere's natural greenhouse effect and causing a discernable increase in global mean temperature (Houghton et al., 2001). If the emissions of these gases continue unabated then climate changes will continue to occur and affect many aspects of the environment, including natural ecosystems, the hydrologic cycle and managed systems such as agriculture. Plant growth is affected directly by the changing concentrations of atmospheric gasses, primarily CO_2, and also affected indirectly by the influence of changing atmospheric gas composition on regional climate and local weather patterns. One area of considerable research is the impacts of these changes on agricultural production. Current indications are that global agricultural production

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will not decline significantly with a doubling of atmospheric CO_2concentrations. However, the direct and indirect effects of rising [CO_2] may have significant consequences for regional production that would require adapting crop and crop varieties grown and agricultural management practices (Reilly et al., 1996, 2001).

General Circulation Models (GCMs), developed by government and academic institutions around the world, predict that global mean temperature (GMT) will increase as CO_2 increases, and that the capacity of the atmosphere to hold water will increase. Under double pre-industrial [CO_2][1], GMT is predicted to increase in the future by from +2 to +5°C. Average global precipitation will also increase overall, although in some regions losses will occur. In the United States, for example, the two GCMs employed for this study predict opposite effects of climate change on precipitation. The University of Illinois at Urbana-Champagne (UIUC) GCM projects increasing precipitation over most of the conterminous United States, while the Australian Bureau of Meteorology Research Centre (BMRC) GCM projects severe shortages. Given differences of this kind, impact assessment studies generally make use of several GCMs to drive a given ecosystem model. This approach gives a range of possible futures to consider in planning responses to climate change.

While the increase in CO_2 concentrations is directly measurable, the direct impact on plant growth remains unclear. In experiments in controlled environments and to a lesser extent in field studies, a CO_2 'fertilization effect' has been observed; agricultural crops grown at higher concentrations of CO_2 experience increased growth rates, improved water use efficiency, and higher yields (Makino and Mae, 1999; Allen et al., 1998; Maroco et al., 1999). However, most studies of this effect have evaluated the response of single crops or fields through one growing season where climate and soil conditions are held constant. Because plant response to CO_2 depends on other limitations in the environment, such as water and nutrient availability, and soil characteristics, uncertainty remains about how accurately and consistently the same effects can be applied to simulations over landscape scales. In addition, there remains uncertainty as to how plants will respond to the rapid rate of CO_2 increase and whether a saturation point, beyond which plants no longer respond, exists (Bowes, 1993; Makino and Mae, 1999).

Water resources in a greenhouse-warmed world will be determined by large scale changes in climate patterns and small scale changes in plant physiology. One approach in studying possible impacts is to apply climate predictions to models of the hydrologic cycle. Researchers have used this approach on different scales of watersheds, ranging from simulation of flow in a small mountain catchment (Wolock and Hornberger, 1991; Battaglin et al., 1993) to analysis of trends on the 33 largest rivers in the world (Miller and Russell, 1992). The impacts of climate change on water resources management have been studied through simulations of major water supply basins for cities such as Boston (Kirshen and Fennessey, 1995) and agricultural regions such as the Pacific Northwest (Sias and Lettenmaier, 1994).

Modeling studies to determine impacts on water resources have also been done on the national scale for the United States, most recently in the US National Assessment (Gleick et al., 2000). In this comprehensive study, the authors found that the timing and regional patterns of precipitation will change, snowmelt will occur earlier in mountainous regions, and many areas will become more vulnerable to floods and droughts. They also noted that contradictory results in the research about the timing, intensity and regional impacts of changes in water resources make further research in this area necessary.

Some impact assessment studies include consideration of climate change effects on vegetation, which will also affect the water balance. A higher concentration of atmospheric CO_2 is expected to cause a decline in plant transpiration and improve water use efficiency, which would leave more water available for runoff (Wigley and Jones, 1985). However, the higher $[CO_2]$ would, if water and nutrients are available, also increase plant cover in some areas increasing the proportion of precipitation consumed by plants (Allen et al., 1991; McCabe and Wolock, 1992). In turn, the amount and seasonal pattern of precipitation will influence the amount and type of vegetation supported in each region. The effects of climate change on water resources and vegetation are closely linked, and must be considered together.

In this series of papers, we use the impact assessment models EPIC (Williams, 1995) for crops, Hydrologic Unit Model of the United States (HUMUS) (Arnold et al., 1999) for water resources and BIOME3 (Haxeltine and Prentice, 1996) for natural ecosystems, to study the responses of these sectors to climate change. Using a range of future climate scenarios, we model the impacts on dryland (untreated) agriculture (Part 3), and on water resources (Part 4). We then examine the extent to which crops will require irrigation, the amount of water available to meet that demand, and how total potential crop production in the United States might be affected (Part 5). Additionally we use BIOME3 to examine the fate of natural ecosystems under the same climate scenarios. In this paper we describe EPIC and HUMUS and how they were validated against historical data. BIOME3 is fully described and validated in Part 6.

2. Methods

2.1. STUDY REGIONS

We chose the study regions to ensure compatibility between the agricultural and hydrologic impact assessment models. The HUMUS water resources model is run at a scale of 2101 eight-digit hydrologic basins in the conterminous United States as defined by the US Geological Survey (USGS, 1987). These are aggregated into 204 four-digit basins and further into the 18 two-digit basins—the Major Water Resource Regions (MWRR). A set of representative farms, one in each of the 204 four-digit basins, was developed for the EPIC simulations. Crop yield simulated at these farms was extrapolated to the total area of agricultural land within each four-digit basin

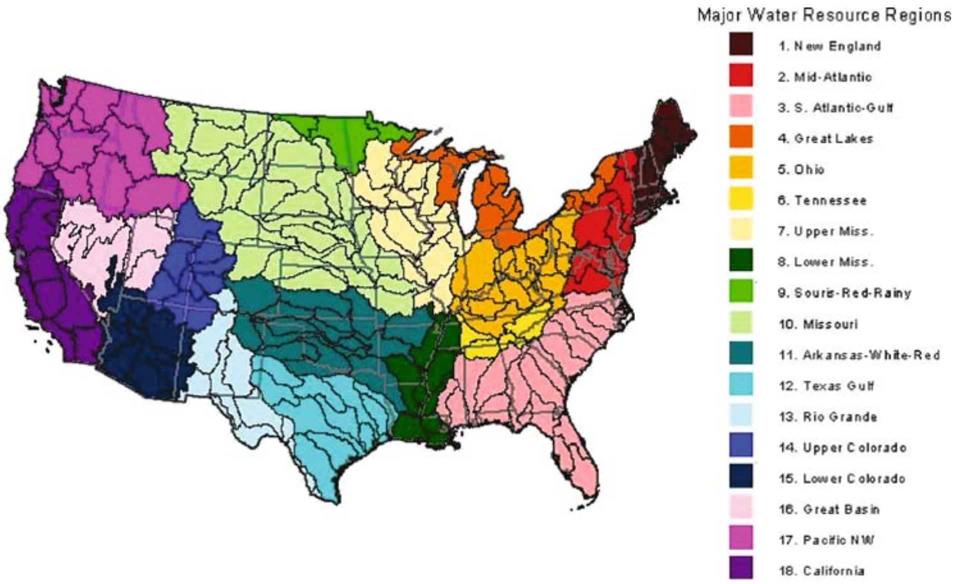

Figure 1. Major water resource regions and the 204 four-digit modeling regions for this study, with state borders for reference.

and aggregated for analyses of total national agricultural production. This level of detail is sufficient for EPIC to capture the major differences in agricultural practices and soil characteristics throughout the country. In addition, by so doing, results of the water resources and agricultural modeling can then be easily related. Figure 1 shows the outline of each of the 204 four-digit basins and the 18 MWRRs in which they reside.

2.2. EROSION PRODUCTIVITY IMPACT CALCULATOR (EPIC)

EPIC (version 7270) is a bio-physical process-based model that simulates agricultural production and related processes such as runoff, soil erosion and nutrient cycling. The model runs on a daily time step at the scale of small, uniform farm fields (1–100 ha). Data on daily weather, physical and chemical soil properties, and crop management parameters (e.g. fertilizer application, crop variety, and tillage) are required to run the model. The algorithms that constitute EPIC are fully described by Williams (1995).

EPIC calculates the maximum daily increase in plant biomass allowed by the daily solar radiation incident on the field. The algorithms used to model potential plant growth are driven by photosythentically active radiation (PAR), the 0.4 to 0.7 micrometer wave-band 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 which is crop specific. Solar radiation also provides the energy that drives evapotranspiration (ET).

Crop growth is simulated by calculating the potential daily photosynthetic production of biomass. The daily potential growth 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. Stockle et al. (1992a, b) adapted EPIC to simulate the CO_2-fertilization effect on radiation use efficiency (RUE) and ET. Elevated atmospheric CO_2 concentration increases photosynthesis in C_3 plants and reduces ET in both C_3 and C_4 plants because of reduced stomatal conductance. Improved water use efficiency occurs in both C_3 and C_4 plants. A non-linear equation was developed in EPIC to express the RUE response to increasing CO_2 concentrations following experimental evidence summarized by Kimball (1983). Their analysis showed crop yield increases of 33% with a doubling of atmospheric CO_2, and assign a 99% confidence in this response ranging from 24 to 43%. Stockle et al. (1992a, b) modeled this response as a function of crop type. EPIC has not been specifically tested against observations from CO_2 enrichment experiments. The parameters developed by Stockle et al. have been found to be consistent with recent results arising from FACE experiments (Amthor, 2001). In this study, EPIC was run under two CO_2 concentrations—365 ppmv to represent minimal CO_2 effects and 560 ppmv (a doubling of the pre-industrial concentration) to represent strong CO_2-fertilization effects.

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 above-ground biomass at maturity by a harvest index (proportion of the total biomass in the harvested organ). As a process based model, EPIC is capable of simulating crop response to climate conditions outside the historical experience. Brown and Rosenberg (1997) studied the effects of temperature changes up to $+6°C$ and precipitation changes as large as $\pm 30\%$ in an analysis of EPIC model sensitivity to climate change. EPIC has also been used in a number of other climate change studies including Brown and Rosenberg (1999a, b), Izaurralde et al. (2003) and Easterling et al. (1992, 1996).

We developed 204 'representative farms' to simulate agricultural production in each four-digit basin. A representative farm describes an agricultural enterprise typical of a given region with respect to soils, climate, and farming system (Easterling et al., 1992). For each farm, we selected the dominant agricultural soil in the four-digit basin using the STATSGO database (USDA Soil Conservation Service, 1992) and EPIC soils database (Williams et al., 1990). Baseline climate data for the years 1960–1989 was taken from archives of historical weather station observations maintained by the HUMUS hydrologic simulation project at Texas A&M University (Arnold et al., 1999). Information about farm management practices (e.g. tillage, fertilization) came from a database compiled by the US Department of Agriculture (USDA)[2] describing actual practices used by US farmers. Statistics on total land area devoted to agriculture within each four-digit basin were obtained from the USGS National Atlas of the US, which draws its data from the USDA

Census of Agriculture. In later calculations of national forage and grain production, we assume that all of the agricultural land within a basin is devoted to a single crop.

2.3. HYDROLOGIC UNIT MODEL OF THE UNITED STATES (HUMUS)

The HUMUS is a GIS-based modeling system. The HUMUS component provides input required to drive the soil and water assessment tool (SWAT) at the sub-basin scale (Srinivasan et al., 1993). HUMUS can be applied to a wide range of basin sizes depending on the availability of input data and the study objectives. Here, we simulate the hydrologic cycle at the scale of the eight-digit USGS Hydrologic Unit Areas (HUA) (USGS, 1987). For this simulation, we assume natural streamflow, which differs from actual (observed) streamflow because it assumes no large-scale storage, diversions or withdrawals. Input data were assembled for the conterminous United States at the scale of 1:250,000 and integrated into the HUMUS geographical information system database. We treat climate, land use, and soil type as uniform within each eight-digit basin. Finer resolution is possible with the HUMUS model, but to do so for the entire United States would greatly increase computational requirements and provide detail in excess of that needed for this study.

These data in the HUMUS GIS system were used to drive the SWAT hydrology model. SWAT represents the basin water balance through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). Processes simulated by SWAT include infiltration, ET, net primary productivity, lateral flow, and percolation. Surface runoff is estimated using a modification of the SCS curve number method (USDA, Soil Conservation Service, 1972). The variable in SWAT which approximates streamflow is water yield. A measure of net water flow out of each watershed, water yield is calculated as the sum of surface and lateral flow from the soil profile and groundwater flow from the shallow aquifer. The model runs on a daily time step with input of daily records of maximum and minimum temperature, precipitation, humidity, radiation and windspeed. For this study, generated daily weather from the WXGEN weather generator (Richardson and Nicks, 1990) was used to determine baseline climate conditions. The Stockle et al. (1992a, b) algorithms used in EPIC are also used in SWAT to account for the potential impact of higher CO_2 on the hydrologic balance. As in EPIC, HUMUS simulations were run with [CO_2] of 365 and 560 ppmv.

3. Model Validations

3.1. EPIC

Validity of EPIC crop simulation responses to weather effects has been demonstrated in many studies for a variety of regions and crops. Kiniry et al. (1990)

concluded that EPIC was able to reproduce observed yields of corn, wheat and soybean under a variety of management and climate conditions. Rosenberg et al. (1992) found that EPIC-simulated yields in the central US compared favorably with historical county yields, yields from agronomic experiments and yields estimated by local agricultural experts. In a regional study, Easterling et al. (1996) found that EPIC simulations of representative farms using climate and soils data on a 0.5° grid scale explained 65% of the variation in corn yields in eastern Iowa and 54% of the variation in wheat in western Kansas for the period 1984–1992. In addition, Brown and Rosenberg (1999b) compared EPIC yields of corn, sorghum, soybean and wheat with NASS yields and yields from agronomic experiments and found that EPIC overestimated historical yields slightly and more closely approximated the yields from agronomic experiments.

On the other hand, the validity of EPIC (or any other process model) simulations of crop yields in response to anticipated climatic changes cannot be established directly. At best the effects of changes in temperature, precipitation, radiation, humidity and [CO_2] as well as interactions among these climatic variables can be estimated through sensitivity studies as Brown and Rosenberg (1997) have done for EPIC. Despite this limitation, the process model remains the most useful tool available for estimating climate change effects since it makes use of experimental data on photosynthesis, respiration, transpiration and other plant processes measured in controlled environments where climatic conditions of the possible future can be imposed for seasons or even years if necessary. This in contrast with statistical techniques wherein coefficients derived from conditions encountered under the range and variability of current climates is extrapolated to what may turn out to be very different climatic conditions.

Here, we compare the EPIC yields simulated at the baseline climate for the three major grain crops grown under dryland conditions in the US against data from two historical sources. The first is NASS yields for the years 1972–1994 (Figure 2a). The second comparison is with yields from agricultural experiments throughout the US in the 1980's and 1990's (Figure 2b) (See Brown and Rosenberg, 1999b for detailed documentation of the experimental data). We paired EPIC yields, which were simulated at the geometric center of each four-digit basin, with historical and experimental yields at the nearest location. The EPIC simulations of alfalfa hay production were also validated by reference to NASS data. We compared EPIC-simulated irrigated grain yields with historical county yields for the period 1960–1989 (NASS Published Estimates Database, 2001). Our purpose is to show that the model is an appropriate tool to use in estimating the agronomic potential of the United States over the past 30 years. We use the most realistic weather, soil and management parameters available on a nationwide scale, but have not calibrated the model specifically to these conditions, so the model output will not agree perfectly with the historical crop yields.

Prior validations have found that EPIC agrees more closely with experimental yields than with historical yields (Rosenberg et al., 1992; Brown and Rosenberg,

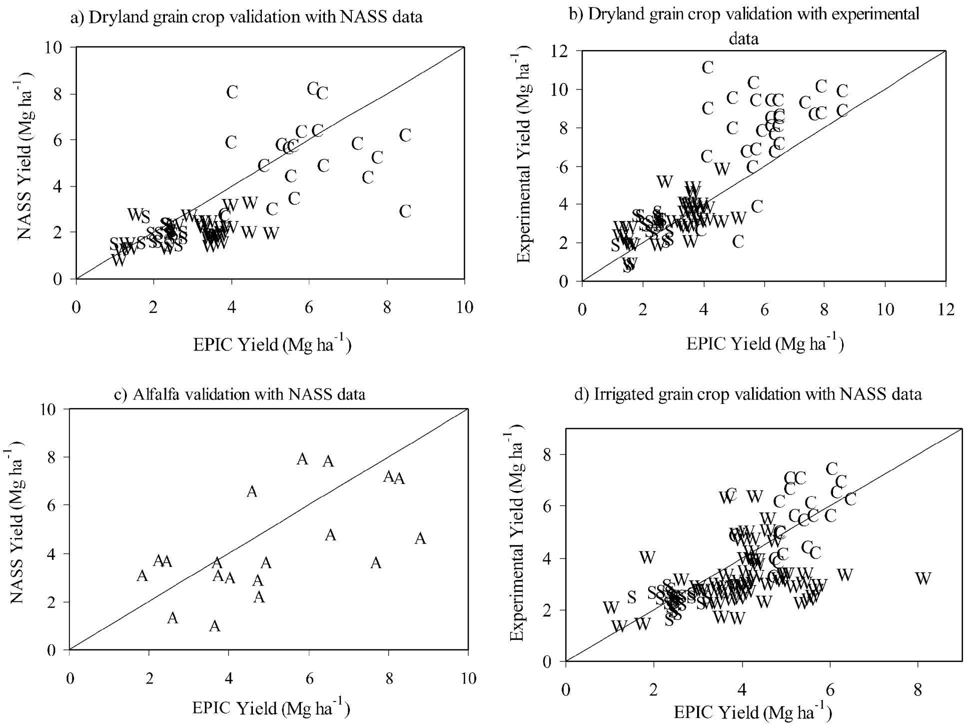

Figure 2. Comparison of EPIC-simulated and actual yields for grain crops under dryland and irrigated conditions and for dryland forage crops.

1999a, b; Izaurralde et al., 1999). This has been attributed to the high levels of farm management specified in the EPIC simulations and to the fact that EPIC does not consider severe episodic events that may sharply reduce yields (e.g. hail, floods or pest outbreaks). In this study, however, tillage and fertilizer management parameters are based on surveys conducted by the US Department of Agriculture and closely approximate actual rather than optimum management practices. As a result, the validation work in the current study shows that EPIC underestimates the experimental yields (Figure 2b) and agrees more closely with historical yields (Figure 2a).

In order to validate the performance of EPIC in simulating forage crop production, we compared the simulated alfalfa hay yields with historical county yield data from USDA-NASS for the years 1972–1994 (Figure 2c). The relationship between historical and simulated yields is more variable for alfalfa than for the three grain crops and EPIC slightly overestimates historical yields. However, given that EPIC management is static over the modeling region and the wide variety of management practices used in alfalfa production, their agreement appears acceptable for the purposes of this study.

In addition, we compared NASS county yields for the same period as the baseline climate simulation (1960–1989) with yields of the irrigated grain crops (Figure 2d).

This validation shows that EPIC slightly underestimates irrigated corn yields, while overestimating irrigated wheat yields. Simulated yields of irrigated soybean agree best with historical data. The underestimation of corn yields by EPIC may be due to the parameterization of fertilization practices. To isolate the effect of irrigation on yield, the same fertilization rates were used in the irrigated and non-irrigated crop simulations. In practice, however, irrigated crops often receive more frequent applications of fertilizer. So, while the incidence of water stress is reduced in EPIC irrigated yields, the incidence of nutrient (primarily nitrogen) stress is higher than for dryland crops. While the comparison of irrigated grain crops with historical data is more variable than the comparison for dryland crops, both charts (Figures 2a and 2d) show agreement sufficient for the purposes of this study.

3.2. HUMUS (SWAT)

Streamflow simulated by the SWAT component of HUMUS has been validated with observed data at scales ranging from a major water resource region (Arnold et al., 2000) to a small stream catchment (Arnold and Allen, 1996). Validation studies for a range of SWAT hydrologic variables and geographic locations are summarized in Arnold et al. (1999). Validating SWAT predictions of natural streamflow on a continental scale for assessment of the HUMUS model is difficult because corrections have to be applied to observational data to approximate the natural streamflow. Gerbert et al. (1987) estimated average annual natural streamflow from observations at 5,951 US gauging stations over the period 1951–1980 and these data (hereafter USGS-estimated) have been used in several studies. Wolock and McCabe (1999) tested their continental-scale hydrologic models with these estimates. Arnold et al. (1999), found agreement between HUMUS and USGS-estimated streamflow with aggregations at the state level (regression slope 0.86) and at the level of 78,863 STATSGO soil association regions (regression slope 1.01).

While Arnold et al. (1999) found that HUMUS-simulated water yields were within 50 mm of the USGS-estimated values for 45% of the conterminous US, they also noted that HUMUS under-predicts runoff in mountainous regions. This effect is attributed to a lack of observed weather data at high elevations—most weather stations in mountainous areas are located at the more accessible lower elevations, which typically receive less precipitation. In addition, they found that HUMUS over-predicts runoff in irrigated regions (e.g. the Great Plains, Mississippi Delta), as the model applies irrigation uniformly to each basin in which irrigation is practiced. Brown et al. (1999) found excellent agreement between the USGS-estimated and HUMUS-simulated stream flow at the MWRR level. However, HUMUS overestimated water yield in regions with irrigation, and underestimated it in the mountainous Pacific Northwest region. They examined the agreement at smaller scales and found it adequate for their simulation of water resources at the continental scale.

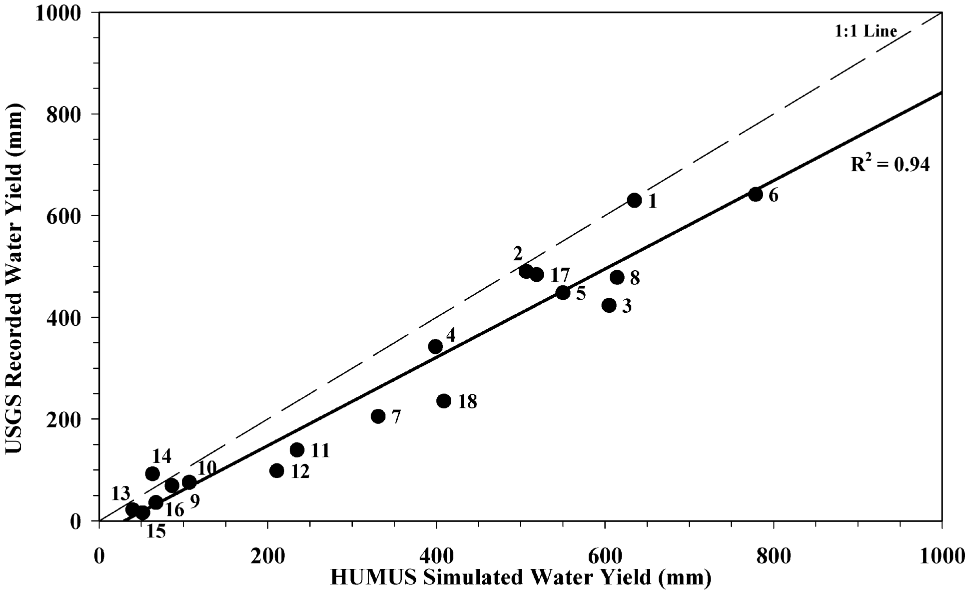

Figure 3. Comparison of HUMUS-simulated water yield with historical streamflow estimates from Gerbert et al. (1987) in the 18 MWRRs (numbered individually) in the conterminous United States.

We also use the USGS-estimated streamflow values from Gerbert et al. (1987) to validate the HUMUS simulation of water resources at the MWRR scale and at the modeling scale of eight-digit basins. One confounding factor is that the periods of record differ; our baseline period is 1960–1989 while the annual streamflow data from Gerbert et al. are averaged over the time period of 1951–1980. While records of actual streamflow exist for the 1960–1989 time period, there is no corresponding estimate of natural streamflow such as that of Gerbert et al., that can be used for such a validation. The simulated baseline water yields agree well with the USGS-estimated values for the MWRRs, with an R^2 value of 0.94 (Figure 3). On average, HUMUS slightly overestimates annual water yield at this scale, likely as a result of the uniform application of irrigation in major agricultural regions.

In order to examine regional effects in detail, a statistical analysis comparing USGS-estimated and HUMUS-simulated streamflow at the scale of eight-digit basins was made (Table I, Figure 4). There is considerably more variation between simulated and USGS-estimated water yields at this scale, and the patterns vary within individual MWRRs. The relationship between simulated and USGS-estimated water yields was significant for all of the MWRR at $p > 0.0001$ except for Basin 8 (Lower Mississippi). The lack of significance in that basin is evidence of the bias in HUMUS caused by uniform application of irrigation water. In addition, this basin is unique because a significant amount of streamflow originates in another MWRR (Upper Mississippi). The same situation applies to the Lower Colorado (Basin 15), which differs substantially in hydrologic and agricultural characteristics.

TABLE I
Summary of statistical comparison between HUMUS-simulated water yield and USGS streamflow estimates (Gerbert et al., 1987) using mean annual values for each eight-digit HUA within each MWRR

MWRR	Number of observations	Observed mean[a]	Simulated mean[b]	RMSE	R^2	y-intercept	Slope
1 (NE)	51	630	635	105	0.24*	482	0.23
2 (MA)	90	490	507	146	0.21*	345	0.27
3 (SAG)	194	423	605	258	0.21*	244	0.32
4 (GL)	107	343	399	135	0.31*	154	0.50
5 (OH)	119	448	550	136	0.39*	20	0.78
6 (TN)	31	642	779	179	0.35*	86	0.72
7 (UMS)	129	205	331	138	0.74*	9	0.59
8 (LMS)	81	479	614	235	0.04[NS]	523	−0.07
9 (SRR)	41	69	87	43	0.71*	14	0.67
10 (MO)	306	76	107	105	0.36*	21	0.57
11 (ARK)	172	139	235	128	0.89*	−4	0.65
12 (TG)	121	98	211	165	0.34*	35	0.38
13 (RG)	68	22	40	48	0.32*	1	0.54
14 (UCO)	60	93	63	85	0.59*	15	1.38
15 (LCO)	83	16	52	45	0.56*	−6	0.47
16 (GB)	70	36	68	74	0.56*	−17	1.17
17 (PNW)	216	484	521	438	0.59*	144	0.93
18 (CA)	130	236	409	335	0.34*	67	0.59

[a]Mean value of USGS-estimated natural streamflow using values by eight-digit HUA.
[b]Mean value of HUMUS simulated water yield using average annual baseline values by eight-digit HUA.
*Regression significant at p-value >0.0001.
[NS]Regression not significant at p-value >0.0001.

The four charts in Figure 4 illustrate the different relationships of USGS-estimated to HUMUS-simulated streamflow in different MWRRs. The simulation for the South Atlantic-Gulf (Figure 4a) region shows a significant overestimation by HUMUS, although there is still a significant correlation (Table I). Figures 4c and 4d show that HUMUS overestimates water yield in the Missouri and California regions, possibly due to the uniform application of irrigation water by the model. The Upper Mississippi region (Figure 4b) does not exhibit this bias, but rather a strong correlation with an R^2 of 0.74. The statistical analysis in Table I indicates that, while HUMUS generally overestimates the USGS-estimated streamflow, the model is able to reproduce significant relationships and capture major trends in the flow of water resources on a national and regional scale.

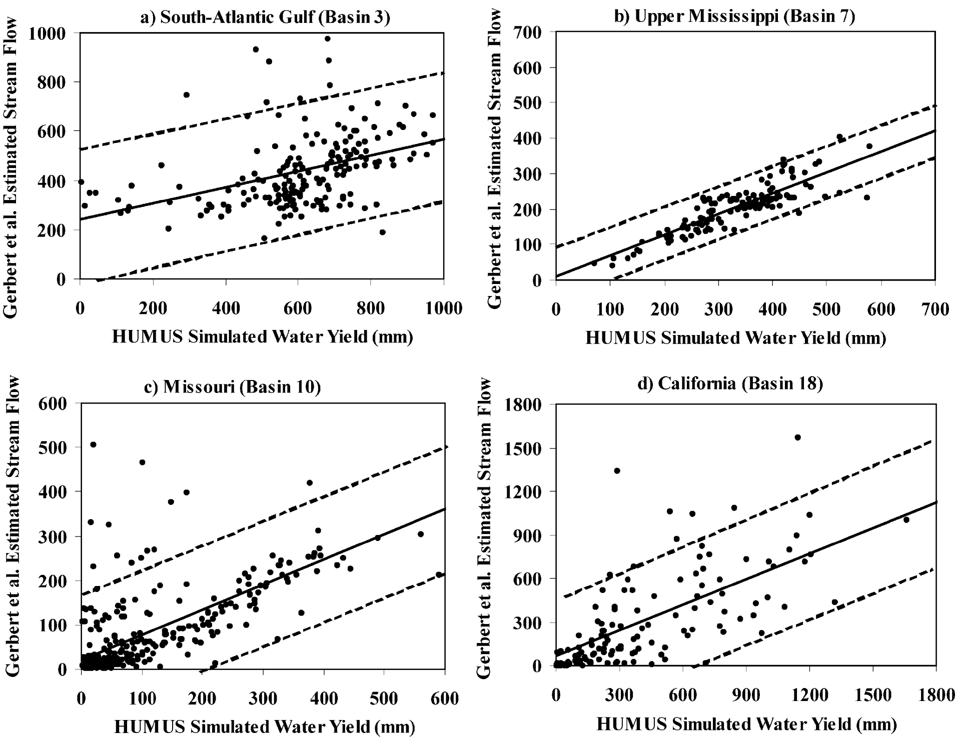

Figure 4. Comparison of HUMUS-simulated water yield with historical estimates from Gerbert et al. (1987) in four selected MWRRs with 90% confidence interval reference boundaries. Points represent the individual eight-digit basins in each of the MWRRs represented.

4. Summary and Conclusions

Here we have presented the general methodology used in this study and the motivation behind it. We have further analyzed the validity of the impact assessment models, EPIC and HUMUS, and conclude that they can reproduce historical conditions of crop yield and streamflow to a level of confidence sufficient for the geographical coverage and scale of this study. In the papers that follow, we present the results of these model simulations for a wide range of possible climate changes. Using two general circulation models, we explore a range of possible changes in climate that could occur based on differences in the degree of warming, the influence of sulfates, and the importance of the CO_2-fertilization effect.

In the following papers we employ simulations using these predicted climate changes and, in addition, simulate two levels of atmospheric CO_2. We reason that the impact of CO_2 on ecosystem function, especially on the water use efficiency and carbon uptake of plants, is not yet fully understood at the landscape scale. Therefore, the simulations are run both assuming that the so-called 'CO_2-fertilization effect' does not impact on crop growth or water use ($[CO_2] = 365$ ppmv) and, on the other hand, that it does impact these processes to the degree consistent with $[CO_2] = 560$ ppmv, i.e. double the pre-industrial concentration.

Acknowledgements

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Notes

1. Double the pre-industrial CO_2 concentration (about 280 ppmv) is projected to be reached by the middle of the 21st century. The IPCC IS92a scenario predicts doubling by 2060, but predictions vary based on the emissions scenarios applied. The most recent scenarios predict a wide range of dates by which the doubling could occur (Nakicenovic and Swart, 2001).
2. Verel Benson, University of Missouri-Columbia, FAPRI. Personal Communication, 1998.

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 3. DRYLAND PRODUCTION OF GRAIN AND FORAGE CROPS

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Abstract. Here we simulate dryland agriculture in the United States in order to assess potential future agricultural production under a set of general circulation model (GCM)-based climate change scenarios. The total national production of three major grain crops – corn, soybeans, and winter wheat – and two forage crops – alfalfa and clover hay – is calculated for the actual present day core production area (CPA) of each of these crops. In general, higher global mean temperature (GMT) reduces production and higher atmospheric carbon dioxide concentration ([CO_2]) increases production. Depending on the climatic change scenarios employed overall national production of the crops studied changes by up to plus or minus 25% from present-day levels. Impacts are more significant regionally, with crop production varying by greater than ±50% from baseline levels. Analysis of currently possible production areas (CPPAs) for each crop indicates that the regions most likely to be affected by climate change are those on the margins of the areas in which they are currently grown. Crop yield variability was found to be primarily influenced by local weather and geographic features rather than by large-scale changes in climate patterns and atmospheric composition. Future US agronomic potential will be significantly affected by the changes in climate projected here. The nature of the crop response will depend primarily on to what extent precipitation patterns change and also on the degree of warming experienced.

1. Introduction

The accumulation of greenhouse gasses in the atmosphere as a result of human activities will impact agriculture both directly and indirectly. Crop development and production are sensitive to and directly affected by the carbon dioxide concentration ([CO_2]) of the ambient air. In addition, the accumulation of CO_2 and other radiatively active trace gasses will alter climate patterns globally, influencing regional weather. Temperature and precipitation will change from the conditions to which crops are currently adapted and changes in cloudiness will alter the timing, quality and quantity of solar irradiance. Regional agriculture will be affected by these changes with consequences for national and global food production.

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The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that global agricultural production will most likely be maintained relative to present production levels under the range of climate change scenarios projected by a set of general circulation models (GCMs) (Reilly et al., 1996) and their finding was supported in the most recent IPCC assessment (Gitay et al., 2001). However, given the uncertainty regarding the regional distribution of climate change, vulnerability of crop yields to climatic variability is a matter of increasing concern (Reilly and Schimmelpfennig, 1999; Luo and Lin, 1999). Reilly (1999) observed that, while global production of food is not seriously threatened by climate change in the short term, if extreme changes in regional climate occur, current agricultural production in some areas will be vulnerable and adaptations will be necessary. Crop simulation models provide much of the basis for these findings.

Prior simulation model-based assessments of agricultural response to climate change show variable responses depending on the GCM used and the regions studied (e.g., Reilly and Schimmelpfennig, 1999; Brown and Rosenberg, 1999a). An assessment for corn and winter wheat in their present day US growing regions found that the regional impacts of climate change could be dramatic and varied, with declines in production of up to 76% in extreme cases, and increases in production approaching 31% with benign changes in climate (Brown and Rosenberg, 1999b). The US National Assessment simulated agricultural production with several crop models under the Hadley Centre and Canadian Climate Model projections (Reilly et al., 2001; NAST, 2000) for two climate change scenarios. Under these scenarios, production of some crops benefits from climate change, particularly the enhanced atmospheric concentration of CO_2, and the changes simulated varied in intensity by region.

It is generally agreed that process-based simulation models are more reliable than the regression-based statistical models that preceded them in assessments of climate change effects on agricultural productivity (e.g., Blasing and Solomon, 1982; Newman, 1982). Yet, the process models should not be given more than their due. Passioura (1996) challenges the very notion of using process models for climate change analyses for two reasons: first, that the processes modeled are essentially non-linear so that their reliability and interactivity outside the range for which they are calibrated is almost unknowable; second, that process models yields are very sensitive to the treatment of the daily weather inputs that drive them. There is, of course, considerable variance in projected climatic change between GCMs. In addition, simulated yields can differ substantially when models are driven by actual and stochastically generated daily weather.

The effects of increased atmospheric [CO_2] on plants have been studied in laboratory and field settings for different crop species over a growing season. It is agreed that under optimum conditions the CO_2 ‘fertilization effect’ increases crop yields, reduces transpiration and improves water use efficiency (Allen et al., 1998; Makino and Mae, 1999; Maroco et al., 1999). However, there is evidence that crop response will slow as CO_2concentrations continue to rise but other resources, predominantly water and nitrogen, become limiting (Gitay et al., 2001; Bowes, 1993; Makino and Mae, 1999). There is also evidence that the accelerated rate of photosynthesis with higher [CO_2] will lead to reduced nutrient and protein content in grain and forage crops. Crop response to CO_2 may be determined in part by the soil water availability – when grown under drought conditions, crop response is reduced (Gitay et al., 2001). Smith et al. (2000) examined the interaction between CO_2 and water and found that higher CO_2 caused a doubling of desert shrub growth in a high-rainfall year, but no increased production in a dry year.

Recent studies of crop production under greenhouse-forced climate change have explored the potential for adaptations to climate change. A study of US agriculture by Adams et al. (1998), using both GCMs and climate sensitivity scenarios, found that technological advances and adaptations could potentially mitigate 50% of the simulated yield declines in sorghum and hay in the US. Using the EPIC model, they also concluded that soil conditions may not allow adaptation by crop migration between regions. Mavromatis and Jones (1998) also found soil type to be an important indicator of agricultural response to historical climate variability, specifically to changes in precipitation as crop production is often limited by soil moisture shortage. Rounsevell et al. (1999) note the uncertainty of soil response to climate change, but they conclude that the most likely response of crops to changes in physical soil properties will be geographic shifts in agricultural land use.

Here we determine a range of potential change in future agricultural productivity in the United States based on a set of climate change scenarios. We assess to what extent projected climate changes could reduce, expand, or shift major regions of production. Potential adaptations of the agriculture sector to climate change, e.g., development of new crop varieties and management techniques, are not considered here, as our focus is on shifts in production potential, rather than on the effectiveness of specific adaptation strategies. We simulate the changes in regional and national production of three major grain crops grown in the United States – corn, soybean and winter wheat – and two major forage crops – alfalfa and clover hay – in response to three GCMs, each at two levels of climate change severity and two levels of CO_2 fertilization. The role of sulfate aerosols remains unclear and is included here to explore whether changes in climate projected by a GCM are sufficiently altered by inclusion of a sulfate effect to impact agricultural production. Part 7 of this series presents an economic analysis of the consequences of the agricultural production changes discussed here. For further information on the GCMs and climate scenarios used, see Part 1 of this series.

2. Methods

2.1. THE EPIC MODEL

The Erosion Productivity Impact Calculator (EPIC, version 7270) simulates agricultural production and associated environmental processes (e.g., runoff, erosion, nutrient cycling) using inputs of daily climate, soil properties, and farm management. We simulate crop yields under a suite of climate change scenarios from three GCMs at two levels of global mean temperature (GMT) increase (see Part 1 in this series for a full discussion of the scenarios). For each climate change scenario, we simulated agricultural production under two levels of atmospheric CO_2 – 365 ppmv representing the approximate current concentration and 560 ppmv representing a CO_2 'fertilization effect'. A full description of the EPIC model characteristics and the CO_2 'fertilization effect' and a validation of the model can be found in Part 2. The algorithms which constitute EPIC are fully described in (Williams, 1995).

2.2. YIELD THRESHOLD (YT)

For the purposes of this study, fields of corn, soybean and winter wheat were simulated for a representative farm in each of the 204 four-digit basins. Not all of these crops grow in all regions in today's climate. We reasoned, however, that climate change could alter the geographic boundaries of the most-productive regions of the country for each crop. We used a yield threshold (YT) in order to identify the representative farm basins and calculate the agricultural land area producing each of the grain crops under the EPIC simulations with different climate change scenarios.

The YT was determined for each crop based on historical county yields, EPIC baseline yield maps and historical yield maps (World Agricultural Outlook Board, 1994; USDA National Agricultural Statistics Service, 2001). Historical maps of production regions for each crop in the United States were used as the basis for a map of the current core production areas (CPAs). Those areas were confirmed with maps of county yields from NASS and baseline simulations with the EPIC model to be the regions of greatest importance for US production of the given crop. A YT was established by first selecting the lowest EPIC-simulated baseline yields within the current CPA and then comparing them with historical county yields for the past 30 years from the USDA-NASS Published Estimates Database (USDA-NASS, 2001). The YTs – established as corn: 2.5 Mg ha^{-1}, soybean, 1 Mg ha^{-1} and winter wheat: 1 Mg ha^{-1} – were then used to identify modeling basins where production of a given crop is unlikely under the baseline and climate change scenarios simulated in this study.

The national potential dryland production of the three grain crops was calculated as the yield on all agricultural land in the CPA. Figure 1 outlines the CPAs for each simulated crop and highlights the six, four-digit basins used to examine regional changes in crop production in Figures 4–8.

Production of the two forage crops, alfalfa and clover hay, was simulated in those regions of the country where each is currently the principal forage crop. No YT was set for these crops as they are typically grown and fed where needed in distinction to the grain crops that are grown in their optimal locations and shipped from there

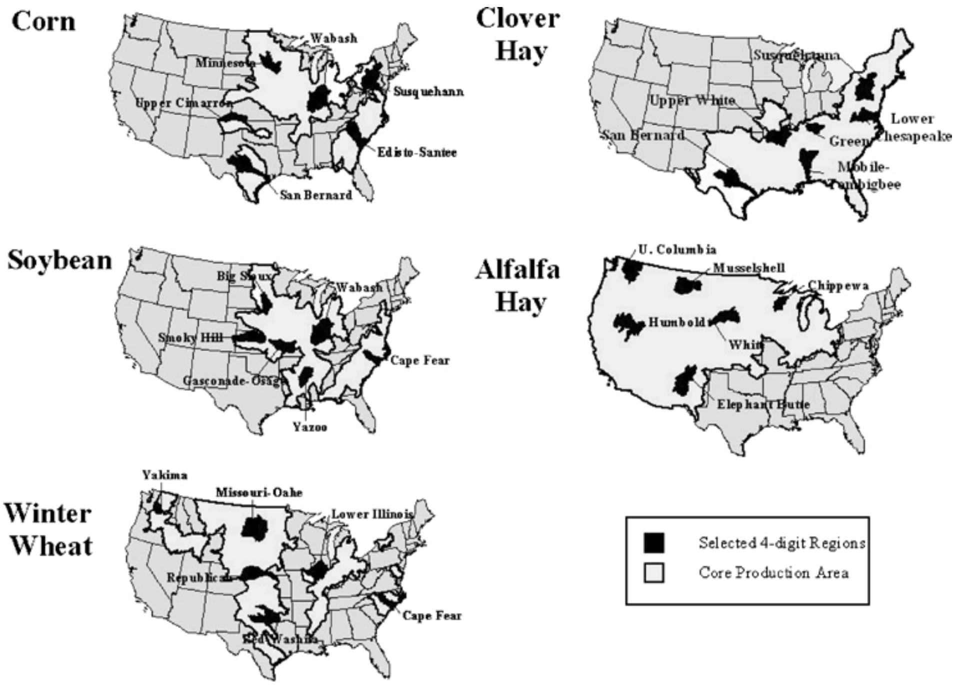


Figure 1. Outlines of the core production area (CPA) for each crop with the six basins used in the regional analysis illustrated in Figures 4–8 highlighted.

to consumer regions. Therefore, forage crop yields vary widely depending on soil and climate conditions in their major production regions. For the regional analysis of forage crops, we selected six four-digit basins within current growing regions (Figure 1).

2.3. CLIMATE CHANGE SCENARIOS

Three GCMs were used to simulate climate over the United States under two levels of temperature increase – GMT of +1 °C and +2.5 °C. All three of the GCMs project an increase in temperature over the conterminous US but the projections of changes in precipitation differ substantially. The Australian Bureau of Meteorology Research Centre (BMRC; McAvery et al., 1991) projects temperature increases ranging from +1 to +5 °C above baseline, with the greatest increases in the Great Lakes region and milder temperature increases in other northern regions. The BMRC scenarios show a significant decline in precipitation across the country, most extreme in the southern regions.

The University of Illinois at Urbana-Champagne (UIUC; Schelsinger, 1997) model projects a warming ranging from +0.5 to +3 °C – moderate compared to BMRC. Again the warming is strongest in northern regions of the country.

Precipitation increases substantially under UIUC scenarios, especially over the western half of the country. The third GCM used in this study is the UIUC modified with sulfate aerosol forcing (hereafter UIUC + Sulfates). The temperature and precipitation trends are similar to the projections under UIUC in geographic distribution. The UIUC + Sulfate projections of temperature increase are the lowest among the three models while precipitation increases substantially over much of the country. For more information on the GCM models and the climatic changes projected under these scenarios, see Part 1 in this series.

3. Results and Discussion

3.1. REGIONALITY AND PRODUCTION OF GRAIN

3.1.1. *Total Cropland*

The area and location of agricultural land in grain production could change as climate changes. The change in the currently possible production area (CPPA) (defined here as area where yield > YT) for corn, soybean and winter wheat under the 12 climate change scenarios is shown in Figure 2. The change in corn CPPA is small, never exceeding ±10% from a baseline of 217 million ha (Figure 2a). In almost all of the scenarios, the CPPA increases, especially with the higher [CO_2]. Cropland area in corn declines under BMRC when there is no CO_2 fertilization effect. There is more variability in the CPPA of soybeans (Figure 2b). For soybean under the BMRC scenario, cropland declines from the baseline of 204 million ha in all but the most benign case (GMT = +1 °C, [CO_2] = 560 ppmv) while with the UIUC scenario, CPPA for soybeans increases by 5–15%. The CPPA for winter wheat shows little change under all scenarios (<5% from the baseline of 238 million ha), except for slight declines observed at a GMT of +2.5 °C and with the BMRC model (Figure 2c).

Changes in the total amount of agricultural land area are not significant for either corn or winter wheat. Soybean CPPA, however, appears more likely to change, declining under BMRC as a result of soil moisture shortages. Due to higher maximum stomatal conductance, soybeans are more sensitive than corn or winter wheat to reductions in water availability. Soybean CPPA increases significantly under UIUC, indicating that soybean production might, under such a climate, expand into regions where it is not currently grown.

3.1.2. *Shifts in Production Regions*

We also use the YT to identify which regions of the country will be affected by the applied scenarios of climate change. Figure 3 identifies the four-digit basins where crop production would change under the most severe of our climate change scenarios (GMT = +2.5 °C and [CO_2] = 365 ppmv) with two of the GCMs (BMRC and UIUC). Based on the YTs defined for each crop, these maps identify basins in which production of each grain crop would be initiated (added production area

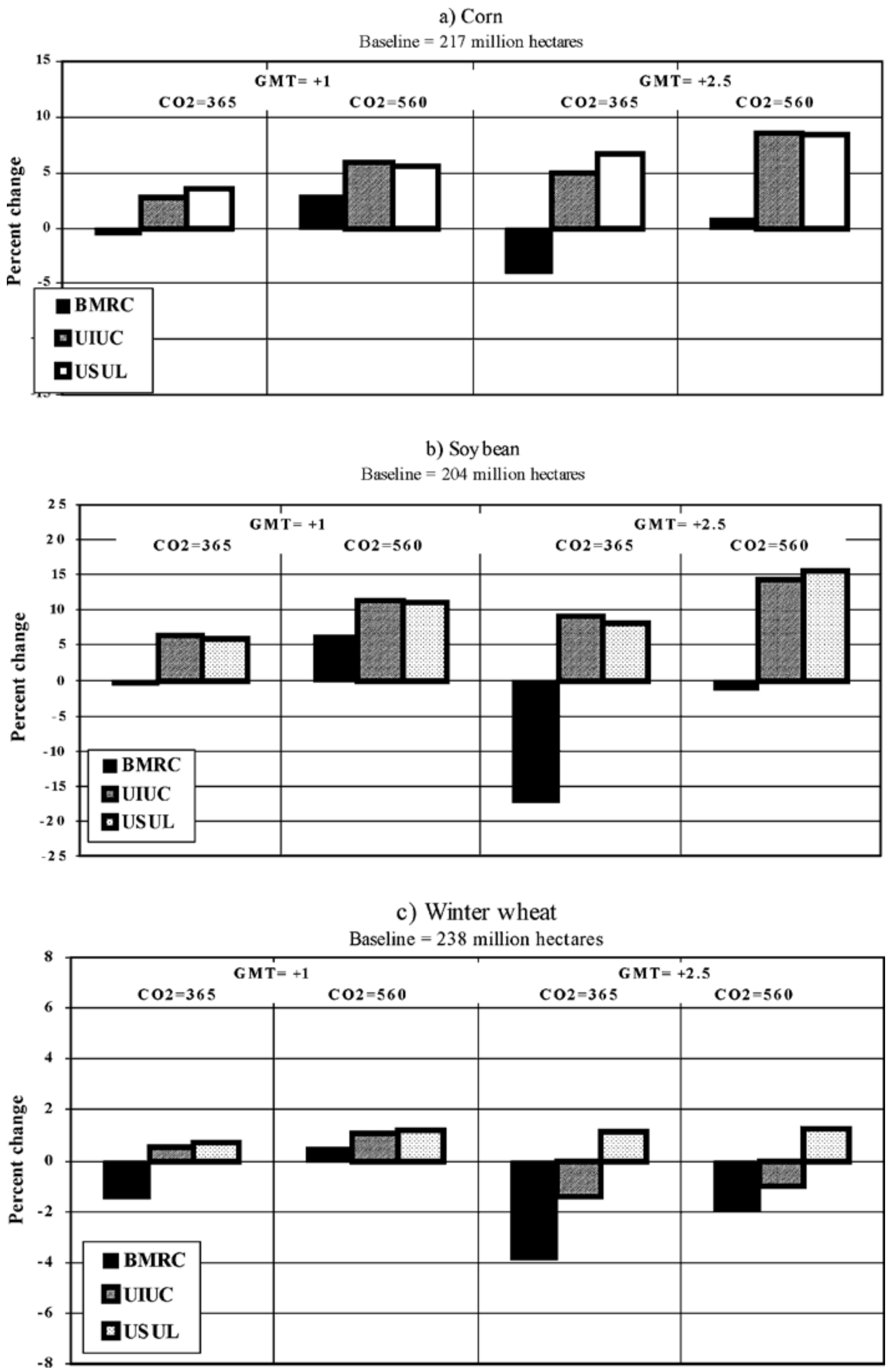


Figure 2. Percentage change from baseline in nationwide currently possible production area (CPPA) for three grain crops and 12 climate change scenarios.

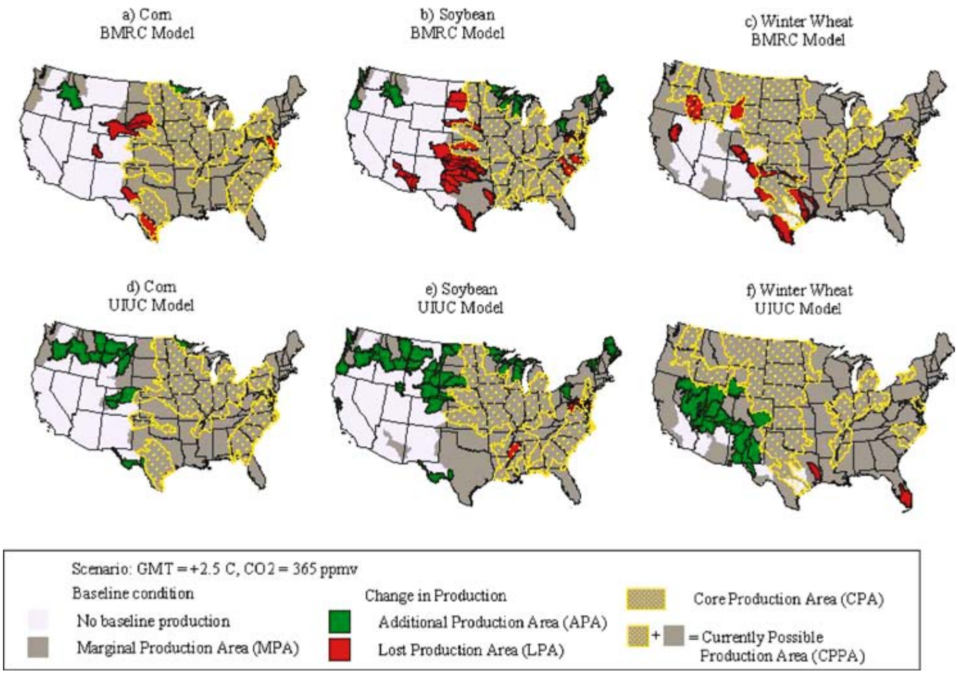


Figure 3. Regions projected to enter or leave production for three grain crops with the BMRC and UIUC GCMs at a global mean temperature increase of $+2.5\,^{\circ}$C and CO_2 concentration of 365 ppmv.

– APA) or abandoned (lost production area – LPA). The CPPA and the CPA are included for reference, and land which falls within the CPPA but not the CPA will be referred to as marginal production areas (MPA).

Several basins fall below the YT for corn production under BMRC, including two in the CPA. One of these is in southern Texas and the other on the shore of the Chesapeake Bay (Figure 3a). In addition, production of corn falls below the YT in the western MPA, specifically in South Dakota, Wyoming and Texas. Even under this severe scenario, there is evidence that crop production in some basins would benefit from the simulated climate change, with an APA in Idaho where a reduction in cold-temperature stress benefits the crop. Prospects for corn under the UIUC scenario are more optimistic, with no basins falling below the YT (Figure 3d). The northern and northwest states as well as a portion of the Rio Grande Valley in southern Texas show APA.

The CPPA for soybean also suffers under BMRC (Figure 3b). As with corn, basins on the western edge of the CPPA appear most vulnerable. Additionally, there are several basins of LPA for soybean, specifically in the Great Plains, the South Atlantic and the Middle Atlantic regions. One four-digit basin in the southern Mississippi Valley, an important soybean-producing region, falls out of production under BMRC. In this region of the country, winter wheat production area is lost in several basins, under both BMRC and UIUC. There are also APAs for soybean in several northern states, including Maine, Michigan and Minnesota, and in portions of the Pacific Northwest. These same basins are predicted to come into soybean production with the climate change predicted by UIUC (Figure 3e). In addition, soybean CPPA is extended westward from the Great Plains states through Montana and the Rio Grande Valley in Texas.

Winter wheat CPPA at baseline covers much of the nation (Figure 3c). Under BMRC, unlike for the other crops, no APA is observed, but a number of basins along the western edge of the CPPA fall below the YT. Basins in Idaho and Texas also go out of production. Under the climate changes predicted by UIUC a large swath from Nevada to New Mexico outside the CPPA at baseline is rendered productive (Figure 3f). Isolated basins in Texas and Florida fall below the YT due to increases in warm temperature stress; however, these basins are not part of the CPA.

Figure 3 indicates that change for all crops is most likely to occur along the border of the CPPA. Most LPA occurs in the western part of the country, with the UIUC model predicting APA for the northwest. However, some regions in the eastern US also appear likely to change. Specifically, one four-digit basin in the Middle Atlantic becomes LPA for both corn and soybean. The changes in climate in that basin are similar to changes in other East Coast basins, but the baseline yields were smaller than for the surrounding basins, and closer to yields in the western MPA. From this analysis, it appears unlikely that the climate changes described here will lead to substantial loss of production capacity in regions that today constitute the CPAs. Changes in climate conditions may, however, necessitate adaptations such as the use of new cultivars and/or management techniques if current levels of production are to be maintained.

In general, conditions for grain crop production improve in the northern regions due to reduced cold temperature stress following warming. This is particularly evident with the UIUC scenarios where an increase in precipitation along with the reduction in temperature stress improves the agronomic potential of the northern Great Plains. The areas coming out of production are predominately in the south or along the MPA border, indicating that global warming can worsen already marginal conditions. New regions came into production from the MPA under certain conditions, primarily, in the west where crop production is limited by water scarcity and the UIUC model predicts increases in precipitation.

3.2. CHANGES IN TOTAL POTENTIAL NATIONAL PRODUCTION

3.2.1. *Grain Crops*

In prior sections of this paper, we report the effects of climate change scenarios on yields of the several crops studied. Here, we calculate the total national production for each crop based on these yield statistics and the total agricultural land area in their baseline CPAs (Figure 1). We also examined the production changes for each crop at six representative four-digit basins listed in Table II and outlined in Figure 1.

TABLE I

Total potential production of dryland crops under the 12 climate change scenarios assuming crops grown in their current US core production areas (CPA), as outlined in Figure 1

GMT (°C)	CO_2 (ppmv) (millions of Mg)	BMRC (millions of Mg)	UIUC	UIUC + Sulfates (millions of Mg)
Corn (baseline = 755)				
1	365	717	740	732
	560	792	813	807
2.5	365	632	710	698
	560	714	771	762
Soybean (baseline = 236)				
1	365	216	222	220
	560	255	261	260
2.5	365	169	195	193
	560	210	229	226
Winter wheat (baseline = 368)				
1	365	347	370	367
	560	437	452	449
2.5	365	322	362	353
	560	409	441	429
Alfalfa (baseline = 867)				
1	365	816	867	862
	560	1011	1068	1062
2.5	365	813	883	856
	560	1014	1086	1058
Clover hay (baseline = 513)				
1	365	428	458	473
	560	484	519	535
2.5	365	345	400	416
	560	391	452	471

National production for each crop under each of the 12 climate change scenarios is presented in Table I, while the change in production at the national level and in selected representative regions is summarized in Figures 4–8.

The national production of dryland corn could potentially change by –20 to +10%, depending on the GCM and projected severity of climate change (Figure 4a). Corn production declines in all scenarios where CO_2 fertilization does not apply with greater declines at higher GMT. Production of corn increases under all GCMs with CO_2 fertilization, except for BMRC at GMT = +2.5 °C. Production of corn in the six selected basins, however, was more varied in response to climate change (Figure 4b). The general trends were similar to the national changes but

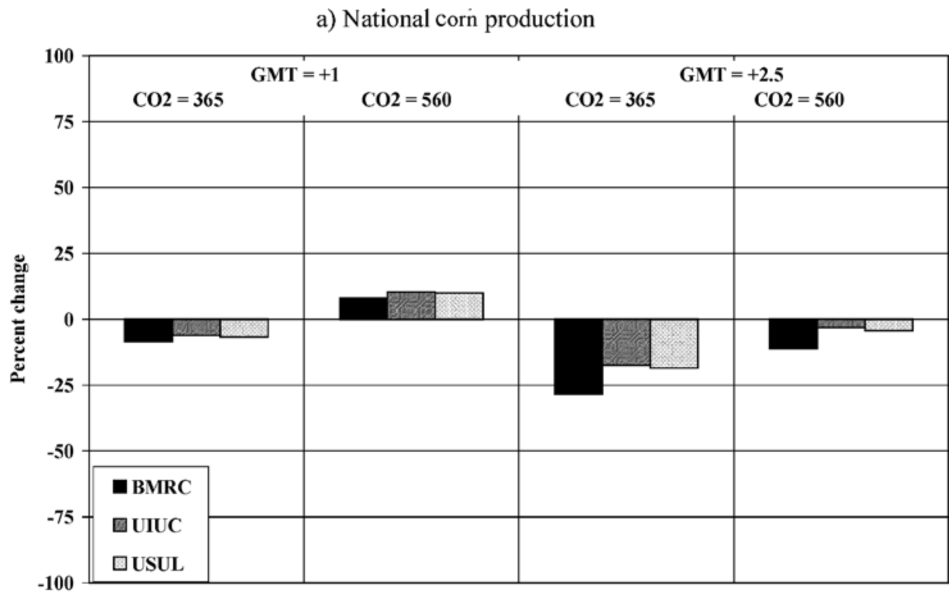
TABLE II
Four-digit basins selected for the regional analysis of each crop as shown in Figures 4–8

Crop	West	⟶				East
Corn	San Bernard (1209)	Upper Cimarron (1104)	Minnesota (0702)	Wabash (0512)	Edisto-Santee (0305)	Susquehanna (0205)
Soybean	Gasconade-Osage (1029)	Smoky Hill (1026)	Big Sioux (1017)	Yazoo (0803)	Wabash (0512)	Cape Fear (0303)
Winter wheat	Yakima (1703)	Red-Washita (1113)	Republican (1025)	Missouri – Oahe (1013)	Lower Illinois (0713)	Cape Fear (0303)
Clover hay	San Bernard (1209)	Upper White (1101)	Green (0511)	Mobile – Tombigbee (0316)	Lower Chesa-peake (0208)	Susquehanna (0205)
Alfalfa hay	Upper Columbia (1702)	Humboldt (1604)	Elephant Butte (1302)	White (1014)	Musselshell (1004)	Chippewa (0705)

the magnitude of change was much greater, ranging from declines below the YT in one region to an increase of 80% in another. Production in several basins declines under all scenarios except the most benign. The greatest increases in production are observed with CO_2 fertilization in effect, boosting production in all regions at both GMT levels.

The potential for significant change in production is greater for soybeans, where changes in national production range from –27 to +12% (Figure 5a). Soybean production increases nationally only under the benign scenario of GMT = +1 °C and [CO_2] = 560 ppmv. For all other scenarios production declines, most severely at higher GMT with no CO_2 fertilization. The regional production of soybean also declines for most scenarios (Figure 5b), and changes in the six representative basins range from declines below the YT to increases of 35%. The negative effects of the BMRC scenarios are noteworthy as soybean yields are depressed in all basins, except at GMT = +1 °C and [CO_2] = 560 ppmv.

EPIC simulations of national production changes in winter wheat are more optimistic, with increases of up to 25% and declines of no more than 10% (Figure 6a). CO_2 fertilization effects are strong under all GCM scenarios, contributing to significant increases in national production. The only substantial production declines are simulated under BMRC without CO_2 fertilization. The regional changes in production are also more optimistic, with almost all representative basins increasing production with CO_2 fertilization (Figure 6b). With [CO_2] at present-day concentrations, production response is variable with some decline of 25% or more when GMT = +2.5 °C.



** Indicates that production in the region fell below the threshold in the climate scenario.*

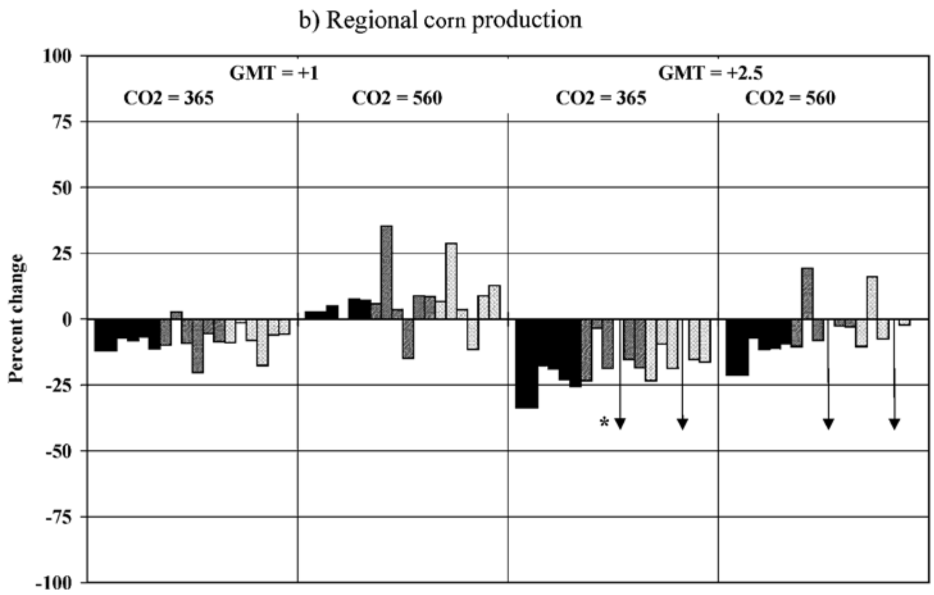


Figure 4. Changes in national and regional production of corn under 12 climate change scenarios. Bars in chart ‘b’ represent the six corn growing regions arrayed from west to east (see Figure 1 and Table II for identification and location of the regions).

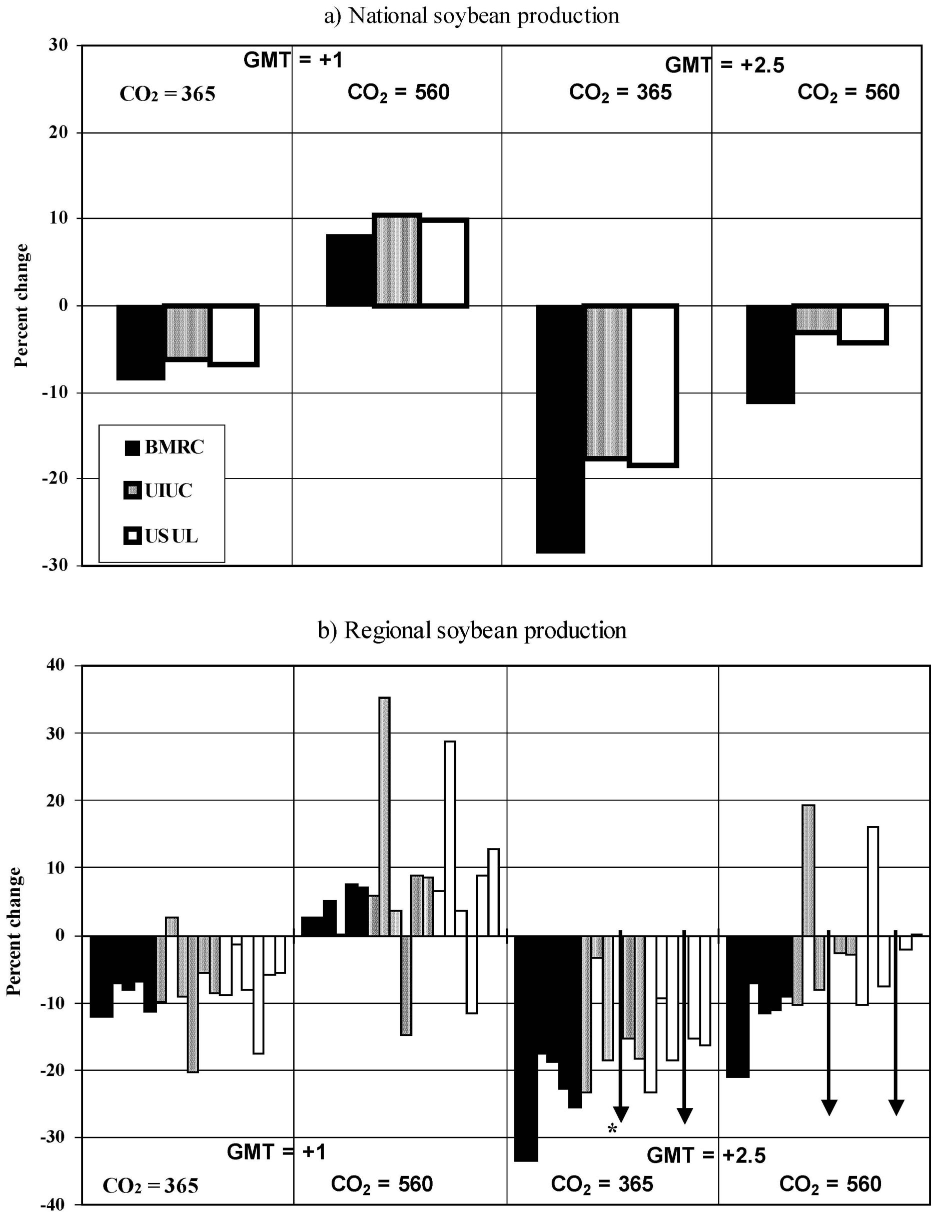


Figure 5. Changes in national and regional production of soybean under 12 climate change scenarios. Bars in chart 'b' represent the six soybean growing regions arrayed from west to east (see Figure 1 and Table II for identification and location of the regions).

3.2.2. *Forage Crops*

On the national scale, changes in alfalfa hay production are similar to those of winter wheat: production declines or remains essentially unchanged without CO_2 fertilization and increases with it (Figure 7a). The changes range from –5 to +25%,

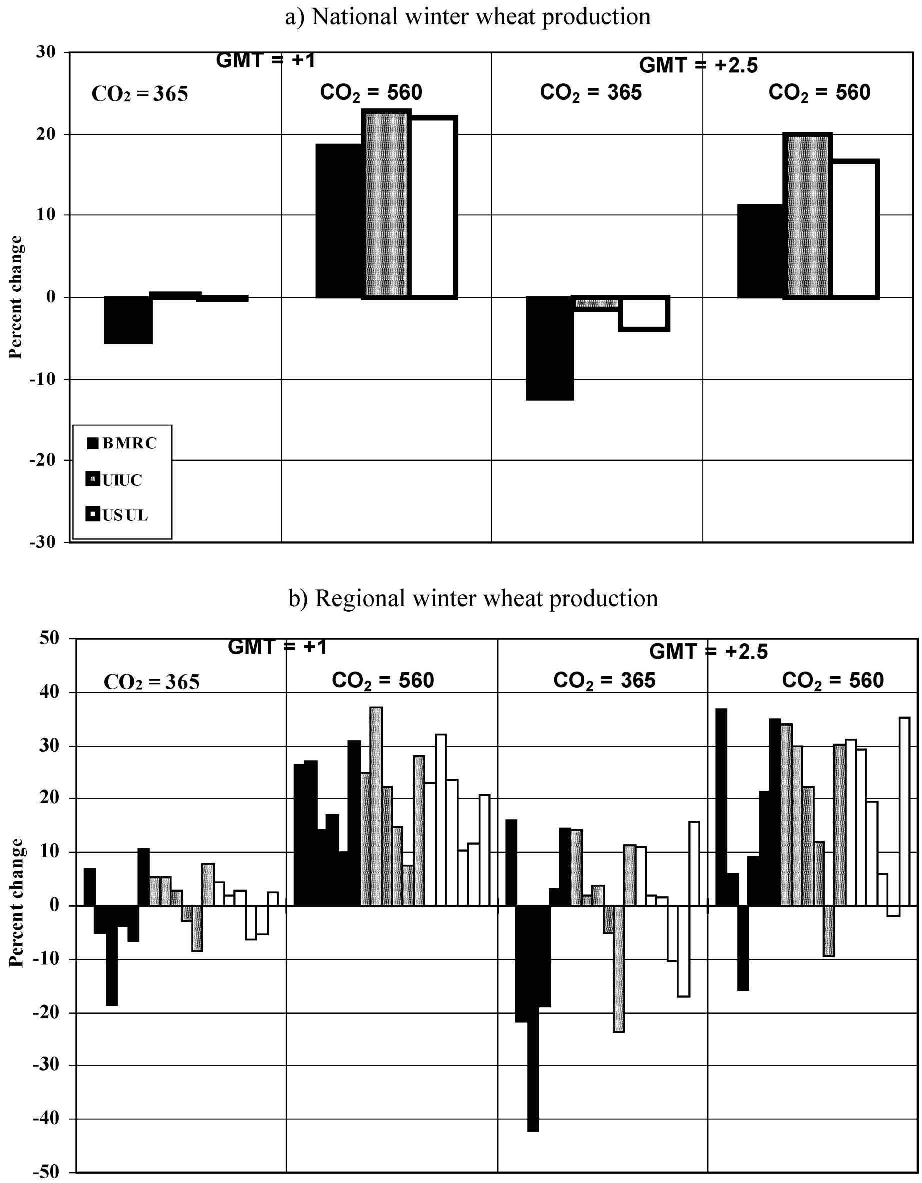


Figure 6. Changes in national and regional production of winter wheat under 12 climate change scenarios. Bars in chart 'b' represent the six winter wheat growing regions arrayed from west to east (see Figure 1 and Table II for identification and location of the regions).

with the declines occurring under BMRC without CO_2 fertilization. The regional changes in alfalfa hay production are more varied in magnitude and include some dramatic increases under UIUC where yields more than double (Figure 7b). Production increases in all basins with CO_2 fertilization. Alfalfa hay production declines but is not as adversely affected as are other crops by the severe (GMT $= +2.5\,^{\circ}$C,

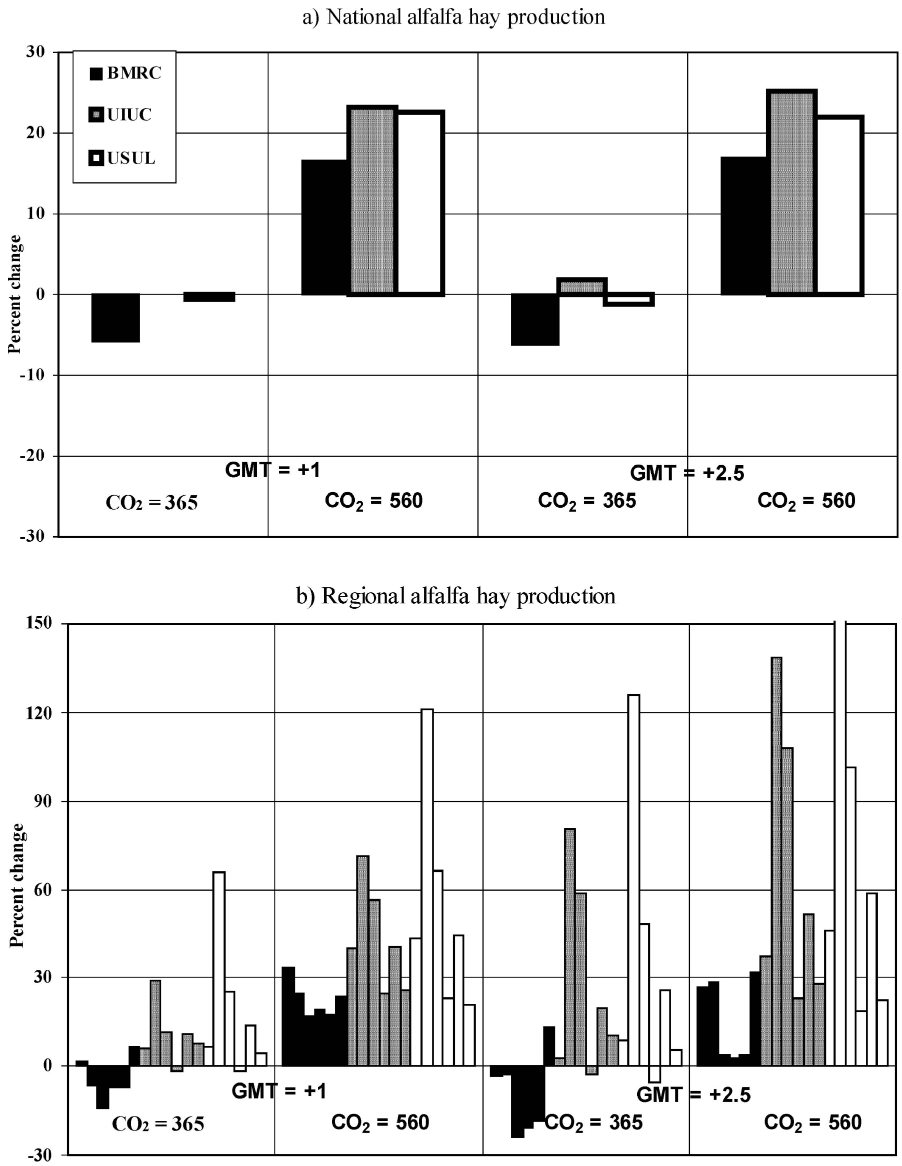


Figure 7. Changes in national and regional production of alfalfa hay under 12 climate change scenarios Bars in chart 'b' represent the six alfalfa hay growing regions arrayed from west to east (see Figure 1 and Table II for identification and location of the regions).

$[CO_2] = 365$ ppmv) climate scenario. The response to higher GMT is also less apparent than for other crops, with only slight increases in the magnitude of change under the UIUC scenarios, and no discernable change under BMRC.

Clover hay production is negatively affected by climate change on both national and regional scales (Figures 8a and 8b). National production declines under all

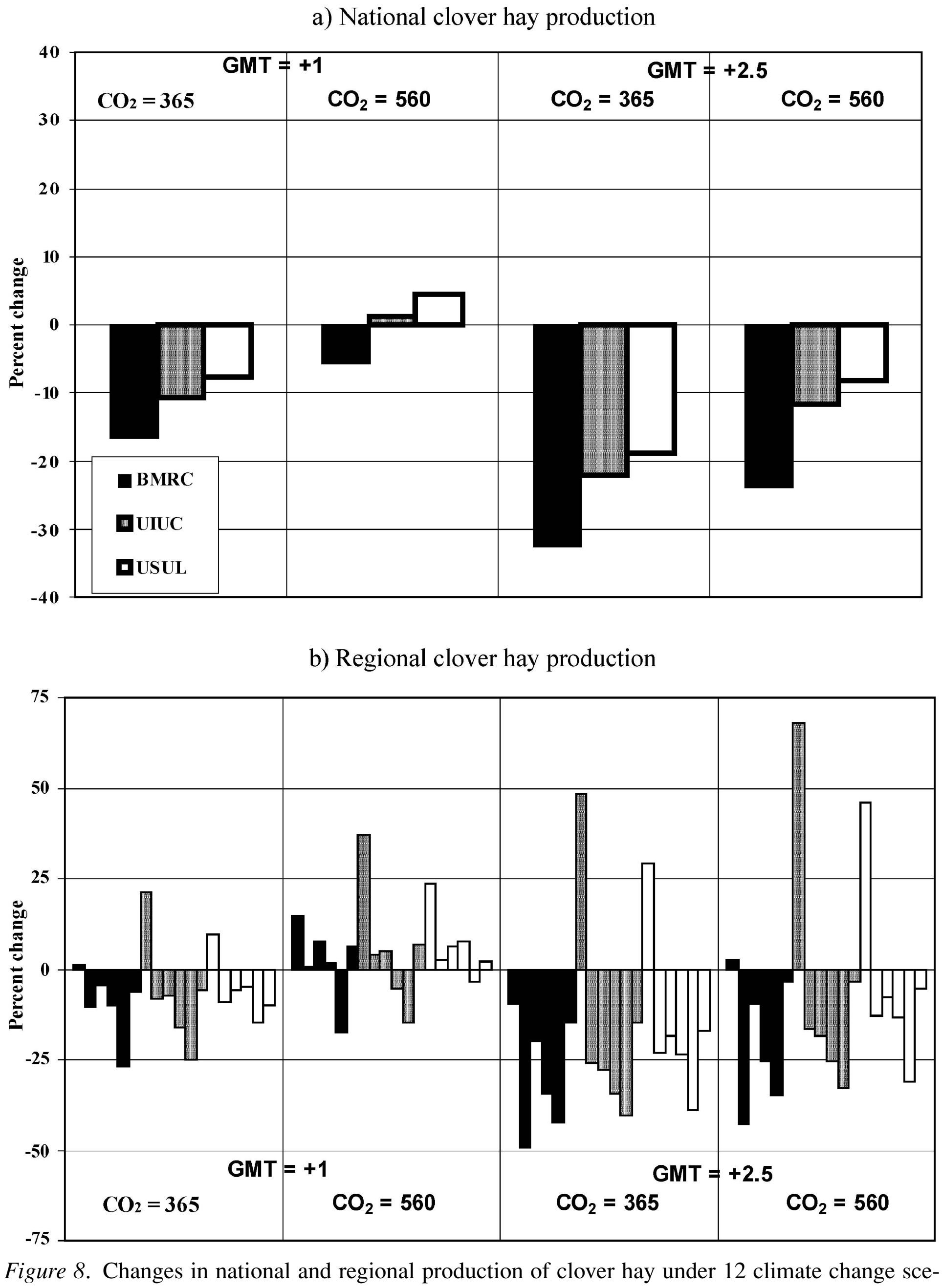


Figure 8. Changes in national and regional production of clover hay under 12 climate change scenarios. Bars in chart 'b' represent the six clover hay growing regions arrayed from west to east (see Figure 1 and Table II for identification and location of the regions).

scenarios except the most benign (UIUC, GMT = +1 °C, $[CO_2]$ = 560 ppmv). Production also declines for all basins, except for the most western basin under UIUC. The changes in clover hay differ strikingly from those of alfalfa hay, in part, because these crops were simulated for different regions of the country – clover in the east and alfalfa in the west.

National production changes for all crops depend primarily on the GCM used to simulate climate. Substantial declines were observed for all the grain crops and clover hay under the most severe climate scenario (GMT = +2.5 °C; $[CO_2]$ = 365 ppmv). In all cases, the higher $[CO_2]$ increases production at GMT = +2.5 °C. At the lower GMT increase, the CO_2 fertilization effect leads to yields above baseline levels for all crops, while at the higher GMT, it lead either to an increase from baseline or to more moderate declines in production. The higher GMT reduces increases in production where they occur, or worsens the decline for all crops but alfalfa hay, in which there was little change. These data indicate that while higher temperatures coupled with CO_2 fertilization may boost crop production somewhat, increasingly higher temperatures are detrimental to crop production. It is increasingly important to study the effects of higher temperatures in the light of recent predictions that GMT could rise by over 5.6 °C in the next 100 years, a more severe warming than earlier assessments had predicted (Houghton et al., 2001).

Figures 4–8 clearly show that extrapolating from individual farms to large regions or averaging production over large areas masks the significance of regional variability. The regions most vulnerable need to be identified so that adaptations can be made, people can prepare to adapt quickly and be flexible in their farming practices in order to minimize the harmful effects of climate change. Regions where production falls below the YT will have to adapt in some manner.

3.3. CROP YIELD VARIABILITY

We simulated 30 years of crop production and averaged the statistics over those 30 years for each scenario to arrive at the average level of production under the 12 climate change scenarios. Here, we use the coefficient of variability (CV) of crop yield to examine whether year-to-year variation in yields is likely to change with these climate change scenarios. The CVs for selected representative farms for the 12 climate change scenarios and baseline are presented in Table III, and their locations are indicated in Figure 9. It is important to note that changes in climate variability were not considered in the GCM scenarios; therefore, changes in the CV of yield will be the result of how the changes in climate, interacting with transient soil properties, affected crop growth over time.

For corn yields, CV in grain crop yields is greatest at baseline in the drier basins (e.g., San Bernard, Middle Columbia). This is true for all of the climate change scenarios. The CV in these basins declines under the wetter UIUC and almost always increases under BMRC because of reduced precipitation.

TABLE III
Coefficients of variation (CV) under baseline and climate change conditions in selected four-digit basins

Crop	Base	GMT = 1 °C, CO_2 = 365 ppmv			GMT = 1 °C, CO_2 = 560 ppmv			GMT = 2.5 °C, CO_2 = 365 ppmv			GMT = 2.5 °C, CO_2 = 365 ppmv		
		BMRC	UIUC	Sulfate	BMRC	UIUC	Sulfate	BMRC	UIUC	Sulfate	BMRC	UIUC	Sulfate
Susquehanna (basin 0205)													
Clover	46.1	38.7	41.5	44.5	38.8	41.5	44.2	38.2	34.7	38.1	38.0	10.0	37.8
Corn	21.3	8.0	10.7	12.6	8.4	10.7	12.6	6.7	6.7	6.9	6.8	6.6	6.6
Soybean	33.1	19.1	24.1	27.0	19.5	24.0	26.9	7.0	9.9	12.2	6.5	20.1	11.9
Wheat	18.1	22.1	18.5	18.8	17.7	14.1	15.0	17.7	22.5	22.9	16.4	35.0	19.4
Southeastern Lake Michigan (basin 0405)													
Alfalfa	14.5	9.6	9.5	9.7	11.0	11.0	11.3	21.3	18.8	15.0	20.6	7.2	14.1
Corn	5.8	6.8	6.6	6.6	6.7	6.9	6.6	6.9	7.3	7.0	7.3	7.3	7.1
Soybean	5.5	6.0	5.3	5.8	6.7	6.0	6.0	8.8	8.4	7.8	8.8	17.6	7.8
Wheat	10.2	15.2	13.4	10.5	15.2	12.9	10.1	17.0	17.3	17.3	17.0	19.9	16.7
Wabash (basin 0512)													
Alfalfa	9.4	10.4	9.3	8.9	10.4	9.3	9.1	24.7	16.3	9.3	24.4	9.6	9.1
Corn	7.6	9.2	9.0	8.5	8.8	8.8	8.7	9.7	9.6	9.2	9.7	9.4	9.2
Soybean	6.8	8.6	9.0	8.6	9.1	8.9	8.6	10.4	10.0	10.0	11.0	25.8	10.0
Wheat	13.4	21.3	18.8	15.5	21.1	19.1	15.4	19.4	26.3	23.4	19.9	15.3	23.7
Yazoo (basin 0803)													
Clover	35.0	44.8	44.9	37.2	44.3	45.0	37.3	37.2	43.3	45.8	37.6	11.5	45.5
Corn	55.6	47.1	56.3	60.2	52.8	64.4	66.2	42.9	57.1	61.2	44.8	58.7	68.9
Soybean	42.6	38.2	47.5	46.7	42.6	52.4	51.9	35.0	53.5	51.7	38.9	65.0	58.5
Wheat	10.5	11.9	12.2	10.6	11.6	11.3	10.2	12.9	12.1	12.5	13.5	42.9	12.0

						Cheyenne (basin 1012)							
Alfalfa	21.4	25.4	21.9	22.2	21.2	21.6	20.7	25.3	23.3	22.8	22.8	19.5	20.1
Corn	43.9	42.3	35.5	36.4	32.9	19.8	22.4	61.7	25.3	27.3	47.3	18.0	14.1
Soybean	37.8	31.4	29.8	28.8	28.7	27.8	27.8	44.0	25.0	26.6	40.3	13.2	21.7
Wheat	30.2	25.7	12.6	32.0	22.3	12.0	32.5	28.7	19.4	21.2	21.8	19.3	21.4
						San Bernard (basin 1209)							
Clover	48.1	47.3	42.0	46.0	47.1	41.7	45.8	53.5	38.8	40.9	53.1	13.0	40.9
Corn	38.3	47.2	21.8	29.7	29.5	9.4	15.3	59.5	9.4	18.6	42.9	5.0	7.9
Soybean	24.2	34.3	18.5	21.7	28.7	14.9	17.6	44.7	15.7	16.1	39.9	23.4	12.7
Wheat	21.3	25.2	22.8	20.0	22.2	22.3	19.1	34.8	23.4	22.1	32.9	38.8	22.4
						San Juan (basin 1408)							
Alfalfa	34.8	32.8	29.0	34.1	28.8	31.6	33.1	44.4	38.1	31.6	46.6	52.0	30.6
Corn	86.5	84.8	84.8	82.9	83.6	78.4	76.0	100.0	90.5	70.9	103.4	52.4	59.3
Soybean	60.0	52.9	56.6	63.5	51.1	55.4	57.6	52.2	53.5	58.2	52.9	37.1	54.9
Wheat	37.3	36.7	36.1	35.2	36.0	34.5	34.1	53.8	42.1	37.5	55.4	82.3	43.1
						Middle Columbia (basin 1707)							
Alfalfa	36.9	34.2	34.8	26.8	223.9	31.7	28.0	36.9	35.3	30.5	34.1	26.2	27.0
Corn	80.8	88.4	61.4	36.7	68.8	35.6	29.5	99.4	45.7	42.4	80.7	22.6	32.3
Soybean	32.5	42.3	35.1	30.9	38.5	32.1	25.7	47.9	31.4	27.3	45.5	35.1	25.3
Wheat	33.3	35.6	30.8	30.5	33.1	32.2	26.2	37.6	29.0	23.9	33.4	31.1	17.6

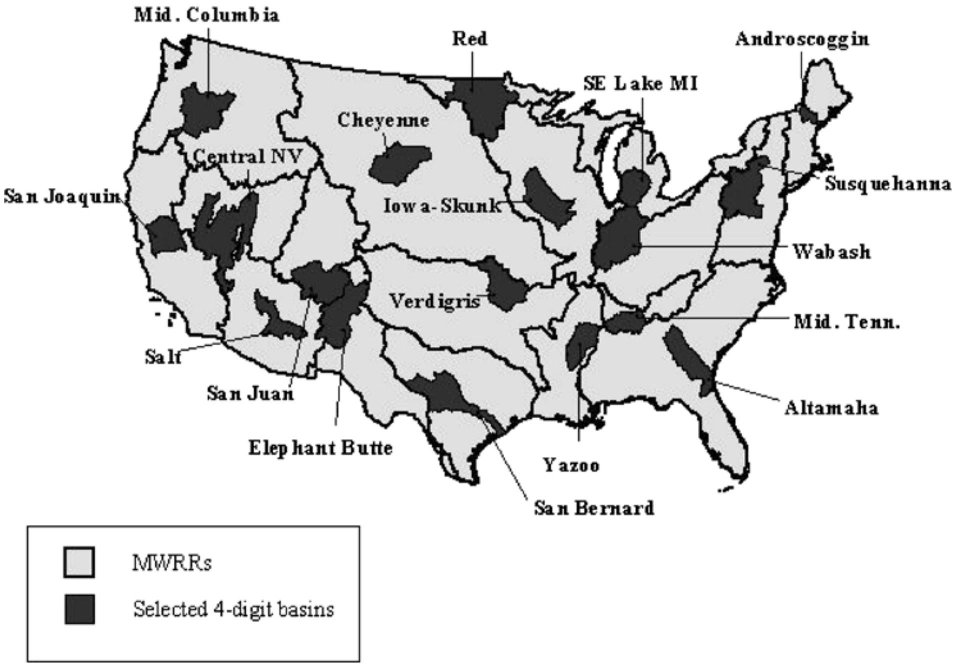


Figure 9. The four-digit basins representing the 18 major water resource regions selected for the analysis of yield variability under climate change.

The importance of an adequate water supply is apparent with the other crops as well. CVs of soybean yields, which are very sensitive to moisture limitations in the EPIC simulations, decline along the East Coast and in the Great Lakes but increase in the dry western basins, especially under BMRC. The influence of the increased precipitation and moderate temperature under UIUC are apparent in these regions in lesser increases or in decreases in variability. In contrast, CV of winter wheat yields declines significantly in the western wheat CPA (Middle Columbia, Cheyenne). Winter wheat yield variability does increase in the eastern and central basins (Southeastern Lake Michigan, Wabash, Yazoo), notably at the higher GMT. The inclusion of sulfates in the UIUC scenarios moderates the increased variability.

The CV of clover hay yield increases consistently in some basins (e.g., Yazoo) while declining in others (e.g., Susquehanna). Variability declines for clover hay at all locations under UIUC with GMT = +2.5 °C and [CO_2] = 560 ppmv. Clover hay is simulated in the eastern region of the country in which crop yield CVs are generally smaller so that CVs for clover under UIUC should be expected to decrease. Alfalfa hay, however, is simulated primarily in the more arid western part of the country. As a consequence, its CV increases under BMRC, especially with GMT = +2.5 °C. Variability also increases under UIUC in some western basins (e.g., Cheyenne), while decreasing in others (e.g., Middle Columbia). This indicates a geographic consistency in the change in variability, rather than a uniform response of variability to the large-scale climate changes in temperature and precipitation.

Yield variability in this study is primarily influenced by local weather and landscape features, such as topography and slope, rather than large-scale changes in atmospheric composition, global temperature and precipitation amounts and distribution. In general, where yields are lower at baseline (e.g., arid western United States) future projected variability is greater. Higher CO_2 concentrations do not have a consistent effect on yield variability in these simulations, as any effect is likely overshadowed by the importance of the variation in precipitation across the study region.

4. Conclusions

Change in production of grain and forage crops is highly dependent on the climate changes projected by the three GCMs employed in this study. Temperature increase was greater under the BMRC than under the UIUC scenarios; precipitation declined under BMRC but increased under UIUC. These basic differences underlie the crop production impacts simulated with the EPIC model.

The difference in impacts are clearly seen in the changes in geographical distribution of productive crop land. Due to the significant loss of moisture under BMRC the area of land under grain crop production declines, especially in the west. Under UIUC with and without the sulfate effect, grain crop production gains in land area, primarily because of increased precipitation. The universal effect of the increase in GMT from $+1$ to $+2.5\,^{\circ}$C is a decline in crop production which is partially offset by the positive impact of CO_2 fertilization. Our results also indicate that national impacts obscure sometimes dramatic regional effects, both positive and negative. More study of potentially vulnerable regions needs to be done at a smaller scale. It appears that the margins of current major crop-producing regions should receive the most detailed attention in future studies since these, as Parry et al. (1988) suggested in their seminal analysis, are likely to be the first impacted by climate change.

Year-to-year variability in crop yields demonstrated in this study are primarily affected by local weather and landscape features rather than by large-scale changes in atmospheric composition and global temperature. Variability was consistently greater in regions where baseline yield is low. However, higher CO_2 concentrations did not have a consistent effect on variability in this simulation. We conclude that any CO_2 effect manifested is overshadowed by the variation in precipitation across the study regions.

The analysis presented here considers only dryland agricultural production. Irrigated agriculture is an important component of US agriculture and the affects of climate change on irrigation practice must be considered. In the following paper (Part 4), we examine the impacts of the 12 climate change scenarios on water resources in the conterminous USA. In Part 5, we estimate potential crop production under irrigation as affected by changing irrigation demand and availability of water to meet that demand.

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 4: WATER RESOURCES

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Abstract. Global climate change will impact the hydrologic cycle by increasing the capacity of the atmosphere to hold moisture. Anticipated impacts are generally increased evaporation at low latitudes and increased precipitation at middle and high latitudes. General Circulation Models (GCMs) used to simulate climate disagree on whether the U.S. as a whole and its constituent regions will receive more or less precipitation as global warming occurs. The impacts on specific regions will depend on changes in weather patterns and are certain to be complex. Here we apply the suite of 12 potential climate change scenarios, previously described in Part 1, to the Hydrologic Unit Model of the United States (HUMUS) to simulate water supply in the conterminous United States in reference to a baseline scenario. We examine the sufficiency of this water supply to meet changing demands of irrigated agriculture. The changes in water supply driven by changes in climate will likely be most consequential in the semi-arid western parts of the country where water yield is currently scarce and the resource is intensively managed. Changes of greater than ±50% with respect to present day water yield are projected in parts of the Midwest and Southwest U.S. Interannual variability in the water supply is likely to increase where conditions become drier and to decrease under wetter conditions.

1. Introduction

Global warming from increases in atmospheric greenhouse gasses will alter weather patterns around the globe and affect the hydrologic cycle and freshwater supplies. The capacity of the atmosphere to hold water will increase, leading to more precipitation and evaporation globally. However, not all regions of the world will experience an increase in precipitation; some regions will experience a drying. In many regions of the world, water is in short supply under current climatic conditions, and accurate predictions of future water supplies are critical to water resources management decisions and adaptation strategies (Alcamo et al., 2000). Public awareness is growing in the United States that water is a finite resource and, as a result, freshwater withdrawals have declined over the last two decades even as population has

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increased (Solley et al., 1998). However, during the same time period, irrigation, the largest consumptive use of water, has increased. But as populations continue to increase, and with water supplies uncertain as climate changes, agriculture may come under increasing pressure to relinquish its claims to water. Future water resources planning may be further complicated by changes in climate, which may alter key components of the water cycle (e.g., precipitation and evapotranspiration). Studies of the effects of climate change on water resources are needed to define the potential magnitude of these changes.

The recent U.S. National Assessment of Climate Change (NACC) notes that global average precipitation will increase but the regional impacts are unknown and difficult to predict (Gleick et al., 2000). One complicating factor in assessing the potential impacts of climate change is that General Circulation Models (GCMs) do not agree on regional changes in precipitation or temperature (Lettenmaier et al., 1999; Kirshen and Fennessey, 1995; Wolock and Hornberger, 1991; Wolock and McCabe, 1999). Therefore, it is important to understand how water supplies might change in any given region under a range of climate change scenarios.

In addition to changes in temperature and precipitation, changes in vegetation can also affect water resources. Plant cover and physiology will change with rising atmospheric carbon dioxide concentration ([CO_2]) and interactions between water resources and vegetation will be altered. Increased precipitation enhances vegetative growth in arid regions and higher temperatures lengthen the frost-free growing season. These effects could increase leaf area index (LAI) and plant cover (Allen et al., 1991). Greater plant cover would increase the amount of water consumed by plants, reducing runoff while increasing overall evapotranspiration (ET). Conversely, the increase in atmospheric CO_2 is expected to influence plant physiology by increasing stomatal resistance and decreasing water lost through ET (Wolock and Hornberger, 1991; Allen et al., 1991). These contradictory effects were noted by Lettenmaier et al. (1999) and Brown and Rosenberg (1997) who found that the increase in ET with higher temperatures compounded the increasing dryness in regions receiving less precipitation and moderated runoff increases in regions where increased precipitation was predicted.

Water is a heavily managed natural resource in arid regions where there are many competing demands for it including municipal uses, industrial production, recreation, wildlife habitat, hydropower and agriculture. Much of the increase in global agricultural production over the past 50 yr is due to increased area of irrigated crops in arid regions. Significant reductions in water supply would make irrigation more difficult or impossible in certain regions, while increases in rainfall could allow marginal lands to support agricultural production, shifts to higher value crops to occur and/or reductions in actual demands for irrigation water. Increases in precipitation and water yield could also have negative consequences for agriculture if they come in the form of damaging storms that erode soils and flood the land, although we do not consider that case in this study.

A study of the sort reported here can provide useful information for overall national water policy. Gleick (1990) developed an index of regional water vulnerability or resilience based on five criteria descriptive of hydrologic basins: (1) ratio of storage to total annual mean renewable supply; (2) ratio of basin consumptive depletions to total annual mean renewable supply; (3) ratio of hydroelectricity to total electricity production; (4) ratio of total annual groundwater overdraft to total groundwater withdrawals; (5) ratio of very high to very low streamflow (variability). Numerical limits are defined for each of these criteria. Under current climate safe limits are exceeded in all five criteria in one of the Major Water Resource Regions (MWRRs) of the conterminous U.S.—the Great Basin. Four safe limits are exceeded in the Missouri and California. Three are exceeded in the Lower Colorado, the Arkansas-White-Red and the Texas-Gulf. The HUMUS simulations presented in this paper show profound changes under at least a few scenarios in most of the 18 MWRRs modeled, it is most interesting to observe the changes that are projected for the most vulnerable basins.

Others have simulated the response of surface water resources to climate change by estimating global river discharge (Miller and Russell, 1992), assessing the impacts on water distribution in individual watersheds (e.g., Boston water supply, Columbia River) (Kirshen and Fennessey, 1995; Wolock and Hornberger, 1991) or multiple watersheds (e.g., Rosenberg et al., 1999 for the Missouri and Arkansas river basins that overlie the Ogallala aquifer). In this study, we examine water resources at the scale of the 2,101 USGS 8-digit hydrologic unit areas within the conterminous United States. We explicitly model the effects of increases in atmospheric CO_2 through the so-called 'CO_2-fertilization effect' in addition to GCM-projected changes in temperature and precipitation—all encompassed in a suite of 12 climate change scenarios. Our purpose is to identify regional changes in annual freshwater supply that might occur and how the seasonal distribution of water supplies might change. Descriptions of the climate change scenarios and the models used in this study can be found in Part 1 of this series. In the paper that follows (Part 5), we use the results of these water resources simulations in combination with the simulations of agricultural production reported in Part 3 to determine whether future water supplies will be sufficient to meet irrigation demands of a future U.S. agriculture. Then in Part 6, we examine natural ecosystem response to the changing climate and water resource regime.

2. Methods

2.1. HYDROLOGIC UNIT MODEL OF THE UNITED STATES (HUMUS)

HUMUS is a GIS-based tool (Arnold et al., 1999; Srinivasan et al., 1993) which provides the input data required to drive the Soil and Water Assessment Tool (SWAT) hydrology model of Arnold et al. (1998). 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, we simulate the hydrologic cycle at the scale of the 8-digit USGS hydrologic unit areas (HUA) (USGS, 1987). Input data sets, including weather data (daily maximum and minimum temperature, precipitation, solar radiation and humidity) soil profiles, vegetation cover and land management, were assembled for the conterminous United States at the scale of 1:250,000 and integrated into the HUMUS geographic information system database. These data are passed to SWAT, which represents the basin water balance on a daily time step through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). The variable in SWAT most comparable to streamflow is water yield, calculated as the sum of runoff, lateral flow from the soil profile, and groundwater flow from the shallow aquifer. For a complete description and validation of HUMUS/SWAT, see Part 2 of this series.

2.2. CLIMATE CHANGE SCENARIOS

The impacts of 12 climate change scenarios on U.S. hydrology were modeled with HUMUS. As explained in Part 1, we captured the range of potential future conditions with three General Circulation Models (GCMs): the Australian Bureau of Meteorology Research Centre (BMRC), the University of Illinois at Urbana Champagne (UIUC) and the UIUC with characterization of atmospheric sulfates (UIUC + Sulfate). Climate change was modeled with each of these at two levels of global mean temperature increase (GMT = +1 or +2.5 °C), and the scenarios were scaled to 0.5° grid cells and applied to the baseline weather stations. To account for the potential impact of 'CO_2-fertilization' on the hydrologic balance, the HUMUS simulations for this study were made under two CO_2 concentrations: present day (365 ppmv) and double the pre-industrial concentration (560 ppmv). Each simulation was run for a 30-yr period under the changed climate conditions (Part 1, Table I). For further information on the GCMs and their climate predictions, see Part 1.

2.3. WATER YIELD VARIABILITY

The coefficient of variation (CV) of annual water yield was calculated for each of the 2,101 8-digit basins over the 30-yr simulation period. CV is defined by (standard deviation)/(mean) $\times$ 100. To provide the scenarios of climate change used to drive the HUMUS model (see Part 1), monthly means of maximum and minimum temperature and precipitation derived from the historical daily weather record were adjusted by the average monthly climate changes predicted by the GCMs. Therefore, changes in climate variability are not captured by these scenarios and any changes in the variability of water yield are due to the response of the HUMUS model to the new precipitation and temperature regimes and the effect of these on the basin's vegetation.

TABLE I

Water yield at baseline and change from baseline for the 18 Major Water Resource Regions (MWRRs) under 12 scenarios of climate change

GCM	Baseline	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate
GMT (°C)	0		1.0			1.0			2.5			2.5	
CO_2 (ppmv)	365		365			560			365			560	
MWRR	mm	Change from baseline (mm)											
New Eng.	635	−14	18	21	5	36	39	−41	42	49	−21	62	69
Mid-Atl.	507	−25	15	16	−14	26	27	−62	37	37	−51	47	47
S. Atl-Gulf	605	−36	11	13	−17	30	32	−91	26	30	−73	45	49
G. Lakes	399	−16	13	8	−2	27	22	−39	31	21	−25	46	35
Ohio	550	−29	19	16	−18	35	27	−73	56	37	−61	56	47
Tenn.	779	−40	27	23	−24	41	40	−106	75	51	−90	75	67
U. Miss.	331	−24	21	2	−12	34	13	−57	65	18	−44	65	29
L. Miss.	614	−56	21	10	−28	49	36	−139	84	34	−112	84	61
Sou-R-Rai.	87	−8	7	3	0	15	10	−23	23	6	−16	23	14
Missouri	107	−16	20	17	−11	26	24	−35	55	48	−31	63	55
Ark-W-R.	235	−31	50	38	−19	65	53	−73	139	116	−62	157	133
TX-Gulf	211	−34	46	29	−19	63	47	−83	123	97	−69	142	115
Rio Gr.	40	−10	15	15	−8	18	18	−21	46	44	−21	51	49
U. Colo.	63	−11	14	26	−9	17	30	−23	47	66	−23	51	72
L. Colo.	52	−14	12	27	−12	14	29	−29	40	63	−29	42	66
Gr. Basin	68	−10	19	46	−10	20	48	−26	57	110	−26	60	114
Pac. NW	521	−26	18	65	−15	32	80	−66	38	102	−66	54	119
Calif.	409	−36	11	49	−31	16	55	−83	32	89	−83	38	95

3. Results and Discussion

3.1. IMPACTS ON ANNUAL WATER SUPPLY

3.1.1. *Water Yield on the National Scale*

Figure 1 illustrates the changes in HUMUS-simulated water yield over the conterminous U.S. in response to climate changes projected by the three GCMs. The effects of higher global mean temperature (GMT) are shown in Figures 1a and 1b. The effects of 'CO_2-fertilization' are shown in Figures 1b and 1c for specific changes in precipitation and temperature projected by the three GCMs (see Part 1, Figures 5 and 6).

Figure 1a shows the response of water yield to a 1 °C increase in GMT. The BMRC model shows a marked drying (−25 to −175 mm) across the country, with the most severe declines in water yield in pockets of the lower Mississippi valley and the Pacific Northwest. A few isolated basins show increases in water yield that do not exceed baseline by more than 50 mm. Under the UIUC scenario, water yield declines in relatively few basins and increases over most of the country. The greatest increase occurs in eastern Texas and Oklahoma. Parts of the Gulf Coast, Upper Midwest and Pacific Northwest experience drying. UIUC +Sulfate shows similar trends but with some exceptions. The Great Lakes and Upper Midwest regions experience drying, while water yield increases markedly (more than 150 mm) in some basins of the Pacific Northwest. The increase in GMT from +1 to +2.5 °C (Figure 1b) amplifies the effects of each GCM, but the regional distributions remain similar. One notable change is observed in the upper Midwest region. The small decline in water yield under UIUC +Sulfates at GMT = +1 °C converts to a moderate increase when GMT = +2.5 °C. Precipitation increases in this region under both scenarios; therefore the switch from decrease to increase in water yield as global mean temperature increases illustrates the potential for non-linear regional impacts of climate change.

Under BMRC, the drying is moderated by CO_2-fertilization in the southeast and northern New England (Figure 1c). CO_2-fertilization makes no significant difference in the arid West. With the high temperatures and low precipitation predicted by BMRC for the West, conditions would become harsher and vegetative cover could be reduced, as the BIOME model shows (see Part 6). In such a case the CO_2-fertilization effect on plants would have little impact on regional hydrology. In contrast, UIUC predicts large increases in precipitation in the West and water yield increases with the CO_2 effect due to suppression of evapotranspiration. Response under UIUC + Sulfate is similar, with greater increases in water yield in the West. Geographic patterns in the Pacific Northwest remain complex but with greater water yields in some basins within the region. CO_2-fertilization under UIUC and UIUC + Sulfates increases water yield substantially in eastern Texas, Oklahoma, and Kansas.

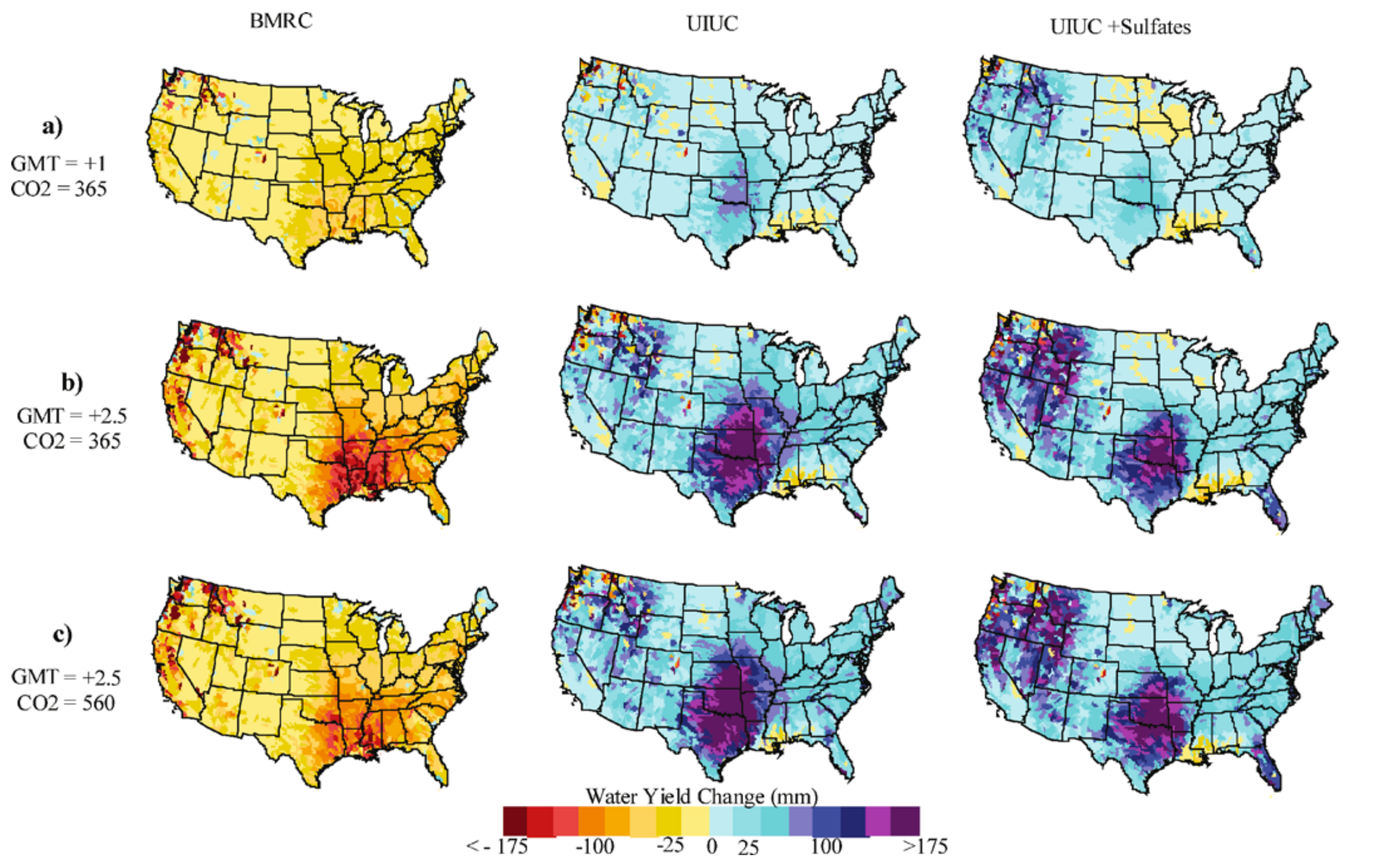

Figure 1. Change in water yield from baseline (mm) for three GCMs with increasing global mean temperature (GMT) with and without the CO_2-fertilization effect.

3.1.2. *Evapotranspiration (ET) on the National Scale*

Changes in ET, reflecting interactions between temperature, precipitation and plant physiology, are shown in Figure 2. In Figure 2a, the response of ET under a 1 °C rise in GMT is consistent with GCM projected changes in temperature and precipitation. BMRC, which projects less precipitation and greater warming than UIUC, decreases ET in the western part of the country where the dryer and hotter conditions limit vegetative cover. BMRC leads to increased ET in the East where higher temperatures increase water use. ET increases under UIUC except in scattered eastern basins as the increased precipitation provides water to plants. UIUC + Sulfate increases ET in portions of the West and moderates decreases throughout the central part of the country. Increases are greatest in the arid western regions where this GCM predicts higher precipitation than does UIUC. An increase in GMT of 2.5 °C (Figure 2b) amplifies the effects discussed above with sharper declines in ET in the West and greater increases in the East and Pacific Northwest.

Atmospheric CO_2 increases stomatal resistance which reduces ET. However, in regions where conditions become more favorable for plant growth, ET may increase with increasing plant cover. Under BMRC, ET is reduced in all regions of the West but the Pacific Northwest. There the BMRC climate changes, higher temperatures at high elevations, longer growing season, and greater water supply, increase vegetative cover (Part 6). The UIUC models show a different pattern, with ET increasing dramatically in the West as the increased precipitation stimulates a denser plant cover. UIUC + Sulfate with CO_2-fertilzation shows a similar response in the West but a greater decrease in ET to the Central regions, especially in eastern Texas and Oklahoma and lower Mississippi regions. Temperature increase under UIUC + Sulfate is small (negligible when GMT = +1 °C and less than 1 °C when GMT = +2.5 °C). ET does not increase significantly with such a slight increase in temperature. CO_2-fertilization leads to increased stomatal resistance and the combined effect is a significantly lower rate of ET for the UIUC + Sulfate scenarios as compared with UIUC.

3.1.3. *Regional Hydrology*

The Major Water Resource Regions (MWRRs) are varied in their climate and hydrologic characteristics. Change in water yield and ET due to forcing by GCM, GMT and [CO_2] are reported for each MWRR in Tables I and II. Baseline water yields are given to illustrate the variety of hydrologic regimes that characterize the conterminous U.S. Water yields decline in all MWRRs under the BMRC scenarios but increase under UIUC and UIUC + Sulfates. The magnitude of the changes is amplified by higher GMT. CO_2-fertilization increases water yield in all regions. The patterns of ET change are more varied by region than by climate change scenario. In the East, ET increases in the absence of CO_2-fertilization, but declines when it is present. In the West, ET declines under BMRC but increases under UIUC scenarios due to greater water availability.

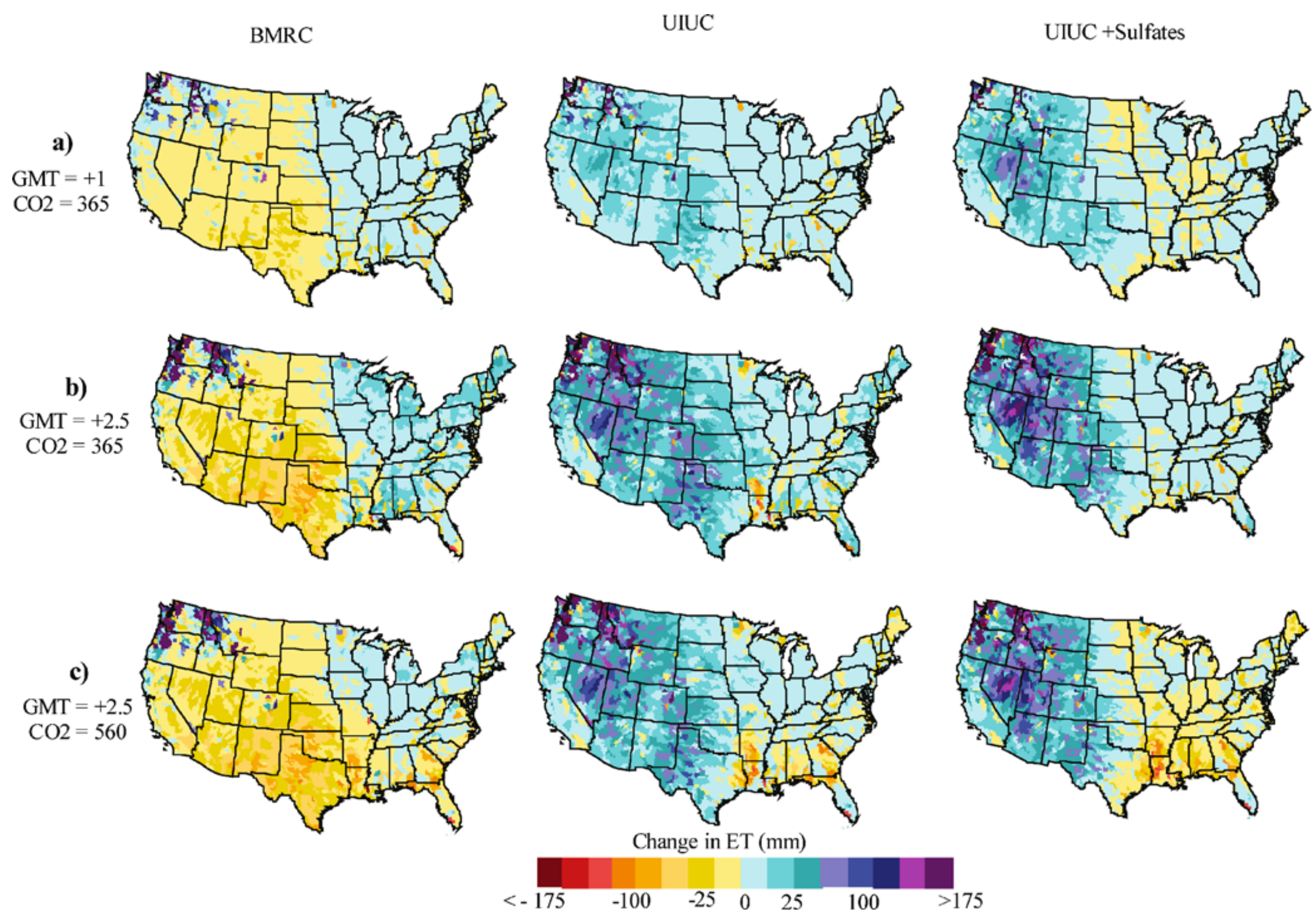

Figure 2. Evapotranspiration change from baseline (mm) for three GCMs with increasing global mean temperature (GMT) with and without the CO_2-fertilization effect.

TABLE II
Evapotranspiration (ET) at baseline and change from baseline for the 18 Major Water Resource Regions (MWRRs) under 12 scenarios of climate change

GCM	Baseline	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate
GMT (°C)	0		1.0			1.0			2.5			2.5	
CO_2 (ppmv)	365		365			560			365			560	
MWRR	mm	Change from baseline (mm)											
New Eng.	399	7	5	3	−18	−19	−21	26	17	11	−1	−10	−15
Mid-Atl.	429	8	8	2	−6	−7	−12	19	21	14	5	7	−1
S. Atl-Gulf	566	2	4	2	−24	−22	−25	9	12	4	−17	−14	−22
G. Lakes	498	16	10	4	5	0	−8	39	25	15	27	14	4
Ohio	541	6	6	−2	−6	−5	−14	17	7	6	5	7	−6
Tenn.	547	3	2	−3	−13	−19	−19	14	−1	1	−3	−1	−15
U. Miss.	511	9	10	1	−2	−1	−10	19	14	9	7	14	−1
L. Miss.	655	2	7	−1	−31	−26	−32	2	−20	1	−29	−20	−32
Sou-R-Rai.	452	5	8	−1	−3	−1	−10	13	13	5	6	13	−3
Missouri	407	−2	23	17	−7	16	11	−8	51	39	−12	44	32
Ark-W-R.	548	−12	25	15	−24	10	0	−35	49	31	−46	31	14
TX-Gulf	584	−14	21	12	−30	2	−7	−38	42	23	−53	21	2
Rio Gr.	329	−20	23	26	−21	20	22	−53	51	52	−53	46	47
U. Colo.	241	−8	26	43	−10	23	39	−24	55	74	−24	51	69
L. Colo.	266	−11	21	37	−12	19	34	−32	45	62	−32	42	59
Gr. Basin	222	−8	37	65	−9	35	62	−21	82	106	−21	80	103
Pac. NW	230	20	43	41	10	30	28	46	110	114	46	96	98
Calif.	220	−4	12	20	−8	8	15	−13	27	35	−13	22	30

Based on their geographical location and agricultural importance, six MWRRs were selected for a comparison of water yield (WY), runoff (Q) and ET response to forcing in Figure 3. Water yield is the sum of runoff, lateral flow from the soil profile and groundwater flow from the shallow aquifer. Therefore any difference between runoff and water yield is due to a changes in the soil profile or aquifer flows. The South Atlantic-Gulf is a humid region with baseline annual water yield of ∼600 mm. Water yield and runoff both decline under BMRC at GMT $= +1\,^{\circ}$C. The decline is amplified by the higher GMT and moderated by the higher [CO_2]. ET increases slightly with no CO_2-fertilization effect, but declines slightly when it is present. While WY and Q show the opposite response (increasing) under UIUC, ET responds as under BMRC. For all three GCMs, the higher GMT raises ET, but the CO_2 effect reduces stomatal conductance and lowers ET rates.

The Ohio basin is also humid at baseline (WY = 550 mm) but is cooler because of its higher latitude. ET is very similar under BMRC and UIUC, although the former predicts a lessening and the latter predicts increases in WY and Q. The BMRC decline doubles in magnitude to 15–20% at the higher GMT. ET increases with higher GMT and does not decline with CO_2-fertilization, indicating a lengthening of the growing season or larger plants due to CO_2-fertilization.

The Missouri region covers a wide range of climates in the Great Plains and Prairie states. The region ranges from humid to semi-arid under baseline conditions, averaging 500 mm of precipitation annually with a relatively high ET of 400 mm. The climate change scenarios have greater impact in this region; WY and Q decline under BMRC by 10–30% and increase under UIUC by 25–60%. The changes in ET are smaller in magnitude, declining slightly under BMRC while increasing under UIUC. ET rates are reduced in all cases by CO_2-fertilization. Under the dryer and hotter conditions of the BMRC, ET declines with higher GMT and higher [CO_2]. The lack of precipitation under BMRC may cause a decline in vegetation cover (LAI) while ET shows the opposite effect with increased precipitation under UIUC.

The Lower Colorado basin is an arid region in which temperatures vary greatly from one sub-region to another. Large decreases in Q and WY (−25 to −75%) occur under BMRC. Under UIUC increases range from 25 to more than 75%. This indicates that substantial change in the hydrologic regime of this basin is possible, although the direction is uncertain. The changes in ET are also larger, declining with BMRC and increasing with UIUC. ET decline may be a result of less water available for evaporation. CO_2-fertilization moderates the decline in ET because of increased plant cover. ET increases under UIUC as a result of greater plant cover with wetter conditions and a longer growing season. The warming may also allow for increased plant growth at higher elevations.

The Pacific Northwest region is wet under current conditions with baseline precipitation of ∼700 mm/yr and water yield of ∼500 mm/yr. WY and Q decline by 15% or less under BMRC and increase by about the same amount under UIUC. Increases in ET in this region are large relative to changes in WY and Q. The

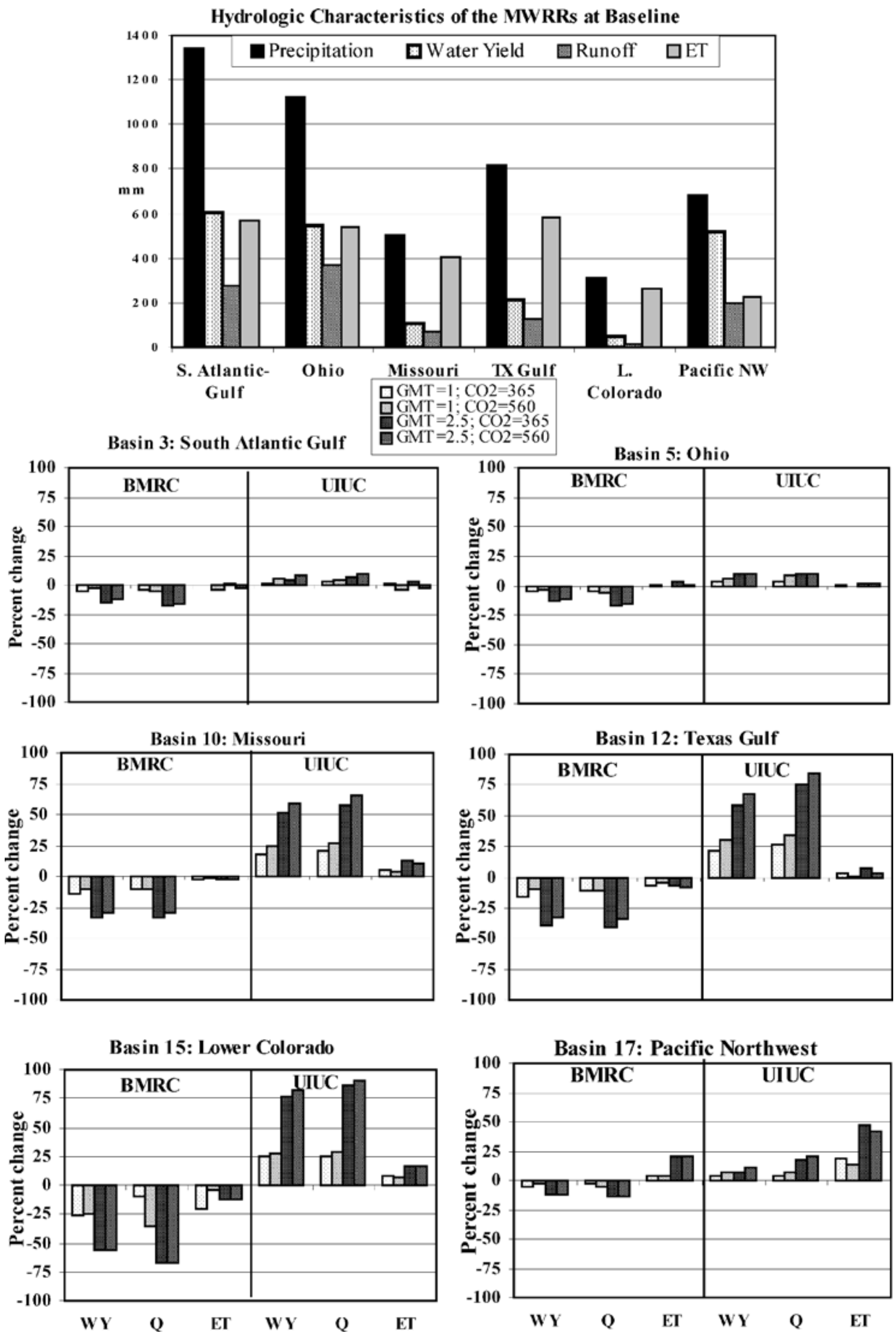

Figure 3. Water yield, runoff and ET changes in six Major Water Resource Regions (MWRRs).

increase in ET under all scenarios indicates a longer growing season in response to higher temperatures. Increases in ET are greater under UIUC because increased precipitation in the arid eastern parts of this region provide the water to evaporate.

3.2. IMPACTS ON SEASONAL WATER SUPPLY

3.2.1. *Effects of Higher GMT*

One uncertainty about water resource response to climate change concerns seasonality of the hydrologic cycle. Here we use 4-digit basins (Figure 4) in the six regions shown in Figure 3 to represent the seasonal changes in water yield at two levels of GMT. CO_2-fertilization effects are considered separately below. The selected 4-digit basins are chosen to represent the range of changes that may occur in basins nationwide, but do not necessarily accurately represent the seasonal change in the large and geographically diverse MWRRs.

BMRC warming leads to reduction in water yield in the Ogeechee–Savannah basin in all months except for a slight increase in September (Figure 5a). WY declines of as much as 10 mm occur in February and October at the higher GMT. The magnitude of change is greater with GMT = $+2.5$ °C while the overall pattern remains the same. With UIUC, water yield increases from baseline, with the greatest increases in winter, mid-summer and fall. Water yields decline by as much as 5 mm in the months of May and August. Sulfates in the UIUC GCM amplify the peaks

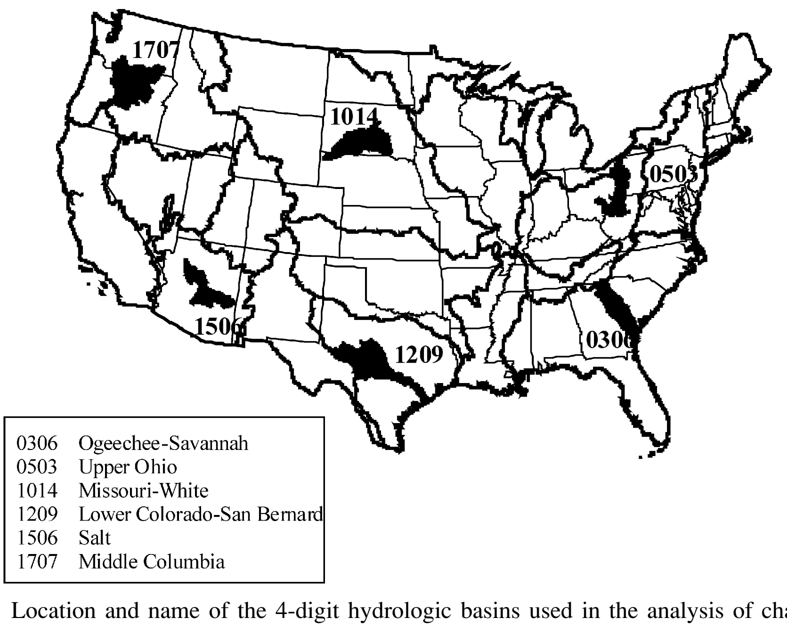

Figure 4. Location and name of the 4-digit hydrologic basins used in the analysis of changes in seasonal water yield found in Figures 5 and 6.

in months of increase. While the general trend is similar to UIUC, more months show a decline in water yield—notably March, May and August. In summer water yield increases reach 15 mm at the higher GMT.

In the Upper Ohio basin (Figure 5b), WY declines from baseline under BMRC in all months but December and February. The greatest decline (−9 mm) occurs in

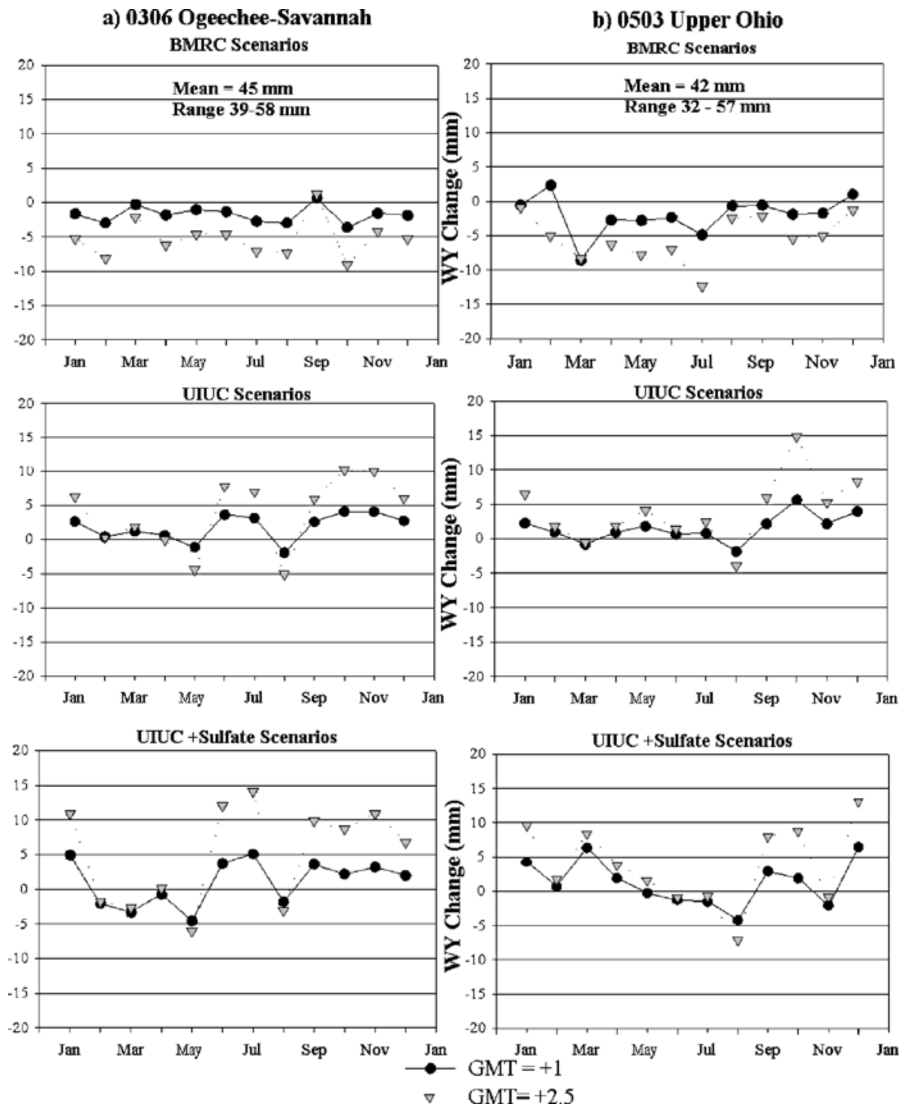

Figure 5. Seasonal water yield change from baseline in the six selected 4-digit hydrologic basins at two levels of global mean temperature (GMT) increase with the mean and range of monthly water yield given for reference.

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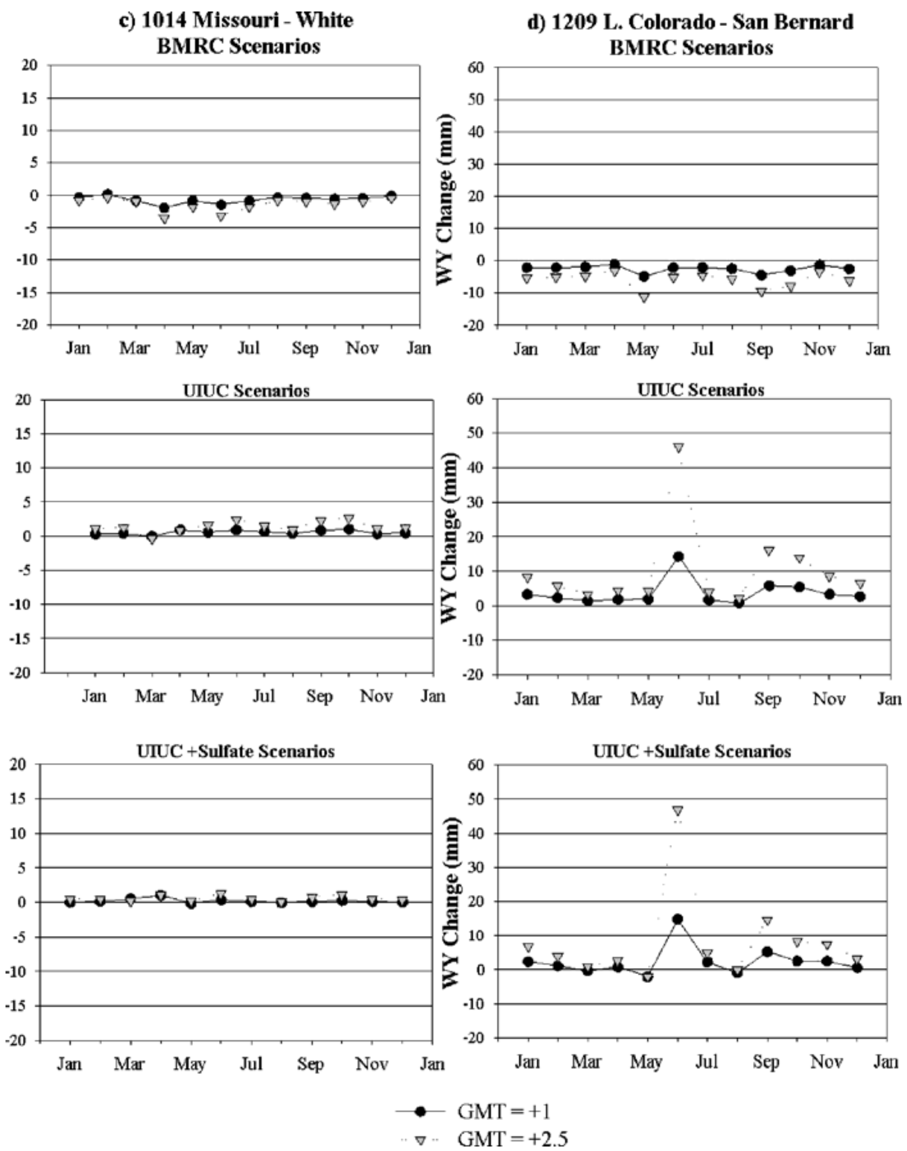

Figure 5. (*Continued on next page.*).

March. WY declines in all months at the higher GMT. While it does not decline further in March, it does decline dramatically (−13 mm) in summer, especially in July. WY increases in most seasons under the UIUC scenarios. With GMT = +1 °C, WY increases in all months but August, with the greatest increases occurring in fall. With GMT = +2.5 °C, the trends remain the same but the magnitude of winter increase is greater. Trends under UIUC + Sulfate are similar. Winter increases in WY and summer decreases are amplified. A large increase in WY occurs in March.

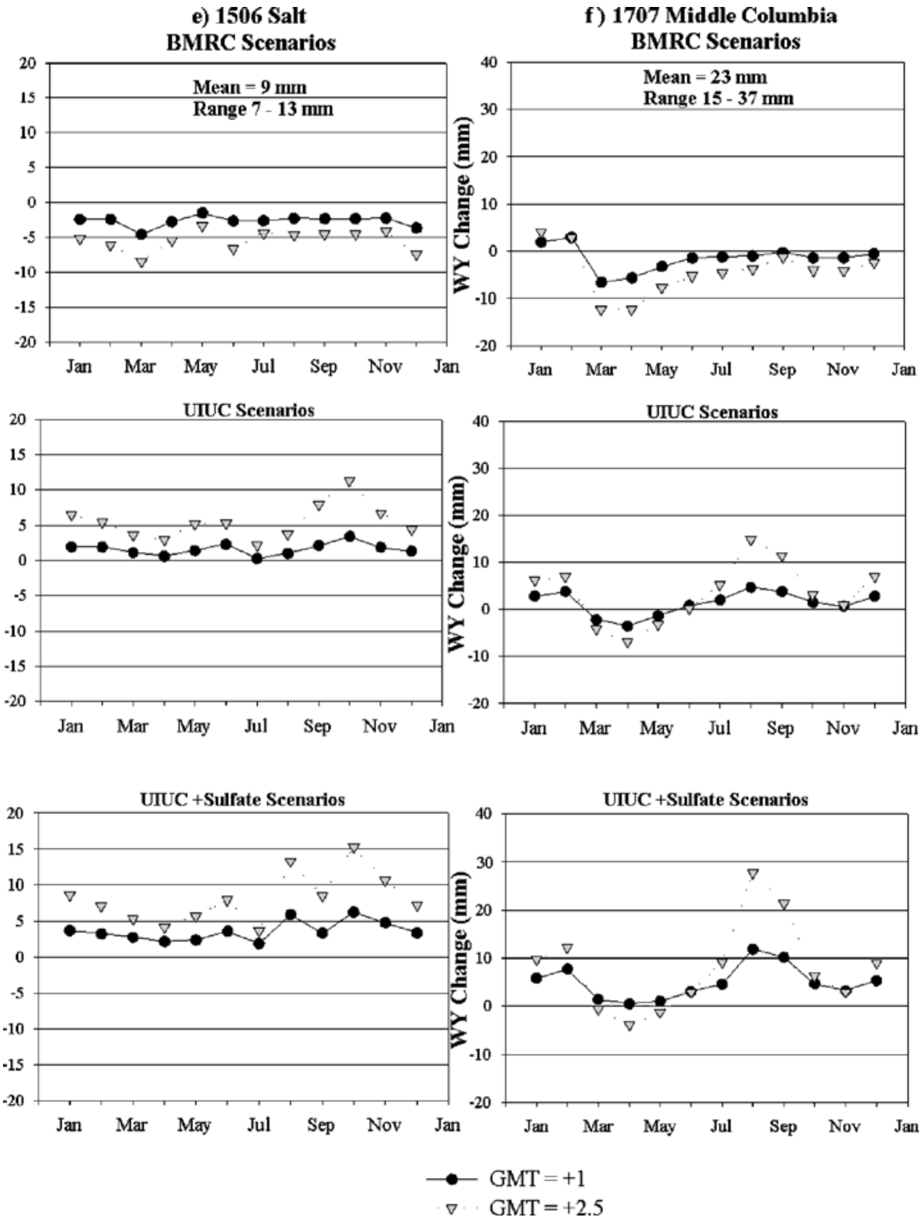

Figure 5. (*Continued*).

Water yield in the Missouri-White basin (Figure 5c) is very little changed from baseline, never exceeding ±5 mm in any month under any of the scenarios. A noticeable drying occurs in the spring and summer months under BMRC, while WY slightly increases under UIUC. In contrast, there is a sharp change in seasonal water yield under UIUC in the Lower Colorado-San Bernard basin (Figure 5d).

The UIUC models show sharp WY increases in the month of June, from 15 to 50 mm above the baseline. There is also a marked increase in fall water yield. Under BMRC, water yield declines uniformly throughout the year with greater drying in May and in the fall months.

Water yields decline noticeably throughout the year in the Salt basin under BMRC (Figure 5e). The greatest declines occur in spring with a dip in December. The UIUC scenarios cause an increase in water yield. The increase is substantial under GMT = +1 °C during June and October. The increases are greater with GMT = +2.5 °C, peaking at +10 mm in October. The trend under UIUC + Sulfates is similar to UIUC alone but with larger increases. Also, there is a more sustained increase through the fall and winter months.

In the Middle Columbia basin (Figure 5f) distinct changes occur in WY patterns under all three GCMs and at both GMT levels; i.e., an increase in water yield in the winter and a decline in spring. Under the UIUC scenarios the summer increase is amplified at GMT = +2.5 °C. With the sulfate effect included, summer and winter increases are more prominent and the spring decline slightly less so. The winter increase and spring decrease in all of the scenarios indicates a greater proportion of winter precipitation falling as rain and a smaller snowpack melt in the spring. The effect varies by degree according to the temperature increase in a given scenario. The increase in temperature under UIUC + Sulfate is very small; hence, this effect is least apparent under this scenario (see Part 1, Figure 5). The increase in late summer and fall precipitation under UIUC would radically change the current pattern of wet winter–dry summer climate of this region.

3.2.2. *Effects of CO_2-Fertilization*

We selected two basins with significant changes in water yield, the Upper Ohio and Middle Columbia, to examine whether CO_2-fertilization notable alters the changes in water yield due to GCM and GMT. We examined only BMRC and UIUC results for this purpose. In the Upper Ohio (Figure 6a) under the BMRC scenarios, enhanced CO_2 causes a slight increase in WY in the winter months and a greater WY increase from June to November. The effect of elevated [CO_2] with the UIUC scenario is much greater, up to 2 mm, and is most apparent in the spring and summer growing season.

The fertilization effect is less apparent in the Middle Columbia basin (Figure 6b), $<$1 mm in all months. This region receives, on average, less precipitation than the Upper Ohio. The Pacific Northwest is sharply divided into a humid region west of the Cascade mountains and arid land to the east. The higher [CO_2] influences water yield by reducing plant demand for water, and the expected result is higher water yield. However, increased precipitation in arid regions may boost vegetative growth, causing a decline in water yield as the growing plant population consumes more water. The interaction of these two effects results in little measurable increase in water yield with enhanced CO_2 in the Pacific Northwest.

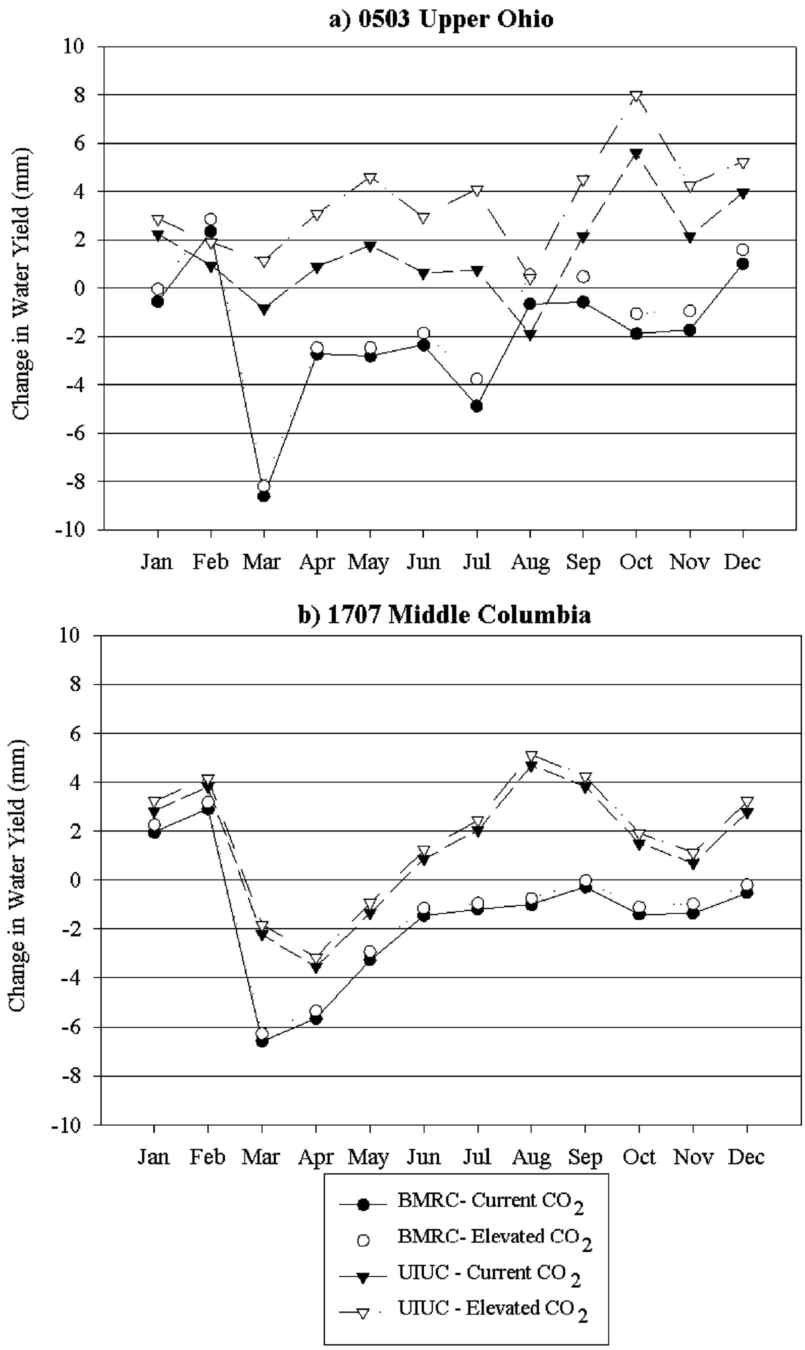

Figure 6. Seasonal water yield change from baseline for two GCMs with and without the CO_2-fertilization effect.

TABLE III

Coefficients of variation (CV) for interannual water yield in 8-digit basins representing each of the 18 Major Water Resource Regions (MWRRs) of the conterminous U.S.A.

GCM			Baseline	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S
GMT (°C)			0		1			1			2.5			2.5	
CO_2 (ppmv)			365		365			560			365			560	
HUA8	Basin	State	Coefficient of variation (CV)												
01060001	Presumpscot	ME	27.5	28.3	27.8	27.7	26.9	26.4	26.3	29.5	27.4	27.3	28.3	25.5	25.6
02050206	Susquehanna	PA	13.2	12.9	13.7	13.5	13.1	13.7	13.5	12.5	14.2	14.2	12.2	14.3	14.3
03060201	Ogeechee	GA	17.8	18.2	17.8	16.8	16.7	16.5	15.7	17.9	17.3	16.7	16.4	16.5	15.5
04030108	Menominee	MI	14.6	15.1	14.1	14.6	13.8	12.9	13.3	17.0	13.9	14.5	15.3	12.7	13.3
05090201	Ohio	OH	21.1	22.1	20.8	21.6	21.2	21.9	20.9	22.6	20.6	21.5	21.8	20.6	21.1
06040002	Duck	TN	21.5	21.9	21.8	21.6	21.8	19.7	21.6	22.8	22.4	22.3	22.7	22.4	22.2
07080103	Wapsipinicon	IA	33.1	33.4	32.5	34.3	32.2	31.5	32.9	34.0	31.5	34.8	32.2	31.5	33.4
08030207	Sunflower	MS	33.6	35.5	33.5	33.6	34.2	32.7	32.8	39.6	32.9	34.0	38.1	32.9	33.3
09020309	Snake	MN	53.3	56.9	50.7	49.9	56.0	51.7	49.7	64.5	50.1	51.5	64.1	50.1	51.3
10140201	White	NE	41.7	42.8	39.6	40.1	42.7	39.4	39.8	46.2	38.0	38.8	45.4	37.3	38.6
11060006	Black	OK	71.1	79.1	59.3	58.7	75.1	56.3	55.7	86.8	48.9	49.6	84.9	47.4	47.6
12090202	Llano	TX	37.1	39.6	30.1	30.3	39.1	29.7	29.9	43.7	25.4	25.3	43.3	25.3	25.4
13050003	Tularosa	NM	77.0	91.4	80.1	77.8	90.3	79.3	76.7	124.4	84.3	80.5	124.4	83.1	79.0
14060006	Willow	UT	95.0	106.5	86.7	76.9	106.7	85.8	75.5	139.6	68.7	51.9	139.6	64.2	50.2
15070102	Agua Fria	AZ	74.5	84.2	66.9	61.0	83.2	66.1	60.0	106.0	54.9	50.2	106.0	54.5	49.7
16060006	Little Smoky	NV	66.1	79.8	65.4	64.8	78.8	64.5	64.2	109.6	71.2	70.3	109.6	70.3	70.4
17030001	Yakima	WA	29.0	28.0	26.1	26.4	27.8	26.0	26.3	31.6	27.0	26.5	31.6	26.5	26.2
18040012	Mokelumne	CA	40.1	41.9	40.4	39.4	41.6	40.2	39.1	43.6	39.5	38.5	43.6	39.5	38.4

3.3. INTERANNUAL VARIABILITY IN WATER YIELD

To assess the effects of the climate change scenarios on variability of water yield (WY) we calculated the coefficients of variation (CV) for selected 8-digit basins in each of the 18 MWRRs, simulated over 30 yr (Table III). Interannual WY variability is greatest under baseline conditions in the West, particularly in the Upper and Lower Colorado, the Rio Grande, and the Arkansas-White-Red MWRRs. Water yields are least variable in the East, the Mid-Atlantic, the South Atlantic-Gulf and the Great Lakes. Climate change does not greatly alter the relative variability in basin water yield. But variability does change within the individual basins. As with precipitation and water yield, changes increase in magnitude with increased GMT. CO_2-fertilization decreases variability within each level of GMT.

In general, changes in variability of WY are small, but trends under the climate change scenarios are evident. CV increases slightly under BMRC scenarios with declining water yields and decreases under UIUC scenarios as water yields increase. CV increases under UIUC + Sulfate in Eastern basins while it declines in Western regions with their high baseline CVs. The Mid-Atlantic region is the exception with declining variability under the BMRC scenarios but increasing variability with the UIUC scenarios. The low variability in water yields in the Tennessee region is increased slightly under UIUC as well as under BMRC, indicating that the stability of water flow in this humid region is not at great risk of becoming more variable. By contrast, CV in the Pacific Northwest region declines under almost all scenarios except when severe drying occurs under BMRC at GMT = $+2.5\,^{\circ}$C.

The changing variability under these scenarios indicates that if conditions become dryer, as they do under BMRC, variability may increase, whereas if water yield increases, as under UIUC, variability may decline. This trend is consistent with historical observations in hydrology in which interannual variability is greatest in the most arid regions.

4. Conclusions

The hydrology of the conterminous U.S. will likely change with global climate change but, because of differences projected by the GCMs, we have used to drive the HUMUS model, our simulations disagree as to whether the U.S. will experience shortfalls or surpluses of water and which regions will be most strongly affected. Currently, semi-arid regions, primarily in the western U.S., will be the first to experience notable changes in regional hydrology. The magnitude of changes in water yield, runoff and evapotranspiration is much greater, often exceeding $\pm 50\%$ of baseline levels in regions where water is currently in short supply. Although the impact of these changes will greatly depend on their timing and duration, changes of this magnitude may require substantial adaptation by water resource managers to cope with increased severity and duration of droughts and/or floods.

In the humid regions of the country, the scenarios suggest less dramatic, but nonetheless significant, changes in both the short and long term (GMT = +1.0 and +2.5 °C). In addition, interannual variability in the water supply will also change slightly, most significantly in arid western regions. If a drying such as is predicted in many BMRC scenarios does occur, variability is likely to increase. If water yields increase as projected by the HUMUS simulations driven by UIUC scenarios, variability may decline. Because of the considerable uncertainty about the sign and size of changes in water supplies, it is important for water resource management to be flexible and adaptable. Traditionally, water resource management has relied on the historic record to project the frequency of severe water supply anomalies. The kinds of changes described in this paper suggest the need to plan for more events outside the range of past experience.

In this analysis of water resources, we have assumed natural streamflow and have not considered withdrawals of water for human uses, changing demand or competition between uses. In Part 5, we will examine the sufficiency of these future water supplies in the U.S. for irrigated agriculture, the major consumptive user of freshwater. This analysis should help determine whether changes in water resources will require substantial changes be made in agricultural production practices in the U.S.

Acknowledgements

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 5. IRRIGATED AGRICULTURE AND NATIONAL GRAIN CROP PRODUCTION

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Abstract. During this century global warming will lead to changes in global weather and climate, affecting many aspects of our environment. Agriculture is the sector of the United States economy most likely to be directly impacted by climatic changes. We have examined potential changes in dryland agriculture (Part 3) and in water resources necessary for crop production (Part 4) in response to a set of climate change scenarios. In this paper we assess to what extent, under these same scenarios, water supplies will be sufficient to meet the irrigation requirement of major grain crops in the US. In addition, we assess the overall impacts of changes in water supply on national grain production. We apply the 12 climate change scenarios described in Part 1 to the water resources and crop growth simulation models described in Part 2 for the conterminous United States. Drawing on data from Parts 3 and 4 we calculate what the aggregate national production would be in those regions in which grain crops are currently produced by applying irrigation where needed and water supplies allow. The total amount of irrigation water applied to crops declines under all climate change scenarios employed in this study. Under certain of the scenarios and in particular regions, precipitation decreases so much that water supplies are too limited; in other regions precipitation becomes so plentiful that little value is derived from irrigation. Nationwide grain crop production is greater when irrigation is applied as needed. Under irrigation, less corn and soybeans are produced under most of the climate change scenarios than is produced under baseline climate conditions. Winter wheat production under irrigation responds significantly to elevated atmospheric carbon dioxide concentrations [CO_2] and appears likely to increase under climate change.

1. Introduction

Expansion of irrigation has enabled dramatic increases in global crop production over the past half-century. The area of irrigated cropland has doubled in that time to cover 17% of the world's total farm land. Irrigated agriculture now produces a third of the world's food supply. Irrigation accounts for the largest consumptive use of freshwater in the United States where 20 million hectares (18%) of cropland is irrigated (Howell, 2001; USDA NASS, 1997). Of the 18 major water resource

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regions (MWRRs) in the US, the freshwater withdrawals for irrigation are greatest in California, the Pacific Northwest and the Missouri River basins.

As the atmosphere warms in response to increasing concentrations of atmospheric greenhouse gases, precipitation patterns will change with consequences for the supply of water for irrigation. The need for irrigation may also change. Demand may be reduced in some areas but it is equally likely that water shortage will reduce crop production in others. Where freshwater supplies become scarce and, concomitantly, irrigation demands rise, water resource managers will face potentially difficult situations. Groundwater resources used for irrigation are not specifically addressed in this paper, but it is obvious that any long-term change in precipitation will necessarily affect groundwater recharge. The direction and magnitude of climate change impacts on water resources remain uncertain and will vary by region (Part 4).

Increased atmospheric carbon dioxide concentration ([CO_2]) will directly impact crop growth by increasing photosynthesis, reducing stomatal conductance and, hence, plant transpiration, phenomena collectively termed the 'CO_2-fertilization effect'. Water use efficiency, the ratio of photosynthetic production to evapotranspiration (water use) is, thus, also improved by CO_2-fertilization. This effect has been well documented in laboratory and field studies, but its potential impact on national agricultural production is still a matter of conjecture. Reduced transpiration rates will reduce plant water stress and may, thereby, reduce the amounts of irrigation water needed by crops. Pospisilova and Catsky (1999) suggest that increased water use efficiency may lead to improved drought resistance. In addition, the reduction in photosynthesis due to water stress is relatively less severe with CO_2 fertilization (Grant et al., 1999). Not all effects of CO_2-fertilization are beneficial. Although increased water use efficiency with higher [CO_2]-increased yields of irrigated potato crops in a semi-arid region physiological changes caused the crop to be nutrient poor with a low nitrogen content (Ramirez and Finnerty, 1996).

Changes in temperature and precipitation regimes will prompt farmers to change crops, cultivars and management practices, including irrigation, in order to mitigate adverse effects or take advantage of newly favorable conditions. Higher temperatures and reduced precipitation could substantially increase crop water demand in some areas and prompt the development of irrigation in regions previously devoted to dryland cropping (Peterson and Keller, 1990). In a study of crop response to GCM-projected climate change with doubled atmospheric CO_2 concentrations, Tung and Douglas (1998) found that the adverse effects of higher evapotranspiration outweighed the beneficial effects of CO_2-fertilization in some areas of the US and suggested that irrigation might alleviate some of the adverse effects. In another simulation study of CO_2 induced climatic changes, Allen et al. (1991) found increased evaporative demand and irrigation water requirement for alfalfa, winter wheat and corn in the Great Plains due to higher temperatures and changes in precipitation patterns. In yet another study of climate change impacts, crop production and irrigation requirement were simulated under several climate scenarios for a selection of US counties (Peterson and Keller, 1990). The percentage of cropland irrigated in the western US was found to increase when global mean temperature was increased by 3°C, and a decline in production resulted from inadequate water for irrigation.

Using a suite of GCM-derived scenarios of climate change, Strzepek et al. (1999) modeled water supply and demand for crop irrigation in the US Corn Belt with climate change. They found that, in climate change situations involving increases in precipitation, dryland farmers need not invest in irrigation, but rather that water logging becomes a concern in the spring. They concluded that the relative abundance of water for US agriculture can be maintained in the short term. Climate change impacts will not necessarily be continuous and monotonic, they note, and surprises and non-linearities may occur for which current management practices are inadequate. Progressively greater changes in agricultural production and practices as a result of climate change impacts are expected by 2050 and beyond. The latter finding of Strzepek et al. (1999) is consistent with recent assessments of climate change which project that US agricultural production will likely be maintained over the next 50–100 years (Reilly et al., 2001; Reilly et al., 1996; IPCC, 2001).

In Parts 3 and 4 of this series we addressed potential changes in dryland crop production and water resources in the United States under 12 climate change scenarios. Here, we couple the results of those analyses with additional EPIC simulations of irrigated grain crop production to assess potential future demands for irrigation water and the adequacy of water supplies to meet these demands. We focus this part of the analysis on current US corn, soybean and winter wheat production areas (Figure 1). Our purpose is to examine the extent to which crop water demand will change with large scale changes in climatic patterns with and without the interacting effects of CO_2-fertilization, and whether changes in freshwater supplies will allow demands for irrigation to be met.

2. Methods

2.1. SIMULATION MODELS

The scenarios used in this study consist of a baseline climate taken from a 30-year historical record of daily weather and 12 scenarios of climate change (Part 1, Table I). Climate change was simulated with each of the Global Climate Models (GCM)—Australian Bureau of Meteorology Research Center (BMRC), University of Illinois at Urbana Champagne (UIUC) and UIUC with sulfate aerosol forcing (UIUC +Sulfates) at two levels of Global Mean Temperature increase (GMT = +1 and +2.5°C) and two levels of a CO_2-fertilization effect consistent with an atmospheric CO_2 concentrations, near present day (365 ppmv) and double the pre-industrial level (560 ppmv).

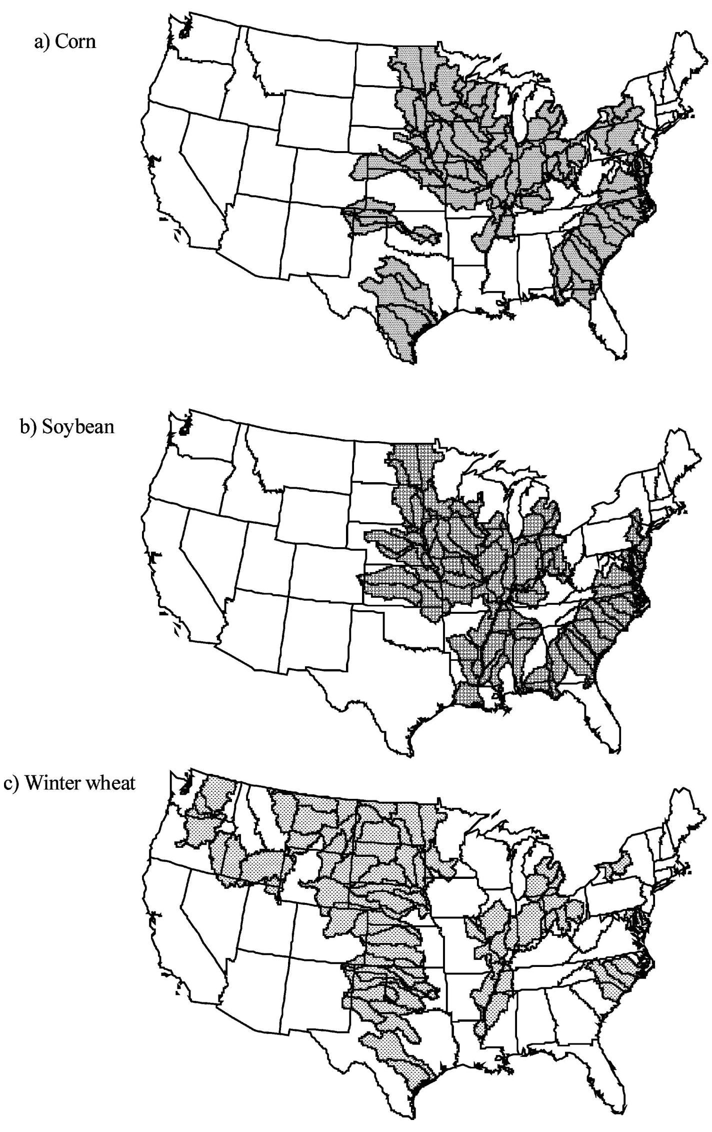

Figure 1. Outline of the current US growing regions for corn, soybean and winter wheat with the four-digit EPIC simulation regions delineated.

Simulations of climate change impacts were made with the Hydrologic Unit Model of the United States (HUMUS) (Arnold et al., 1999; Srinivasan et al., 1993) and the Erosion Productivity Impact Calculator (EPIC) (Williams, 1995). Both models are run on a daily time step with inputs of maximum and minimum temperature, precipitation, radiation, humidity and wind speed. The models are fully described and validated in Part 2 of this series. HUMUS was used to simulate runoff (Q), water yield (surface flow + groundwater flow + lateral flow − loss from

TABLE I
Total national production of corn, soybean and winter wheat in millions of Mg and percent change from baseline under 12 climate change scenarios

GMT° C	CO_2 ppmv	BMRC Mg × 10^6	BMRC % change	UIUC Mg × 10^6	UIUC % change	USUL Mg × 10^6	USUL % change
Corn [Baseline = 807]							
1	365	763	−5	770	−5	768	−5
1	560	825	2	826	2	823	2
2.5	365	700	−13	725	−10	719	−11
2.5	560	758	−6	778	−4	771	−4
Soybean [Baseline = 250]							
1	365	229	−8	231	−8	231	−8
1	560	266	6	267	7	267	7
2.5	365	188	−25	200	−20	199	−20
2.5	560	223	−11	233	−7	231	−8
Wheat [Baseline = 421]							
1	365	408	−3	403	−4	398	−5
1	560	486	15	475	13	470	12
2.5	365	410	−3	389	−8	376	−11
2.5	560	487	16	459	9	443	5

evapotranspiration), and other hydrologic parameters for 2101 8-digit watersheds in the conterminous United States (Figure 2).

The term 'water yield' is used here as a surrogate for natural streamflow which we treat as the water supply for purposes of irrigation. We do not attempt to account for actual water management practices such as impoundments, diversions, etc. EPIC uses the same climate change scenarios as well as soil, landscape and crop management data to simulate dryland and irrigated grain crop yields, crop irrigation demand and evapotranspiration. The land unit employed with EPIC is the 4-digit hydrologic basin of which there are 204 in the conterminous US (Figure 2). One farm represents each 4-digit basin. Here, we use the water yield variable from HUMUS to determine how much water would be available to irrigate corn, soybeans and winter wheat in their current primary growing regions (Figure 1) under each of the 13 scenarios.

2.2. IRRIGATION MANAGEMENT IN EPIC

The amount of irrigation water applied to each crop was simulated by the EPIC model. Under the assumption that the needed water is available, the simulations apply irrigation in the amount demanded periodically throughout the growing season. Irrigation is triggered by plant water stress, soil water tension, and moisture deficits

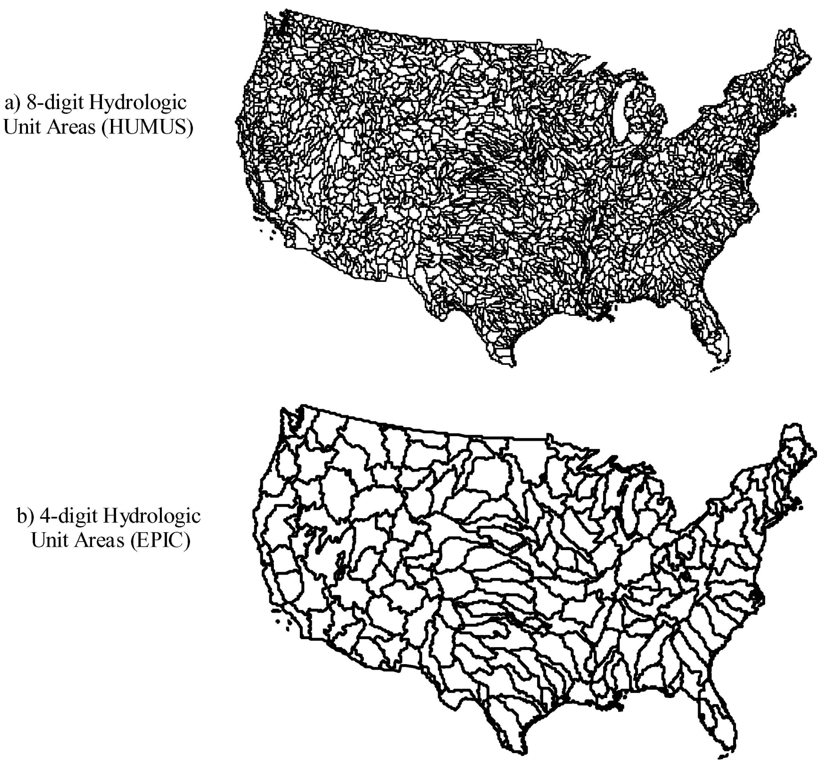

Figure 2. Modeling units used for the EPIC (4-digit basin) and HUMUS (8-digit basin) simulations taken from the USGS (1997) characterization of US watersheds.

in the soil root zone. Irrigation water is applied to the extent necessary to refill the soil reservoir and relieve water stress. This approach allowed us to determine the optimum amount of water for each crop in each location under each of the climate change scenarios. Thereafter, we identify the regions where water supplies are adequate or insufficient to meet demand.

2.3. DETERMINING CROP IRRIGATION DEMAND AND ADEQUACY OF THE WATER SUPPLY

EPIC was used to simulate both dryland and irrigated yields of the three grain crops in the 204 4-digit hydrologic unit areas, or watersheds, as defined by the US Geological Survey (USGS, 1987). We assumed that crops would be irrigated if irrigated yields exceeded dryland yields. We obtained data on total and agricultural land area in each of the 4-digit basins. Dryland production (P_D) was calculated by multiplying the yield (Mg ha^{-1}) by the agricultural land area of the region (ha). To calculate irrigated production (P_I), we had first to determine from the results of the HUMUS model runs whether water is available for irrigation.

We calculated the irrigation demand (I_D) for a region as [irrigation × agricultural land area]. The water yield from HUMUS was aggregated from the 8-digit to the 4-digit basin scale to be compatible with the EPIC simulations (Figure 2). Irrigation water supply (I_S) is equated here with the total annual water yield, [WY × total land area], calculated for each 4-digit basin. In regions where $I_S > I_D$, P_I was calculated as [crop yield × agricultural land area]. Where $I_D > I_S$, P_I was calculated by assuming irrigation of as much land as water supply permits. The remaining agricultural land in the region was assumed to be in dryland production (P_D). We then calculated the water remaining for other purposes after full irrigation. Finally, we calculated the agricultural land area that could not be irrigated due to insufficient water supply under each scenario ($I_D > I_S$), multiplying it by dryland yield per unit of land area.

For the purposes of this study, we assumed that all water within a given 4-digit basin would be available for irrigation and that no water would cross watershed boundaries. In reality, there are many competing demands for water resources, especially in drier regions where irrigation is generally needed most, and water is often transported to meet those demands.

3. Results and Discussion

3.1. WATER SUPPLY AND IRRIGATION DEMAND

Another innovation of this study is the use of crop yield, an economic measure, to define the location and amount of land that can be irrigated. For each of the three grain crops, change in total available water simulated with HUMUS, total irrigation per unit land area applied with EPIC simulations, area of land that can be profitably irrigated, and amount of water remaining after irrigation (WY-irrigation) are shown in Figures 3–5 for the 12 climate change scenarios. These figures give an indication of what each climate change scenario projects will be the accessible water supply for each major crop in its current growing region and to what extent climate change will affect irrigated crop yields and the amounts of water remaining for non-agricultural uses.

The changes in water yield (supply) for irrigation of the US corn crop are shown in Figure 3. With the BMRC model (Figure 3a), water yield over the entire regions shows a net decline with respect to that under the baseline climate under both GMTs and CO_2 concentrations. The situation is worsened by increased GMT and moderated by elevated [CO_2]. As a consequence of reduced precipitation, the amount of land that can be irrigated also declines under all BMRC scenarios. For instance, over the entire growing region irrigated acreage is smallest under the scenario GMT = +2.5°C and [CO_2] = 365 ppmv, because supplies (water yield) are most sharply reduced in this case. Under BMRC scenarios, crops demand irrigation in areas previously under dryland production, increasing the total amount of irrigation water demanded in the growing region. The decline in precipitation, and

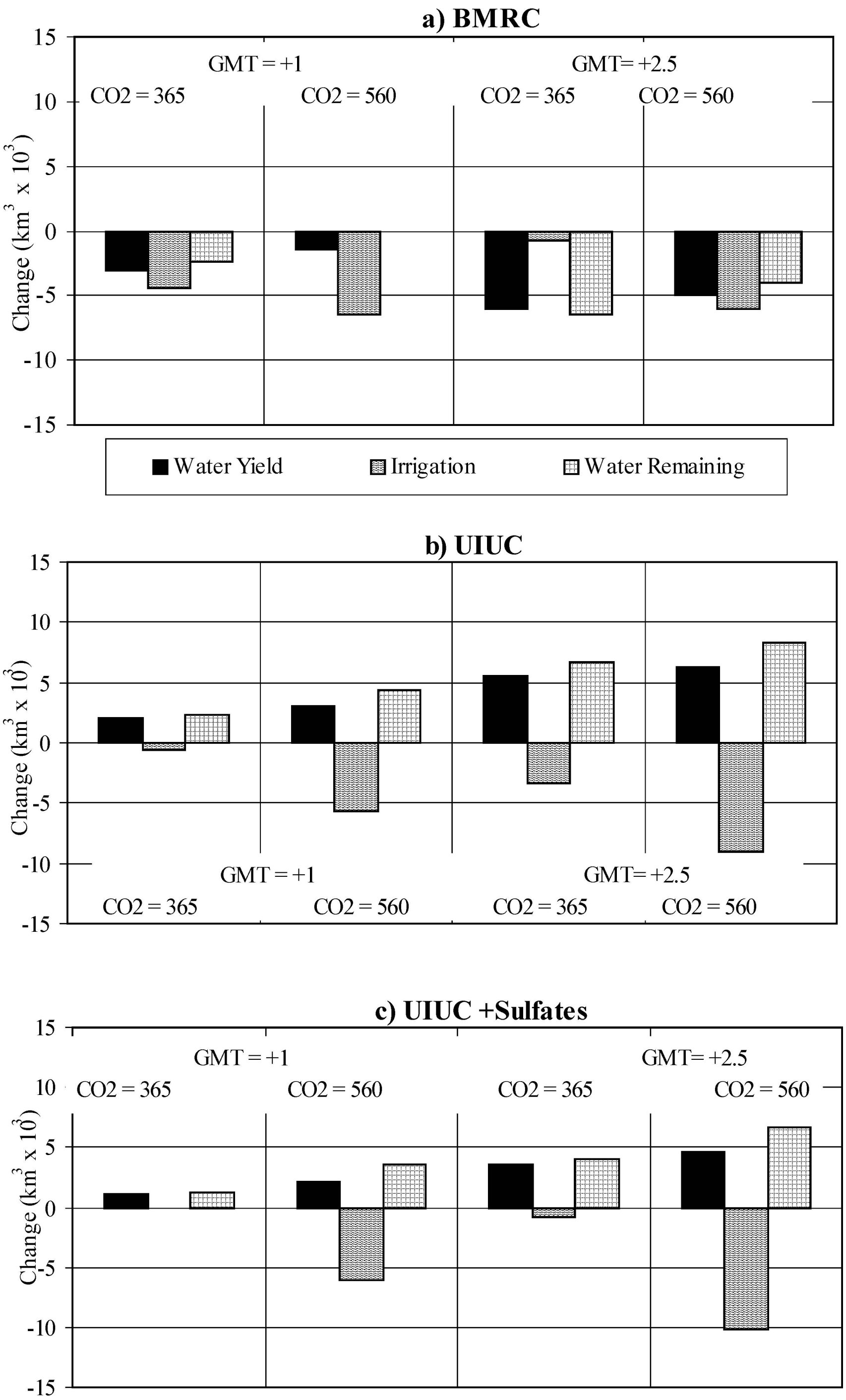

Figure 3. Change in water yield, irrigation water consumed by the crop and water remaining for other uses after irrigation demand is fully met (WY-IRR) in the corn production region.

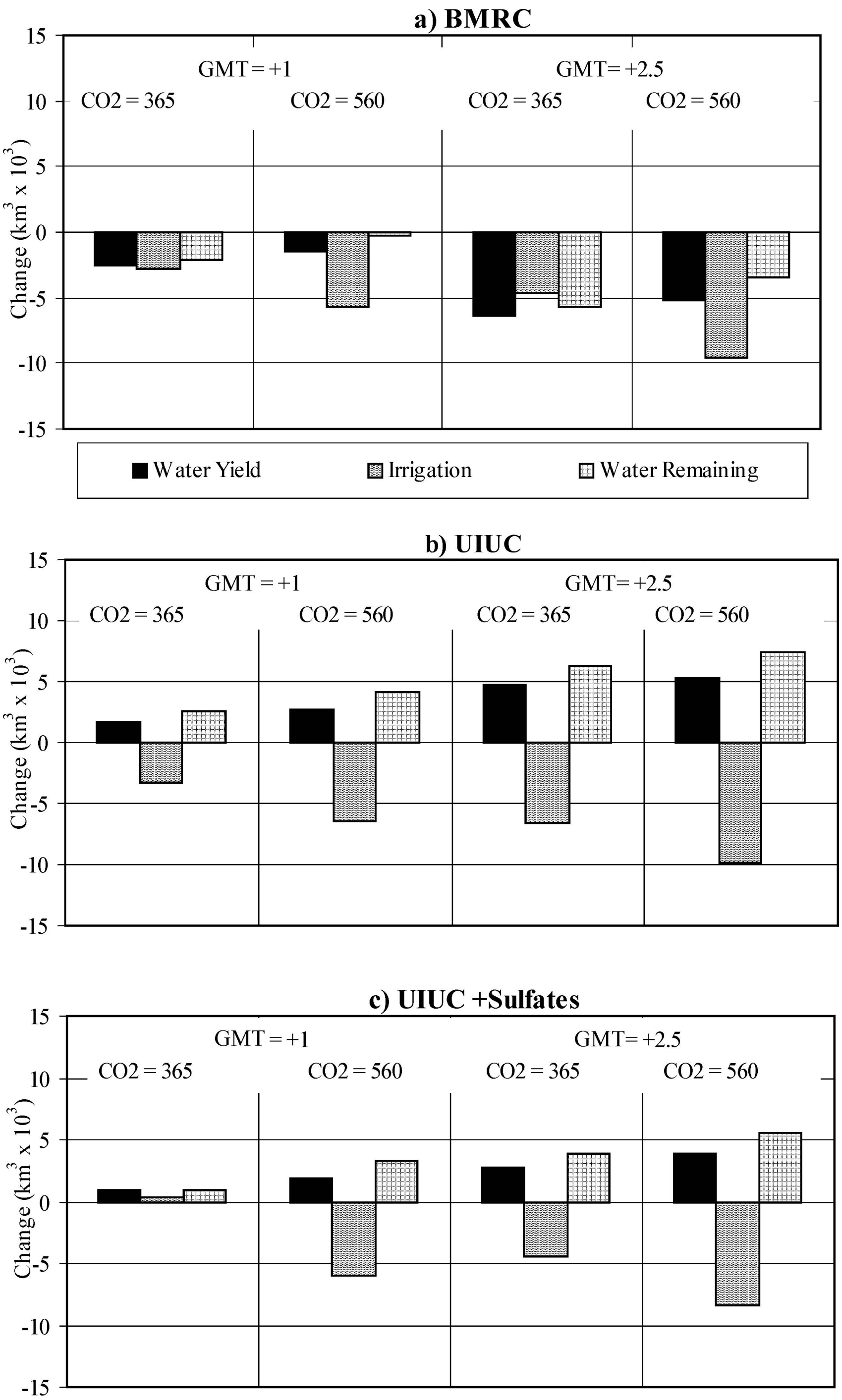

Figure 4. Change in water yield, irrigation water consumed by the crop and water remaining for other uses after irrigation demand is fully met (WY-IRR) in the soybean production region.

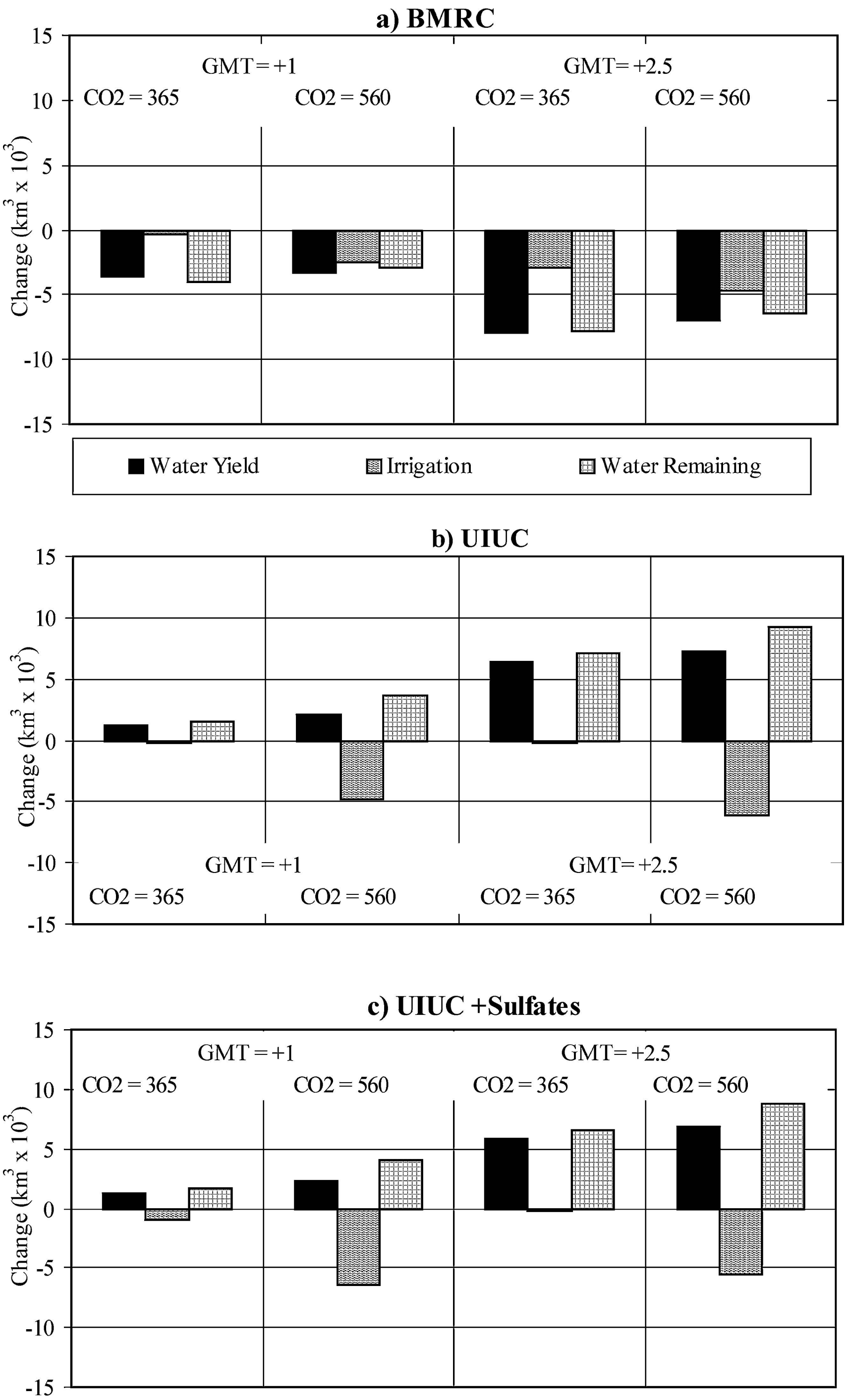

Figure 5. Change in water yield, irrigation water consumed by the crop and water remaining for other uses after irrigation demand is fully met (WY-IRR) in the winter wheat production region.

therefore decline in water supply for irrigation, under BMRC reduces the amount of irrigation water actually applied to crops to less than baseline levels under all scenarios. Under the BMRC scenarios where $[CO_2] = 560$ ppmv, irrigated land area declines as water demand declines. This decrease in crop water demand results in a lesser decline, with respect to baseline, in water remaining after irrigation withdrawals. The decline in water remaining is greater with CO_2 fertilization at higher GMT, indicating that with this simulation, the positive water use efficiency effects of elevated CO_2 have a lesser impact than temperature change at GMT = +2.5°C.

Under UIUC (Figure 3b), water yield increases substantially from baseline for all scenarios. The increase in water yield is greater with increasing GMT and with elevated $[CO_2]$. Because of the increased precipitation, irrigation demands decline and the amount of water available after irrigation increases. The same patterns hold for UIUC + Sulfates (Figure 3c), but the effects are smaller as sulfates moderate the increases in both temperature and precipitation under UIUC. The decline in irrigation is greater with enhanced $[CO_2]$, reflecting improved crop water use efficiency and reduced water consumption.

Changes in water yield and irrigation follow the same basic patterns for soybean (Figure 4). Whereas water yields decline under BMRC, they increase under UIUC. Irrigation water applied to crops declines under all scenarios either because of a reduced supply (BMRC) or reduced demand (UIUC). The similarity in response is expected as the growing regions for corn and soybean are substantially the same (Figure 1).

The production regions for winter wheat are different from that for corn and soybeans, but the trends in water yield and irrigation are similar (Figure 5). Water yield declines under BMRC and increases under UIUC, both trends resulting in reduced irrigation. The decline in irrigation is smaller under UIUC even as water yield increases substantially. This indicates that even with a much wetter climate, irrigation will still be beneficial to winter wheat. A portion of the growing region is arid land where increases in precipitation would not completely eliminate crop water stress and the need for irrigation.

3.2. NATIONAL PRODUCTION

3.2.1. *Total national grain crop production*

The percentage change in total national production of the three grain crops is shown in Figure 6 while the actual production numbers are presented in Table I. Corn production declines under all three GCMs at GMT = +1°C without CO_2 fertilization and regardless of CO_2 fertilization when GMT = +2.5°C. The greatest declines in corn production occur under the dry BMRC scenarios. The UIUC model with sulfates predicts a greater loss of production than without sulfates. Increases in corn production occur only under the most benign scenario, GMT = +1°C with CO_2-fertilization. The changes are all within ±10% of baseline except for the BMRC model with the most severe climate change scenario modeled here.

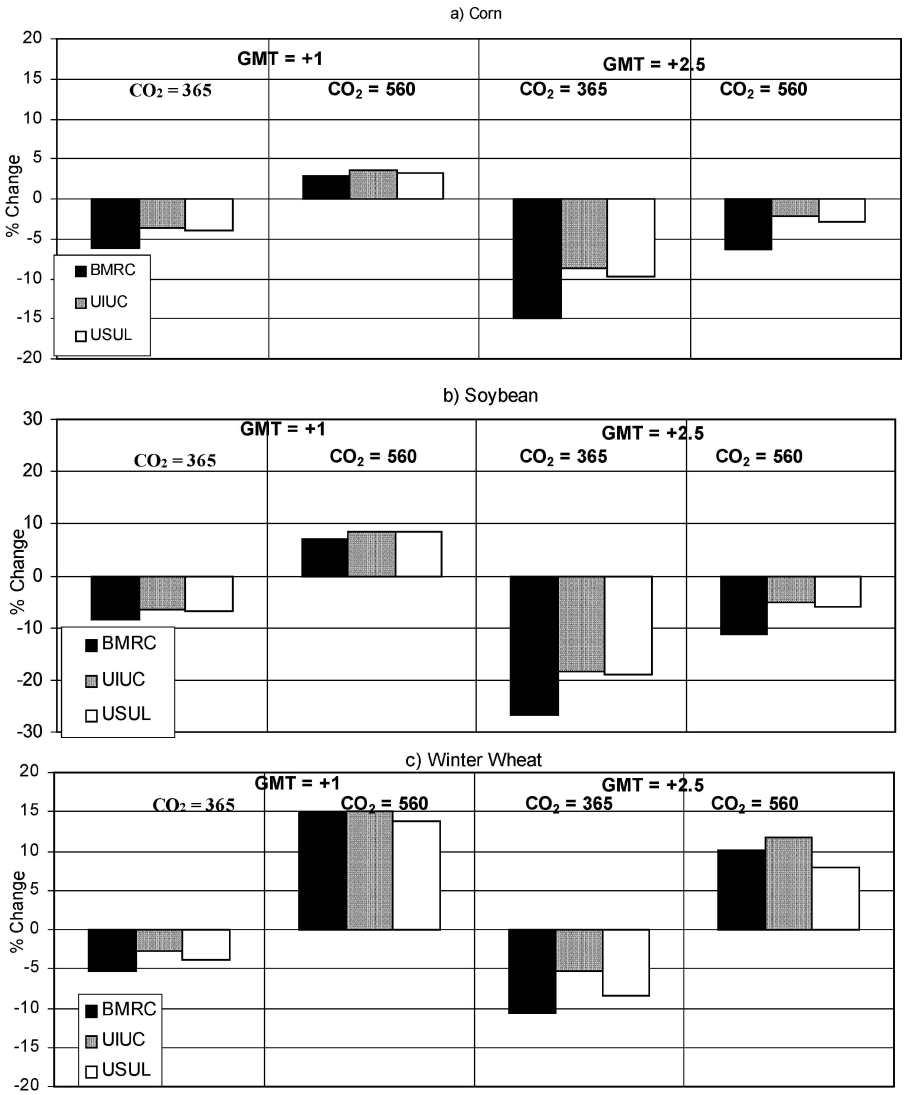

Figure 6. Percentage change in the total national production of grain crops when irrigation is applied to the extent that water is available and irrigation benefits the crop.

The same pattern occurs for changes in soybean production, although the magnitude of the change is greater, about 25% under BMRC where GMT = +2.5°C and $[CO_2]$ = 365 ppmv. Soybean production is adversely affected by the increase in GMT, especially under BMRC where higher temperatures combine with reduced availability of water.

Winter wheat production shows a consistent response to elevated atmospheric CO_2, increasing even where GMT = +2.5°C. Where they occur, production losses are smaller for winter wheat than for corn or soybean and production gains are greater. Differences in crop response to the climate change scenarios are influenced by the regional distributions of climate change as they occur in the different growing regions.

Production of all three crops responds strongly to the changes in climate simulated in the various GCM × GMT × [CO_2]-fertilization scenarios. The GCMs affect the magnitude of the changes in production but not their sign. For corn and soybean production, climate change will most likely result in decreased irrigated production even under conditions of greater water availability. In contrast, winter wheat production responds positively and significantly to elevated [CO_2], indicating that irrigated production will likely increase with climate change.

3.2.2. *Irrigated versus dryland production*

Irrigating the three grain crops where irrigated yields exceed dryland yields resulted in higher overall national production under all climate change scenarios (Figure 7). The results discussed in Section 3.3.1 are represented in the solid bar, showing production where the supply of water for irrigation is limited by the water yield in the region. The striped bar represents the optimal production, that which would occur if all crops were irrigated to meet their full demand for water, constraints on its availability notwithstanding.

For corn, baseline production would be 40 million Mg higher with a constrained supply of irrigation water. That number increases by another 10 million Mg were the supply of irrigation water unlimited. The impacts of irrigation on production under climate change are greatest under BMRC and smallest under UIUC. The improvement is least with CO_2 fertilization and with the UIUC scenarios that predict increased precipitation. Both effects reduce irrigation demand. The increase when water is unlimited is greatest under the BMRC scenarios because water supply is most seriously constrained with this GCM. All UIUC scenarios also show increases in production when water is unlimited, except under the GMT $= +2.5$°C and [CO_2] $= 560$ ppmv scenarios where there is sufficient water for irrigation even under the constrained conditions due to increased precipitation and irrigation demand. is, consequently, decreased.

Results are similar for soybean production, with the exception of a relatively greater response when water supply to the crop is unlimited under the UIUC scenarios at GMT $= +2.5$°C and [CO_2] $= 560$ ppmv. The improvement with irrigation is slightly less with CO_2-fertilization, which boosts dryland as well as irrigated production. Under UIUC + Sulfate, improvements in crop production with restricted and unrestricted irrigation are greater than under UIUC.

Improvements are greatest for winter wheat where production increases by 20–40 million Mg with constrained irrigation and up to 90 million Mg with unlimited irrigation. The greatest improvements occur under BMRC while the UIUC and UIUC + Sulfate models show a similar pattern of improvements in production.

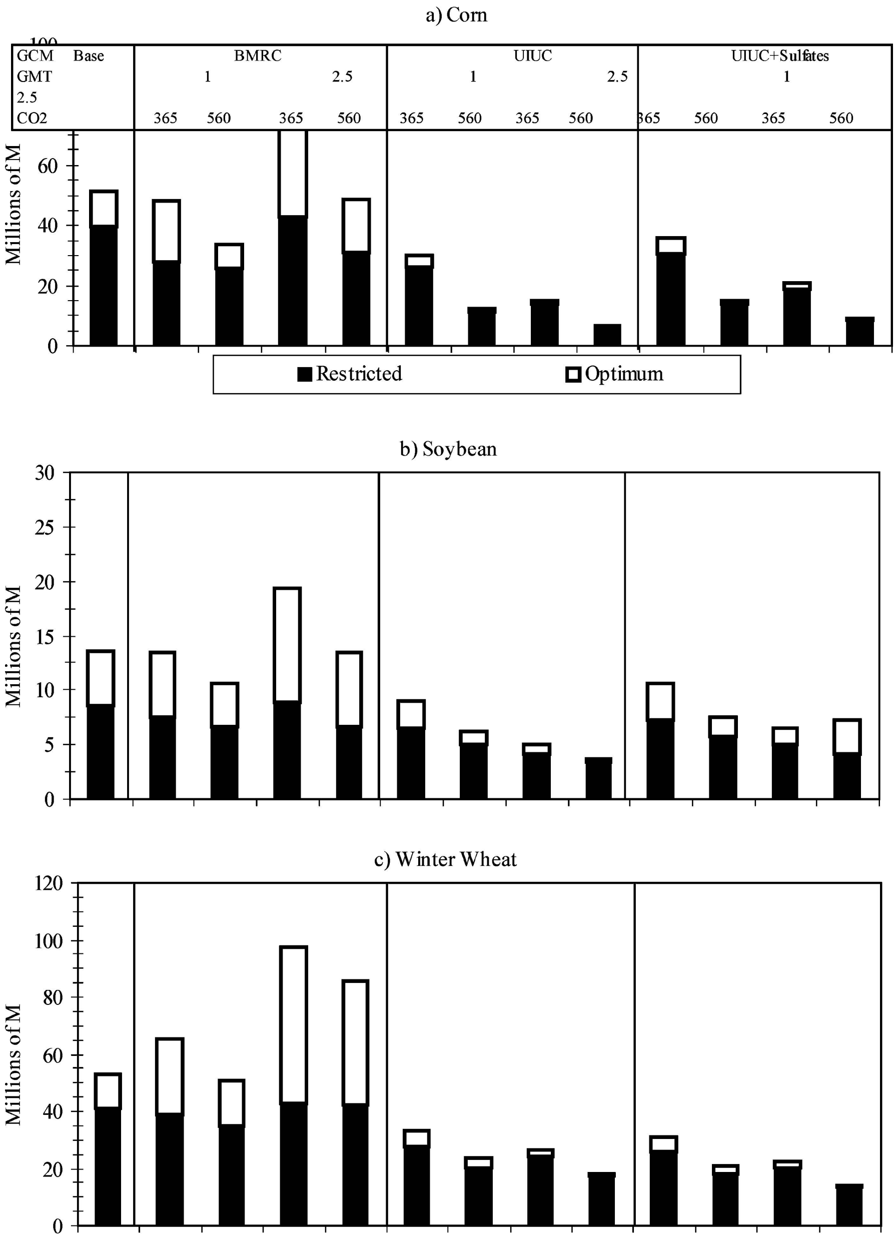

Figure 7. Change in simulated total national dryland grain crop production in response to optimum and restricted irrigation under climate change scenario forcing.

Production with unlimited irrigation under the BMRC scenarios at GMT = 2.5°C is more than twice that achieved under constrained irrigation, indicating that water is severely limiting to the potential wheat production in these scenarios. In contrast, the elimination of restrictions on water supply under the UIUC models improves production only slightly because water yield is sufficiently abundant under these scenarios to irrigate crops almost to the full extent of irrigation demand.

3.2.3. *Change in area of irrigated crop land*

In the simulations reported above and under all climate change scenarios, crops were irrigated when demand required and water was available. The amount of land capable of producing irrigated crops changes with climate change scenarios. Under BMRC, the land area under unlimited irrigation declines for all three crops by from 2–18 million ha (Table II). There is a slight increase in potentially irrigable land at GMT = +1°C and $[CO_2]$ = 560 ppmv for corn and soybean production.

The UIUC climate change scenarios can potentially increase the area of irrigable land by from 2–13 million ha. The area irrigated is greatest at the higher GMT and with CO_2 fertilization. Under UIUC +Sulfates, the potential land area irrigated again increases for all crops, but the increase is smaller than under UIUC because the climate changes predicted under the former are smaller. The increases range from <1 to 13 million ha, with winter wheat showing the greatest potential for increase and soybean the smallest.

TABLE II
Change in area of land for which water supplies allow unlimited irrigation

		(Millions of Ha)		
GMT (° C)	CO_2 (ppmv)	BMRC	UIUC	UIUC + Sulfates
Corn				
1	365	−2.22	3.66	2.11
1	560	2.25	8.27	7.14
2.5	365	−6.79	8.26	5.43
2.5	560	−2.44	10.04	9.26
Soybean				
1	365	−2.03	2.05	0.78
1	560	0.95	6.32	3.88
2.5	365	−4.19	6.40	4.07
2.5	560	−2.17	8.98	6.89
Winter wheat				
1	365	−10.75	8.19	7.89
1	560	−2.72	11.53	11.40
2.5	365	−18.22	12.40	10.58
2.5	560	−12.42	13.91	13.68

A negative change indicates a reduced capacity for irrigation primarily due to water supply shortage.

4. Conclusions

Land area for irrigation of corn, soybean and winter wheat decline under all scenarios of climate change considered in this study. In the case of the UIUC scenarios, the need for irrigation is diminished because precipitation becomes more plentiful. Were the UIUC futures to play out land managers would be more concerned with strategies to reduce water logging and flood damage to their crops. With the BMRC scenarios, irrigation declines because of lost water yields. In such a situation agriculture might be doubly disadvantaged as sectors other than agriculture compete for shares of the diminished supplies. Under most UIUC climate change scenarios, especially those with elevated CO_2 in which demand for irrigation water declines, enough will be available to irrigate the three grain crops to their fullest demand. If climate change results in a drying like that predicted by BMRC, then water for irrigation will be in short supply, and conflicts among competing uses of water would likely surface.

Adaptations to the impacts of climate change have not been considered in this study. In actuality, when faced with changes in temperature regimes and precipitation patterns, farmers will adapt their crop production methods, making use of different cultivars or crops better suited to the changes. Improved efficiencies in irrigation application and timing could also reduce the amount of water used in agriculture.

Our focus in this methodological study has been on total national production of key grain crops and to provide projections for use in integrated assessments of climate change. The regional changes in crop production and irrigation needs will necessarily be more complex than represented here as seasonal changes in water yield and local conflicting demands for water are considered.

Acknowledgements

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 6. DISTRIBUTION AND PRODUCTIVITY OF UNMANAGED ECOSYSTEMS

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Abstract. Human activities have altered the distribution and quality of terrestrial ecosystems. Future demands for goods and services from terrestrial ecosystems will occur in a world experiencing human-induced climate change. In this study, we characterize the range in response of unmanaged ecosystems in the conterminous U.S. to 12 climate change scenarios. We obtained this response by simulating the climatically induced shifts in net primary productivity and geographical distribution of major biomes in the conterminous U.S. with the BIOME 3 model. BIOME 3 captured well the potential distribution of major biomes across the U.S. under baseline (current) climate. BIOME 3 also reproduced the general trends of observed net primary production (NPP) acceptably. The NPP projections were reasonable for forests, but not for grasslands where the simulated values were always greater than those observed. Changes in NPP would be most severe under the BMRC climate change scenario in which severe changes in regional temperatures are projected. Under the UIUC and UIUC + Sulfate scenarios, NPP generally increases, especially in the West where increases in precipitation are projected to be greatest. A CO_2-fertilization effect either amplified increases or alleviated losses in modeled NPP. Changes in NPP were also associated with changes in the geographic distribution of major biomes. Temperate/boreal mixed forests would cover less land in the U.S. under most of the climate change scenarios examined. Conversely, the temperate conifer and temperate deciduous forests would increase in areal extent under the UIUC and UIUC + Sulfate scenarios. The Arid Shrubland/Steppe would spread significantly across the southwest U.S. under the BMRC scenario. A map overlay of the simulated regions that would lose or gain capacity to produce corn and wheat on top of the projected distribution of natural ecosystems under the BMRC and UIUC scenarios (Global mean temperature increase of $+2.5\,^{\circ}$C, no CO_2 effect) helped identify areas where natural and managed ecosystems could contract or expand. The methods and models employed here are useful in identifying; (a) the range in response of unmanaged ecosystem in the U.S. to climate change and (b) the areas of the country where, for a particular scenario of climate change, land cover changes would be most likely.

1. Introduction

During the last two centuries, more than at any time in the past, human activities have profoundly altered the distribution, quality and function of terrestrial ecosystems. Current estimates of land use and cover, for example, assign about one tenth of the total land surface of Earth (134×10^6 km^2) to croplands, a quarter to

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grasslands and savannas, and another quarter to forests. The remainder is occupied by wetlands, deserts, tundra and settlements (IPCC, 2000). Terrestrial ecosystems provide many goods and services from which humanity derives important benefits including food, fiber, medicines, and the cycling of energy, water and nutrients. However, human use of the land has often affected ecosystem quality negatively, by for example, accelerating wind and water erosion (Lal, 1995), encouraging desertification (Middleton and Thomas, 1997) and altering gas exchanges between land and the atmosphere (Houghton, 1999).

As the human population continues to grow in the 21st century so, too, will its need for the goods and services that terrestrial ecosystems provide. Furthermore, the growing demand will likely occur in a world in which the rising concentrations of atmospheric CO_2 ([CO_2]) and other greenhouse gases alter the climatic conditions to which existing ecosystems are adapted. These human-induced changes in climate might also affect the geographic distribution and productivity of unmanaged ecosystems as well as nutrient cycling and biodiversity. Thus, climate change of any kind that might occur during this century has to be analyzed within the context of increasing global populations and demand for land and in the context of how ecosystems respond to these changes.

In previous papers of this series, we established how, for a given set of climate change scenarios, the land areas devoted to production of the major crops could change. Lands, which lose the capacity to produce a given crop profitably – under either dryland or irrigated conditions – would be: a) used to produce other crops, b) planted to grasses and trees, or c) allowed to revert to native vegetation. This paper (Part 6 of the series) addresses these contingencies by applying the biophysical and biogeochemical model BIOME 3 (Haxeltine and Prentice, 1996) to simulate impacts of a set of climate change scenarios (described in Part 1) on the distribution and productivity of unmanaged ecosystems in the conterminous U.S. Changes in productivity are related to the changes in farm productivity, simulated with EPIC (Williams, 1995) for the major agricultural regions of the country (Parts 3 and 5), to estimate land cover change between agriculture and native vegetation. Since land use change involves national and global economic considerations as well as local agronomic factors, results of this analysis are integrated in the following paper (Part 7) through the analytical framework of the global change assessment model (GCAM) developed by Pacific Northwest National Laboratory (see Parts 1 and 7 for details).

2. Model Description, Model Validation and Scenarios

2.1. THE BIOME 3 MODEL AND ITS USES

As described by Haxeltine and Prentice (1996), BIOME 3 is a grid-cell model that predicts steady-state global natural vegetation patterns using a rule-based algorithm to determine plant functional types and by determining the leaf area index (LAI) that maximizes net primary productivity (NPP). BIOME 3 uses a minimal set of five woody and two grass plant functional types for large-scale (global) modeling. Optimal values of NPP for each plant functional type are used as competitive indices to determine plant dominance, except where grasses have been excluded. Quasi-empirical rules are used to capture the opposing effects of succession driven by light competition and natural disturbance by fire. These rules are such as to preclude ecological anomalies, for example, the dominance of grass-type vegetation under wet soil conditions (i.e., soil moisture > 75% of water holding capacity or when annual precipitation exceeds 2200 mm). BIOME 3 determines the distributions of plant functional types based on growing degree-days, mean temperature of the coldest and warmest month and the α-moisture index (Haxeltine and Prentice, 1996; Leemans and Van den Born, 1994; Leemans et al., 2001). Eighteen biome types can be predicted in BIOME 3 based on estimates of NPP, LAI, and plant functional types. Table 5 of Haxeltine and Prentice (1996) contains the classification scheme to assign model output to biomes.

Photosynthesis in BIOME 3 is a function of environmental variables and leaf parameters. The maximum rate of photosynthesis achievable under light-saturated conditions is regulated by the catalytic capacity of the rubisco enzyme and leaf N content. Environmental factors – such as atmospheric CO_2 concentration – influence photosynthesis, stomatal conductance and leaf area development. BIOME 3 runs mostly on a monthly time step and requires climate and soil data as input. Main model outputs by grid cell include: dominant and secondary plant functional types, LAI (m^2 m^{-2}), total NPP (g C m^{-2} yr^{-1}) and water balance components. Detailed descriptions of BIOME 3 can be found in Haxeltine (1996) and in Haxeltine and Prentice (1996). Many output variables can be extracted from BIOME 3 including dominant biome type, LAI, NPP, absorbed photosynthetic active radiation, respiration costs, soil moisture content, and runoff. In this paper, we discuss only BIOME 3 results for biome types and NPP variables. Information on the response of hydrological variables to climate change scenarios is derived from the HUMUS model (Arnold et al., 1999) and EPIC (Williams, 1995) results presented and discussed in Parts 3, 4 and 5.

The explicit linking of vegetation and climate patterns is an active field of research. For example, Jolly and Haxeltine (1997) used BIOME 3 to model glacial-interglacial climate changes in East Africa. The modeled response of vegetation to [CO_2] and climate appeared to have explained the replacement, as evidenced by the fossil record, of a tropical montane forest by a scrub biome. BIOME 1, a predecessor of BIOME 3, has also been used to estimate the distribution of biomes around 6,000 yr ago and to compare it against that inferred from paleo-vegetation data (Williams et al., 1998).

2.2. VALIDITY OF BIOME 3 IN THIS APPLICATION

Figure 1 compares the distribution of major biome types within the conterminous U.S. as modeled by BIOME 3 under current climate (baseline) with the natural biome distribution produced by Küchler (1964). There are similarities and differences between the two maps. There is visual coincidence in the distribution

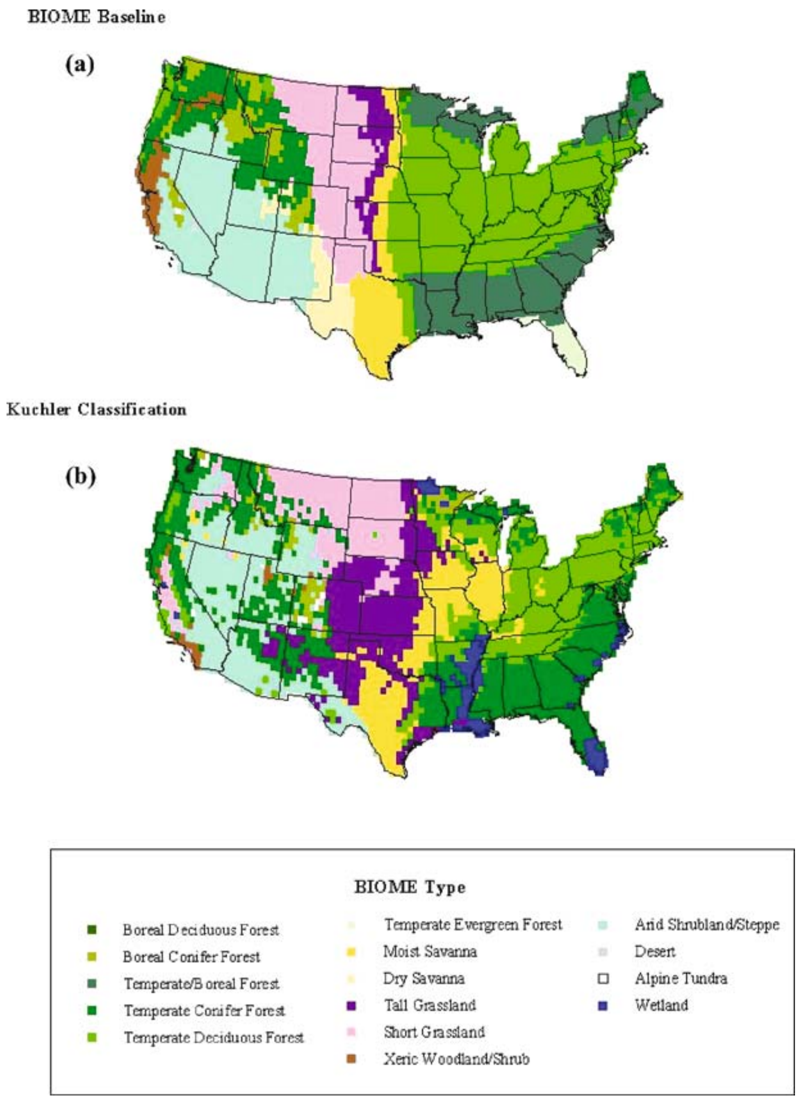


Figure 1. Potential vegetation by biome type under (a) current (baseline) climate as predicted by BIOME 3 and (b) according to the Küchler classification.

of short grass lands in the north, but not in the south of the country. The model predicts the occurrence of a narrow North–South band of tall grass land that, compared with the natural classification, is too narrow and displaced to the west in the Great Plains. Similar results were obtained by Neilson (1995) with the MAPPS (Mapped-Atmosphere-Plant-Soil-System) model. Neilson (1995) argued that the reason for a prediction of the tall grass prairie so far west is that MAPPS, like BIOME 3, predicts vegetation in equilibrium with climate, while the tall grass prairie distribution indicated by Küchler is the result of fires set by Native Americans that allowed for an eastward expansion of this biome. The predicted belt of the moist savanna is narrow and runs from North to South, while the Küchler belt runs predominantly in a NE–SW direction and barely reaches the Canadian border. The BIOME 3 Arid shrub land/steppe spreads uniformly across the southwestern U.S. while the Küchler distribution of natural vegetation in the same region appears much more complex. There is correspondence, albeit not perfect, between the simulated and Küchler classified temperate deciduous forest in central and northeastern sections of the U.S. Similar observations can be made about the evergreen forest in the southeastern U.S. and the conifer forest at altitude in the northwestern U.S.

Lugo et al. (1999) used high-resolution bioclimatic data of the conterminous U.S. to derive a map of natural ecosystems according to the Holdridge Life Zone System (Holdridge, 1967). This map was compared with four others derived using Bailey's and Küchler's systems, output from the first version of the BIOME model (Prentice et al., 1992), and from land cover interpretations derived from satellite images (Loveland et al., 1991). To allow for a common-base comparison, all mapped vegetation was collapsed into four categories: forest, cropland, grassland and shrubland. Of the four maps, the delineations produced by the BIOME model compared best with the Holdridge life zones. From these comparisons, we also surmise a good agreement between BIOME's output and Küchler's potential vegetation. Incidentally, all major ecosystem boundaries produced with the BIOME run presented in Lugo et al. (1999) are very similar to those we obtained running BIOME 3 (Figure 1). We deduce from these comparisons that the BIOME 3 model provides both a realistic and objective baseline of the potential distribution of natural vegetation in the conterminous U.S. The natural distribution of vegetation predicted by BIOME 2, a predecessor model, at continental and global scales under current climate has been compared with that produced by MAPSS (VEMAP Members, 1995). Although some differences are evident, both models – BIOME 2 and MAPPS – produced essentially similar vegetation maps under current climate. From the point of view of climate change assessment, both models represent improvements over previous, empirical approaches (VEMAP Members, 1995; Watson et al., 1997).

The NPP map predicted by BIOME 3 under baseline climatic conditions (Figure 2a) shows maximum annual growth rates (1,200 g C m^{-2}) in warm temperate and subtropical regions of Florida, Georgia and along the Gulf coast through the states of Alabama, Mississippi and Louisiana. Values of NPP decrease in a fan-like manner toward the West and the North. In the temperate/boreal forest region of Minnesota, Wisconsin and Michigan, estimates of NPP are only half of those estimated in the SE. In the grassland region of the Great Plains states, annual NPP decreases from 900 to 500 g C m^{-2} in the general direction SE–NW. Annual NPP is least ($\sim$200 g C m^{-2}) in the arid shrublands of the SW covering parts of California, Nevada and Arizona. NPP is predicted to increase toward the Pacific coast and in the Northeast direction.

Are these estimates realistic? We compared our regional estimates of NPP with the data synthesized by Olson et al. (2001) and available from the Oak Ridge NPP database (http://www-eosdis.ornl.gov/NPP/npp_home.html). The NPP database was assembled as part of the Ecosystem-Modeling Data Intercomparison activity to compare global carbon model estimates against measurements. The data are made available in three classes (A, B, and C) according to the level of detail in the documentation. For this comparison, we selected NPP data from Class A sites, which are considered to be well documented study sites with complete aboveground and belowground NPP measurements (Figure 3). Only sites whose biome field descriptions coincided with those estimated by BIOME 3 were included in the comparison. The regression line in Figure 3a reveals that BIOME 3 overpredicted NPP for forests at low measured NPP, while it underpredicted measured NPP at high NPP values. Overall, BIOME 3 explained about 70% of the total variation in the forest data. For the case of grasslands (Figure 3b), BIOME 3 overestimated the measurements of NPP in standing biomass by 50%.

Zheng et al. (2001) have pointed out that differences in scale at which the observations and predictions are made (field vs. 0.5 $^\circ$ grid cell) make direct comparisons between them difficult. Zheng et al. (2001) examined these challenging issues of scale and aggregation and, using appropriate stratification procedures and modeling, produced a grid-cell based global database of primary productivity suitable for testing biogeochemical models (Figure 2b). A comparison of the two maps in Figure 2 further illustrates that, while BIOME 3 overpredicts NPP values, especially in the Great Plain region, it does captures regional trends in NPP.

2.3. SCENARIOS AND DATA

The 13 climate-change scenarios described in Part 1 were used to drive BIOME 3 in order to study potential changes in distribution and productivity of plant functional types across the conterminous U.S. The scenarios are those that were used to drive the EPIC and HUMUS models in the prior papers of this series (i.e., BMRC, UIUC, UIUC + Sulfate; Global Mean Temperature (GMT) increase = +1.0 and +2.5 °C; and [CO_2] = 365 and 560 ppmv). The conterminous U.S. is covered by 4234 half-degree grid cells. Each grid box contained data on latitude, monthly means of temperature, precipitation and sunshine hours, and soil texture. NPP values were aggregated up to the scale of the 204 4-digit hydrologic units using a weighted average procedure as described in Parts 3, 4 and 5.

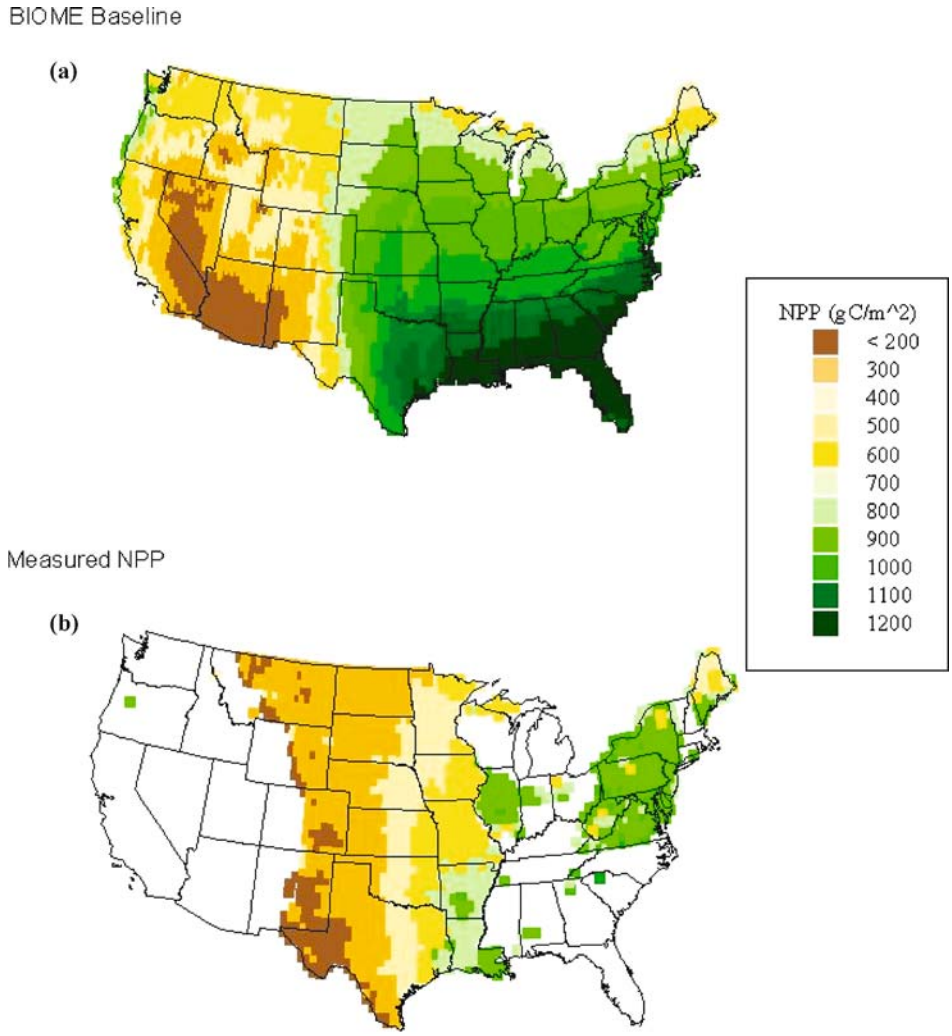
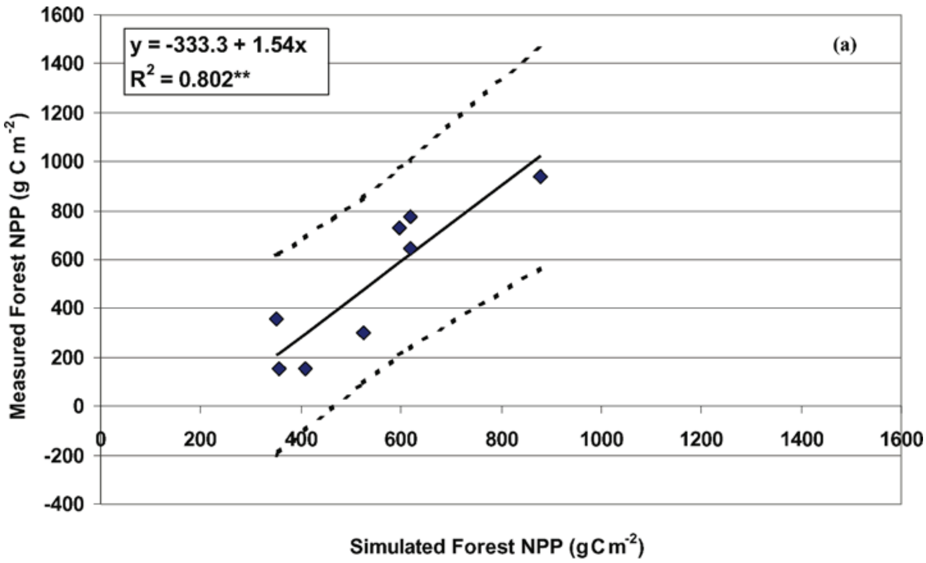


Figure 2. Annual net primary productivity (NPP, g C m^{-2}) of unmanaged ecosystems under (a) current (baseline) climate as predicted by BIOME 3 and (b) as reported by Zheng et al. (2001).

3. Results and Discussion

3.1. CLIMATE CHANGE SCENARIOS

As presented in Figures 3 and 4 of Part 1, the three GCM projections of climate change used in these studies indicate large and contrasting regional changes in both precipitation and temperature. Changes in temperature would be most severe under the BMRC scenario (Figure 3 in Part 1), especially with a GMT increase of 2.5 °C. The NE region of the country experiences the greatest warming (>4 °C) under



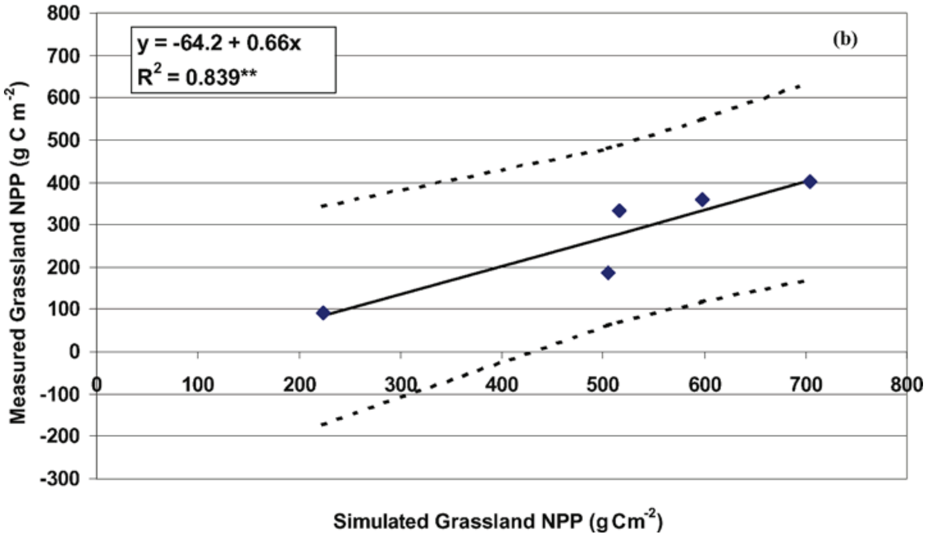


Figure 3. Relationship between values of NPP (g C m^{-2} yr^{-1}) simulated with BIOME 3 and measured at Class A vegetation sites (Olson et al., 2001) for (a) forests and (b) grasslands.

this scenario. In contrast, the UIUC + Sulfate scenario would bring the smallest changes in temperature with the SE of the country experiencing almost no change in mean annual temperature. Under the BMRC +2.5 °C scenario (Figure 4 of Part 1), more than half of the country – primarily the southern half – would become significantly drier than under current climatic conditions. At the other extreme, the UIUC + Sulfate +2.5 °C scenario would make the West much wetter than it is today (>300 mm increase in precipitation).

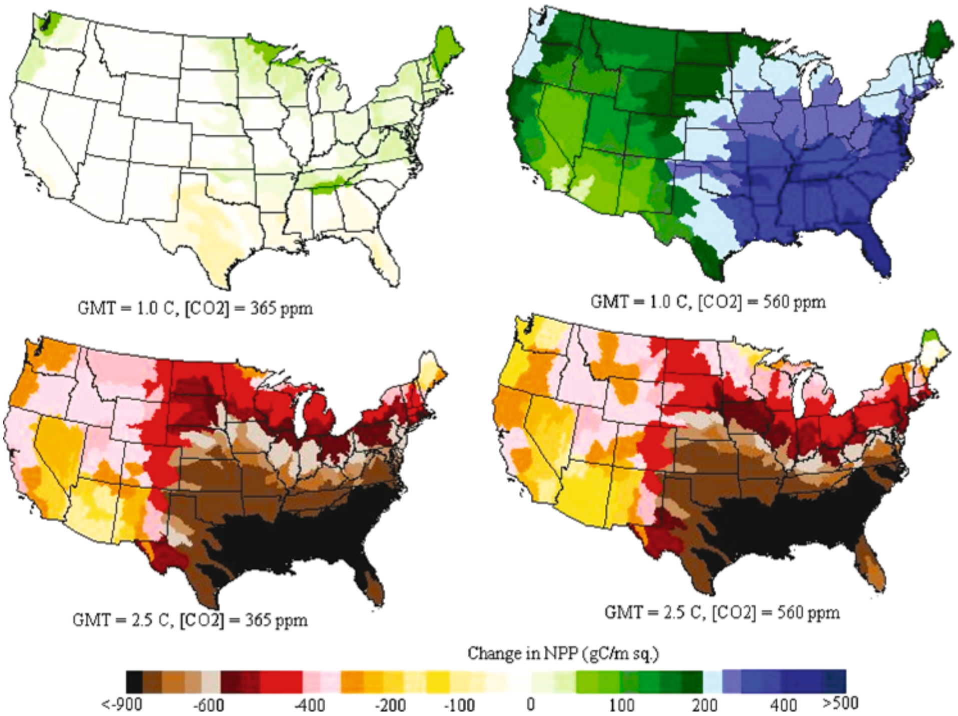


Figure 4. Predicted changes in net primary productivity (NPP, g C m^{-2}) under the BMRC climate scenarios (GMT = 1 and 2.5 °C, [CO_2] = 365 and 560 ppmv).

3.2. EFFECTS OF GCM AND GMT ON NET PRIMARY PRODUCTIVITY

Changes in NPP portrayed in the maps on the left side of Figures 4–6 show the effects of climate change scenario alone. The influence of the CO_2-fertilization effect is seen in the maps to the right side of these figures and is discussed below.

A climate change like the BMRC GCM at GMT = + 1 °C (Figure 4, upper left panel) would increase NPP slightly (~100 g C m^2) in the NE quarter of the country and the upper SE, as well as in the coniferous forest of the Pacific NW. However, a 2.5 °C increase in GMT would cause major losses in NPP throughout the country, especially in the SE. This would lead implicitly to large changes in ecosystem structure (discussed below).

Under the UIUC scenario (Figure 5, upper left panel), the country would present two contrasting regions in terms of NPP changes. With GMTs of both +1 and +2.5 °C, NPP would decrease (200–600 g C m^{-2}) almost everywhere in the SE but it would generally increase (100–400 g C m^{-2}) in the West. The greatest gain in the West occurs at GMT = +2.5 °C because of the substantial increase in precipitation associated with the UIUC scenario.

Under the UIUC + Sulfate (Figure 6) scenarios, the U.S. is even more sharply divided than under the other GCM scenarios. West of an imaginary line near

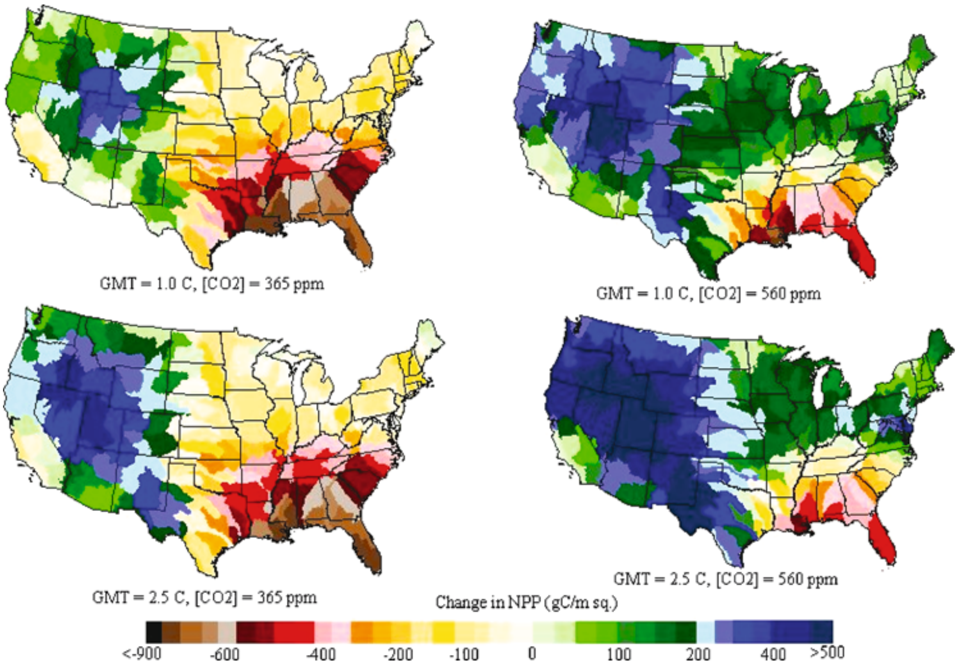


Figure 5. Predicted changes in net primary productivity (NPP, g C m^{-2}) under the UIUC climate scenarios (GMT = 1 and 2.5 °C, [CO_2] = 365 and 560 ppmv).

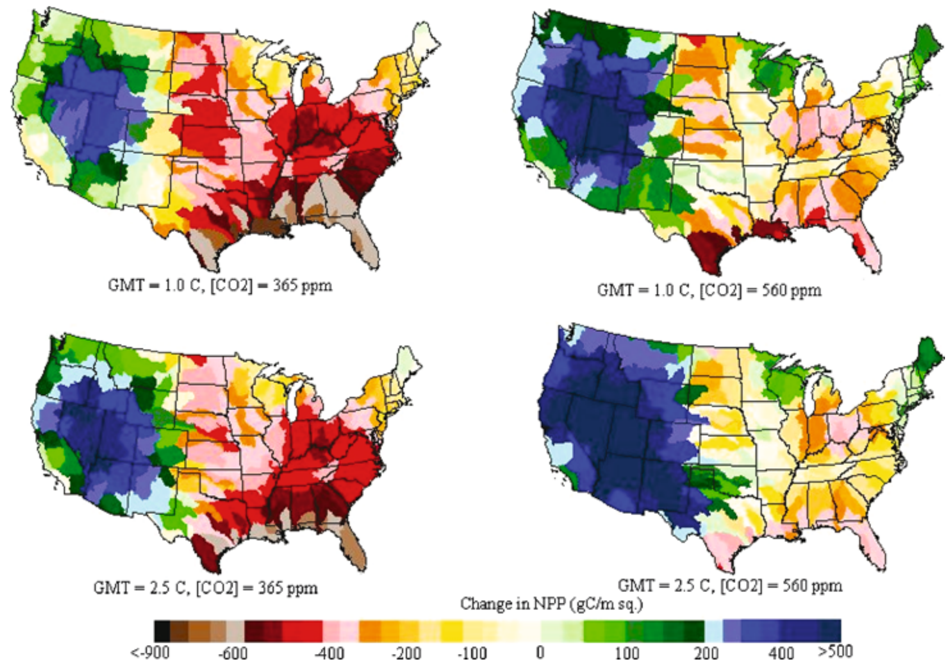


Figure 6. Predicted changes in net primary productivity (NPP, g C m^{-2}) under the UIUC + Sulfate climate scenarios (GMT = 1 and 2.5 °C, [CO_2] = 365 and 560 ppmv).

longitude 105° W from eastern New Mexico through Colorado, Wyoming and Montana, natural ecosystems show consistent increases in NPP (100–400 g C m^{-2}). East of the line, NPP of natural ecosystems declines by 200–400 g C m^{-2}. From the South Atlantic States and along the Gulf Coast to Texas and in portions of the Great Plains, NPP losses range from 400 to 900 g C m^{-2} or more.

3.3. EFFECT OF CO_2-FERTILIZATION

The right-side panels of Figures 4–6 show simulated changes in NPP with CO_2-fertilization consistent with an atmospheric concentration of 560 ppmv (the left panels show NPP at $[CO_2] = 365$ ppmv). In all cases, CO_2-fertilization moderates losses in ecosystem NPP and strengthens positive effects. Under the BMRC scenario at GMT $= +1$ °C and the UIUC scenario at both GMT levels, losses in NPP are converted to gains in large areas of the country.

These deterministic results are similar to those obtained with the EPIC model for dryland crops like corn and wheat (Part 3). As reviewed in Part 1, positive effects of CO_2-fertilization on crop yields have been observed under field conditions in a wide range of experiments using open top chambers (e.g., Kimball, 1983; Rogers et al., 1996) and free air carbon dioxide enrichment (FACE) facilities (e.g., Mauney et al., 1994; Kimball et al., 1995). Results of enrichment studies in unmanaged ecosystems are more ambiguous, however. Drake et al. (1996) found that the C3 sedge *Scirpus olneyi*, a dominant wetland species of the Chesapeake Bay, exhibited enhanced photosynthesis and reduced respiration when growing in a CO_2-enriched open-chamber environment. While elevated CO_2 increased net ecosystem production, it did not increase the size of the belowground carbon pool. Oechel et al. (1994) found that benefits of CO_2-fertilization to tussock tundra vegetation in Alaska diminished in the second year of continuous exposure to air enriched in CO_2. Oren et al. (2001) reported results from a FACE installation at the Duke Forest, NC, where maturing pines growing on a nutrient-poor site did not benefit from CO_2 enrichment of the ambient air. Conversely, maturing forests growing in nutrient-amended soils responded synergistically to elevated CO_2. Using FACE technology in an intact Mojave Desert ecosystem, Smith et al. (2000) measured a doubling in new shoot production of a dominant perennial shrub in a wet year with a 50% elevation in atmospheric $[CO_2]$. However, elevated CO_2 in a dry year did not enhance NPP. Smith et al. (2000) concluded that elevated CO_2 could eventually enhance the long-term success and dominance of exotic annual grasses in the Mojave Desert.

Results of the experiments cited here illustrate how complex the response of native of ecosystems to elevated CO_2 could eventually be. Thus, we caution readers that the results shown on the right-side panels of Figures 4–6 may be overly optimistic because the simulations assume soils with nutrients in ample supply.

3.4. LAND COVER CHANGE

The simulated NPP changes in Figures 4–6 provide a sense of the range of possible outcomes under greenhouse warming. Were any of these, at times drastic, changes in NPP to occur, ecosystem structure would surely be affected. Table I summarizes average NPP (Table I), areal distribution (Table II), and total NPP (Table III) simulated by BIOME 3 for current biome types in the conterminous U.S. and their changes under the 12 climatic-change scenarios. Overall, a moderate GMT increase of 1 °C under the BMRC scenario would translate into rather moderate changes in NPP (Table I) and areal extent (Table II). Consequently, total annual NPP in the conterminous U.S. (Table III) would either remain unchanged without a full expression of the CO_2-fertilization effect ($[CO_2] = 365$ ppmv) or increase by 36% in a scenario with a full expression of the CO_2-fertilization effect ($[CO_2] = 560$ ppmv). In contrast, very drastic changes in NPP (per unit area and total) and area covered were simulated with a 2.5 °C increase in GMT under the BMRC scenario. Examining the behavior of selected across climate change scenarios, the modeled results suggest the possibility of significant reductions or even disappearance of the Temperate/Boreal Mixed Forests (Table II). Correspondingly, two other forest biomes, Temperate Conifer and Temperate Deciduous, show increases in areal extent under the UIUC and UIUC + Sulfate scenarios (Table II). Under current climate, the Arid Shrubland/Steppe could potentially occupy 18% of the conterminous U.S. Were future climates to resemble those projected by the BMRC GCM, the Arid Shrubland/Steppe could increase to occupy 49% of the total U.S. land area.

Such striking changes in biome distribution and NPP would carry severe consequences for the functioning of ecosystems and people. Have changes of this type ever happened? The climate of the mid-Holocene, *ca.* 6,000 yr before present, was warmer and drier than today (Beerling and Woodward, 2001). Using pollen data and a procedure to assign plant taxa to biomes, Williams et al. (2000) reconstructed the distribution of biomes in Canada and the eastern U.S. and concluded that overall, the location of biomes then was similar to that of today. Nevertheless, they reported a 100–300 km eastward displacement of the steppe-forest boundary relative to its present position in Wisconsin and Minnesota, but no such displacement in the central and southern regions of the Great Plains. A direct comparison of our BIOME 3 results and the paleo-climatic information can neither be made nor is intended, but the study conducted by Williams et al. (2000) suggests that significant displacement of biome boundaries can indeed occur even in response to rather moderate warming such as occurred during the mid-Holocene.

The results shown and discussed above assume, of course, that native plants could respond to future climate change as they have done in the past by migration and adaptation. Davis and Shaw (2001) have argued, however, that these “strategies” would be hampered by the unprecedented rates at which climate appears to be changing in combination with ongoing changes in land use that could prevent gene

TABLE I

Modeled net primary productivity (g C m^{-2}) of the different biomes in the conterminous U.S. under current climate and the 12 scenarios of climate change

		BMRC[a]				UIUC				UIUC + Sulfate			
ΔTemperature (°C)	Baseline	1[b]		2.5		1		2.5		1		2.5	
Biome name [CO_2](ppmv)	365	365[c]	560	365	560	365	560	365	560	365	560	365	560
						Mg C km^{-2} (g C m^{-2})							
1. Boreal deciduous forest/woodland	482	50	412	1	0	98	332	59	329	154	302	157	354
2. Boreal conifer forest/woodland	305	297	388	147	207	378	486	415	481	307	399	313	408
3. Temperate/boreal mixed forest	735	690	984	0	0	540	436	518	546	434	429	500	536
4. Temperate conifer forest	385	391	526	301	397	445	560	452	584	422	543	430	547
5. Temperate deciduous forest	741	724	912	437	463	613	827	643	866	552	749	596	812
6. Temperate broadleaved evergreen forest	1082	1045	1466	0	0	820	922	898	1026	748	877	849	966
9. Tropical deciduous forest	0	0	0	0	0	0	924	803	1021	0	0	616	881
10. Moist savanna	820	835	988	0	0	668	805	672	800	515	510	520	523
11. Dry savanna	440	450	538	159	156	374	383	373	413	286	334	349	268
12. Tall Grassland	613	637	802	0	0	620	742	748	880	597	690	616	508
13. Short grassland	555	545	759	0	0	549	650	595	700	438	457	512	0
14. Xeric woodlands/shrub	427	433	579	312	431	526	690	534	748	479	595	487	633
15. Arid shrubland/steppe	229	228	303	134	177	223	311	260	355	215	312	282	386
16. Desert	123	70	42	27	31	59	5	19	0	22	6	5	2
17. Artic alpine tundra	216	0	0	46	68	0	0	0	0	0	0	0	0

[a] Climate change scenarios: BMRC (Bureau of Meteorology Research Centre), UIUC (University of Illinois-Urbana Champaign), UIUC + Sulfates (University of Illinois-Urbana Champaign + Sulfates).
[b] Global Mean Temperature increase above ambient.
[c] [CO_2] in units of ppmv.

TABLE II

Modeled area ($10^3 \times km^2$) occupied by the different biomes in the conterminous U.S. under current climate and the 12 scenarios of climate change

		BMRC[a]				UIUC				UIUC + Sulfate			
ΔTemperature (°C)	Baseline	1[b]		2.5		1		2.5		1		2.5	
Biome name $[CO_2]$(ppmv)	365	365[c]	560	365	560	365	560	365	560	365	560	365	560
						($10^3 \times km^2$)							
1. Boreal deciduous forest/woodland	29	46	119	93	63	56	121	53	95	70	97	71	152
2. Boreal conifer forest/woodland	725	274	274	800	793	519	472	99	56	643	616	421	374
3. Temperate/boreal mixed forest	1,678	2,040	1,632	0	0	80	76	424	190	88	95	362	211
4. Temperate conifer forest	1,036	527	991	951	1,143	2,737	1,593	2,235	1,244	2,989	2,061	2,958	1,844
5. Temperate deciduous forest	2,080	2,093	3,033	5	32	1,920	4,725	3,967	6,315	1,188	3,709	2,966	5,194
6. Temperate broadleaved evergreen forest	93	113	117	0	0	21	75	40	128	21	98	47	142
9. Tropical deciduous forest	0	0	0	0	0	0	11	2	34	0	0	19	52
10. Moist savanna	523	510	444	0	0	716	276	548	48	352	88	322	23
11. Dry savanna	427	500	224	9	27	377	114	379	112	627	156	245	6
12. Tall grassland	328	285	706	0	0	396	304	48	82	60	43	18	4
13. Short grassland	927	1,062	273	0	0	528	195	182	50	575	40	78	0
14. Xeric woodlands/shrub	163	200	219	126	167	1,029	494	927	537	1,573	1,184	1,283	972
15. Arid shrubland/steppe	1,551	1,821	1,497	4,053	4,581	1,101	1,091	642	666	1,342	1,361	759	576
16. Desert	62	156	96	3,587	2,817	147	75	83	70	100	81	77	72
17. Artic alpine tundra	4	0	0	4	4	0	0	0	0	0	0	0	0
Total area	9,628[d]	9,628	9,628	9,628	9,628	9,628	9,623	9,628	9,628	9,628	9,628	9,628	9,623

[a]Climate change scenarios: BMRC (Bureau of Meteorology Research Centre), UIUC (University of Illinois-Urbana Champaign, no sulfates), UIUC + Sulfates (University of Illinois-Urbana Champaign, sulfates).

[b]Global Mean Temperature increase above ambient.

[c]$[CO_2]$ in units of ppmv.

[d]The total area of the conterminous U.S. is an approximation of the true area ($8,000 \times 10^3$ km^2). The area given in Table II was calculated by adding the surface area of 4058 half-degree cells. The surface area (S) of each cell varied with longitude according to the formula $S = R^2(\lambda_2 - \lambda_1)(\sin\varphi_2 - \sin\varphi_1)$, where R is the Earth radius (6,371 km) and λ and φ are longitudinal and latitudinal angles expressed in radians.

TABLE III

Modeled total net primary productivity (Tg C) of the different biomes in the conterminous U.S. under current climate and the 12 scenarios of climate change

		BMRC[a]				UIUC				UIUC + Sulfate			
ΔTemperature (°C)	Baseline	1[b]		2.5		1		2.5		1		2.5	
Biome name $[CO_2]$(ppmv)	365	365[c]	560	365	560	365	560	365	560	365	560	365	560
						(Tg C)							
1.Boreal deciduous forest/woodland	14	2	49	0	0	6	41	3	31	11	30	11	53
2.Boreal conifer forest/woodland	221	81	106	117	163	197	230	41	27	198	246	133	154
3.Temperate/boreal mixed forest	1,230	1,411	1,615	0	0	43	33	220	104	39	41	182	114
4.Temperate conifer forest	399	206	521	287	454	1,220	893	1,010	727	1,261	1,120	1,272	1,009
5.Temperate deciduous forest	1,539	1,514	2,762	2	15	1,179	3,908	2,554	5,471	659	2,780	1,773	4,223
6.Temperate broadleaved evergreen forest	100	118	171	0	0	17	69	36	131	16	86	40	138
9.Tropical deciduous forest	0	0	0	0	0	0	10	2	35	0	0	12	46
10.Moist savanna	429	426	439	0	0	479	222	369	39	182	45	168	12
11.Dry savanna	188	225	121	1	4	141	44	141	46	180	52	86	2
12.Tall grassland	202	182	568	0	0	246	226	36	72	36	30	11	2
13.Short grassland	515	579	208	0	0	290	127	109	35	252	19	40	0
14.Xeric woodlands/shrub	70	86	127	39	72	542	340	495	401	755	704	625	615
15.Arid shrubland/steppe	355	416	453	544	810	246	336	166	236	289	424	214	222
16.Desert	8	11	4	97	86	9	0	2	0	2	0	0	0
17.Artic alpine tundra	1	0	0	0	0	0	0	0	0	0	0	0	0
Total NPP	5,270	5,256	7,144	1,088	1,605	4,614	6,480	5,183	7,356	3,880	5,577	4,566	6,589

[a]Climate change scenarios: BMRC (Bureau of Meteorology Research Centre), UIUC (University of Illinois-Urbana Champaign, no sulfates), UIUC + Sulfates (University of Illinois-Urbana Champaign, sulfates).
[b]Global Mean Temperature increase above ambient.
[c]$[CO_2]$ in units of ppmv.

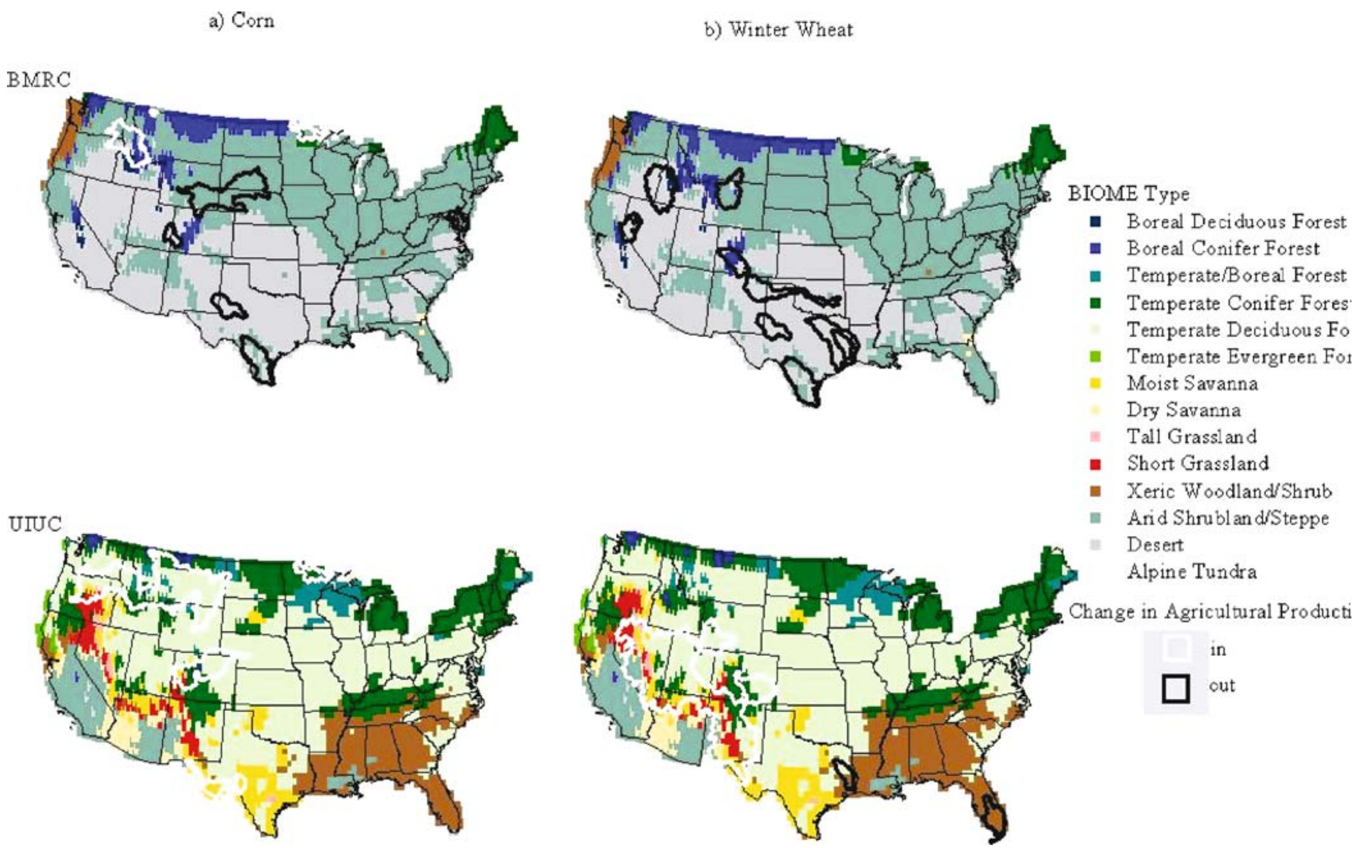


Figure 7. Agricultural regions coming into or out of production (white and black contour, respectively) under the BMRC and UIUC climate scenarios (GMT = 2.5 °C, $[CO_2]$ = 365 ppmv) overlaid with the biome types predicted by BIOME 3 for the same scenarios.

flow. On the basis of the genetic composition of *Chamaecrista fasciculate*, an annual legume naturally occurring in tall grass prairie fragments of the U.S. Great Plains, Etterson and Shaw (2001) predicted that rates of evolutionary response could not keep up with predicted rates of climate change.

Figure 7 shows the predicted distribution of natural ecosystems under the BMRC and UIUC scenarios with a GMT increase of 2.5 °C and no CO_2-fertilization. Overlain on these maps are the regions of the country in which the capacity to profitably produce crops of corn and winter wheat would, according to the EPIC simulations in Part 4, be gained or lost. We assume that native ecosystems would expand into regions abandoned by agriculture. Similarly, we assume, regions entering into agricultural production would do so at the expense of native ecosystems. The West is the region of the country in which simulated land use changes are most dramatic. Natural ecosystems would occupy much new land under the BMRC climate change scenario and lose most to agriculture under the UIUC scenario. This simple analysis given here demonstrates the complexity of environmental change and the challenges we face in developing consistent scenarios with which to examine the best paths for harmonizing environmental needs and societal development in the face of climatic change.

4. Conclusions

This study aimed at characterizing the range in response of unmanaged ecosystems to 12 climate change scenarios. The response was evaluated by simulating, with the BIOME 3 model, shifts in NPP and geographical distribution of major biomes of the conterminous U.S. under a set of climate change scenarios. BIOME 3 captured the potential distribution of major biomes across the U.S. under current climate reasonably well. BIOME 3 also reproduced the general trends of observed NPP acceptably. Values of forest NPP projected by the model agreed well with observations, but grassland NPP was always overestimated. Changes in NPP would be most severe under the BMRC scenario because of the significant increases in regional temperatures projected. The UIUC and UIUC + Sulfate scenarios would bring increases in NPP, especially in the West where precipitation is projected to increase substantially. In general, the inclusion of a CO_2-fertilization effect as a modeling factor either enhanced increases or alleviated losses in NPP brought about by the climate change. Changes in NPP were associated with changes in the distribution of major biomes. Temperate/Boreal Mixed Forests would lose area under most of the climate change scenarios examined. In contrast, the Temperate Conifer and Temperate Deciduous Forests would increase in areal extent under the UIUC and UIUC + Sulfate scenarios. Under BMRC, the Arid Shrubland/Steppe would expand across the U.S. southwest. A map overlay of simulated regions that would lose or gain capacity to produce corn and wheat (Parts 3 and 5) on a map of the projected distribution of natural ecosystems under the BMRC and UIUC scenarios (GMT + 2.5 °C, no CO_2 effect) helped identify areas where natural and managed ecosystems might eventually contract or expand. The methods and models employed here were useful in identifying; (a) the range in response of unmanaged ecosystems in the U.S. to climate change and (b) the areas of the country where tradeoffs between managed and unmanaged ecosystems would be most likely.

Acknowledgements

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 7. ECONOMIC ANALYSIS OF FIELD CROPS AND LAND USE WITH CLIMATE CHANGE

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Abstract. PNNL's Agriculture and Land Use is used to demonstrate the impact of potential changes in climate on agricultural production and land use in the United States. AgLU simulates production of four crop types in several world regions, in 15-yr time steps from 1990 to 2095. Changes in yield of major field crops in the United States, for 12 climate scenarios, are obtained from simulations of the EPIC crop growth model. Results from the HUMUS model are used to constrain crop irrigation, and BIOME3 model is used to simulate productivity of unmanaged ecosystems. Assumptions about changes in agricultural productivity outside the United States are treated on a scenario basis, either responding in the same way as in the United States, or not responding to climate.

1. Introduction

This paper reports on methods developed at Pacific Northwest National Laboratory (PNNL) to place simulation results from biophysical models into a top-down economic framework of global agriculture and land use. The economic framework builds on a partial equilibrium model of global agriculture and land use first described in Edmonds et al. (1996) and further documented in Sands and Leimbach (2003). Here we utilize data from earlier papers in this issue to assess the economic implications of climate change on land use, land prices, and economic welfare. In doing so, we pull together knowledge developed in process-oriented crop growth models under various climate scenarios, and embed it in an economic model of global agriculture, forestry, and land use.

Our goal is to develop a methodology that bridges the gap between top-down global economic models that operate with one country as the smallest geographical area and time steps of several years, and biophysical models with shorter time steps and much smaller geographical areas. Global economic models are often used as an integrating tool for studies of the cost of stabilizing concentrations of greenhouse gases, the role of advanced energy technologies, and feedbacks to the economy through climate and atmospheric concentrations of carbon dioxide. Such integrated analyses are incomplete without the agricultural and forestry sectors as

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these sectors are a significant source of greenhouse gases, a potential source of carbon sinks, and their productivity is affected by climate change.

Our ability to simulate climate impacts on agriculture and forestry varies by country; detailed results from biophysical models are available for the United States but are somewhat sparse for other countries. This leads us to consider climate impacts outside the United States on a scenario basis. Our analysis should be considered qualitative and exploratory; it can be compared to but cannot replace studies of United States agriculture and forestry using detailed mathematical programming models such as FASOM (Adams et al., 1996). Our analysis uses a reduced-form representation of agriculture and forestry that is integrated with a compatible model of the world energy system. We wish to address questions such as: What is the appropriate level of detail in a reduced-form economic model of global agriculture used for integrated assessment of climate change? How might land use shift under alternative climate scenarios? What is the impact on the economic welfare of U.S. consumers and producers of agricultural products?

One common approach is the use of crop growth simulation models to drive an economic model. Studies using this approach include the U.S. Environmental Protection Agency (Smith and Tirpak, 1989), the Basic Linked System of National Agricultural Models (Fischer et al., 1988, 1994; Rosenzweig and Parry, 1994), the MINK study (Rosenberg, 1993; Adams et al., 1995), and the U.S. National Assessment (Reilly et al., 2001). This is sometimes referred to as a structural approach (Adams et al., 1999), where crop models simulate various crop management practices of farmers. An alternative is the spatial analogue approach, where historical data on crop production or land rents across geographical areas with varying climate is used to infer the impacts of future climate change (Mendelsohn et al., 1994; Darwin et al., 1995).

Of these, the U.S. National Assessment is most closely related to our study. Both analyses use a small number of climate scenarios from general circulation models to drive crop growth models for major field crops in the United States. Both studies use crop simulation results for many simulated farms in the United States, but none for crops outside the United States. One major difference between these two studies is the type of economic model employed: the National Assessment uses a detailed mathematical programming model of U.S. agriculture while we use a top-down model of global agriculture with limited detail in any single country.

Major uncertainties remain, especially with regard to future crop productivity, with or without climate change, and the wide variation in climate scenarios across general circulation models. Studies addressing future crop productivity include Schimmelpfennig et al. (1996) and Crosson and Anderson (2002). Given the uncertain impact of climate change on U.S. agriculture relative to agriculture outside the U.S., we have adopted a scenario approach where yield impacts outside the U.S. are assumed to be either unchanged or move in the same direction as in the U.S.

Section 2 of this paper describes the theoretical framework. Section 3 explains how results from other papers in this issue are used to modify productivity parameters. Section 4 presents results for the United States by climate scenario, where yields in the rest of the world are assumed to be unchanged. Results for the United States are sensitive to yield assumptions in the rest of the world; this is addressed in Section 5 with scenarios where changes to crop yield in the rest of the world mimic those in the United States.

2. Economic Framework

The Agriculture and Land Use (AgLU) model simulates food consumption, food production, and land use in 14 world regions with 15-yr time steps beginning in 1990. At the core of AgLU is a mechanism to allocate land among crops, pasture, and forests according to the economic return from each land use type in each region. A joint probability distribution is defined over yield in each alternative land use. With additional information on prices and non-land cost of production, each landowner is assumed to select the land use with the greatest economic return calculated as revenue less non-land cost of production. With simplifying assumptions on the geographic distribution of yield, a reduced-form solution can be obtained for the share of total land in each region allocated to each land use as a function of prices and non-land costs of production. See Sands and Leimbach (2003) for a more complete theoretical description of AgLU and an application to the role of biomass-based fuels in a carbon-constrained world with implications for land use.

Agricultural data for base-year calibration were obtained from the Food and Agriculture Organization (FAO) of the United Nations (2003). Calories are the basic unit of measurement in AgLU. Food consumption is measured as kilocalories per person per day, while crop yields have units of gigacalories per hectare. Much of the original FAO data used to calibrate AgLU are in units of kilograms, which are converted to calories using weights with units of kilocalories per kilogram.

Productivity of field crops is calibrated in the model base year to match historical FAO data. However, these crop yields are not constant over the simulation time frame. Historical crop yields have been steadily increasing over time; crop yields in AgLU increase at a rate specified by the model user.

For each of four crop types, one world price brings global supply and demand into equilibrium. The four crop types are food grains, coarse grains, oil crops, and other crops. The food grains composite is a combination of wheat and rice, and is actually the total number of calories of wheat and rice produced within a region. The coarse grains composite includes corn and all other cereals. Oil crops consist primarily of soybeans in the United States, but other oil crops are included. The "other crops" category includes the total calories of all remaining food crops, such as fruits, vegetables, and starchy roots.

A composite forest product is used to meet demand for both industrial wood and fuel wood. Unlike the other products, forest products are measured in units of cubic meters. The forest products market is also cleared globally, with one world price, though regional prices differ with taxes and subsidies. We also solve for a forward price in the forest market because of the time lag between planting and harvesting trees.

Animal products are split into regional markets. Regional supply must equal regional demand, adjusted for trade in animal products between regions, which is fixed at 1990 levels. This assumption is reasonable given the relatively small amount of trade between regions in animal products, mostly due to high transport costs.

International trade is an important mechanism in AgLU that allows regions with a growing population, but limited amounts of unmanaged land that can be converted to agriculture, to meet demand for food. The composite crops in AgLU are traded freely among regions so that increases in global demand are supplied wherever it is least expensive to grow them. Even though trade in animal products is limited, trade in coarse grains used for animal feed provides a mechanism for indirect trade in animal products. Animal products are treated separately from grains because per-capita consumption of animal products is anticipated to increase relative to grains as incomes grow in developing countries.

2.1. DEMAND

Agricultural production and land use are driven primarily by the demand for food. Consumer demand for food creates direct demands for crops as well as indirect demands through consumption of animal products and processed crops. FAO food balance data for 1990 were aggregated into three broad food categories: crops consumed directly, crops consumed indirectly as processed crops, and animal products. Direct crop consumption is primarily of cereals, but also includes starchy roots, fruits and vegetables. Processed crops include vegetable oils from oil crops, sweeteners from sugar crops, and alcoholic beverages. Animal products include meat, milk, butter, eggs, and animal fats.

The demand equation for crops, processed crops, and animal products is

$$X_{ijt} = A_{ij} P_{ijt}^{\alpha_{ij}} Y_{ijt}^{\beta_{ij}} N_{jt} C_{ijt}, \quad i = \text{crops, processed crops, animal products} \quad (1)$$

where j is a region index, t is time, X is quantity demanded, A is a constant for base-year calibration, P is price, Y is per-capita income, N is total population by region, and C is baseline per-capita consumption in kilocalories per day. Superscripts on P and Y are price and income elasticities, respectively.

Demand for agricultural products varies with population and through the price and income elasticities in Equation (1). Care must be taken in setting price and income elasticities so that simulated consumption stays within a plausible range in each region and food category. Elasticities in developing countries are set to simulate a shift from food grains to processed crops and animal products as incomes increase. Price elasticities for animal products are negative and greater (in absolute value) than price elasticities for crops and processed crops. If animal products become expensive relative to processed crops, as could occur with low rates of increase in crop yield over time, then consumption can shift away from animal products to processed crops. Parameter C can be varied exogenously over time to simulate changes in per-capita consumption unrelated to price and income.

Demand for two types of forest products, industrial wood and fuel wood, is computed as

$$X_{ijt} = A_{ij} P_{ijt}^{\alpha_{ij}} Y_{ijt}^{\beta_{ij}} N_{jt}, \quad i = \text{industrial wood, fuel wood} \tag{2}$$

where X is quantity demanded, P is price, Y is per-capita income, and N is population. The A term is used to calibrate base-year demands to historical data by region. Price per cubic meter is assumed the same for industrial wood and fuel wood. With rising income, demand for industrial wood increases and demand for fuel wood decreases.

Demand for processed crops creates an indirect demand for crop land through the conversion of crops to vegetable oils, sweeteners, and alcoholic beverages. Demand for animal products creates an indirect demand for crop land and pasture land used as animal feed, but with a net loss of calories through the conversion from crops to animal products. Demand for biomass fuels also requires crop land, especially in scenarios with high prices of fossil fuels, or scenarios that place a high value on limiting carbon dioxide emissions. Prices of agricultural products adjust to equate supply and demand, where supply is determined by a land allocation mechanism and assumptions on yield.

2.2. SUPPLY

Supply of crops, biomass, pasture, and forest products is calculated as the amount of land allocated to each land use times average yield. Animal products are produced with a combination of crop-based feed and pasture. A tree diagram (Figure 1) shows

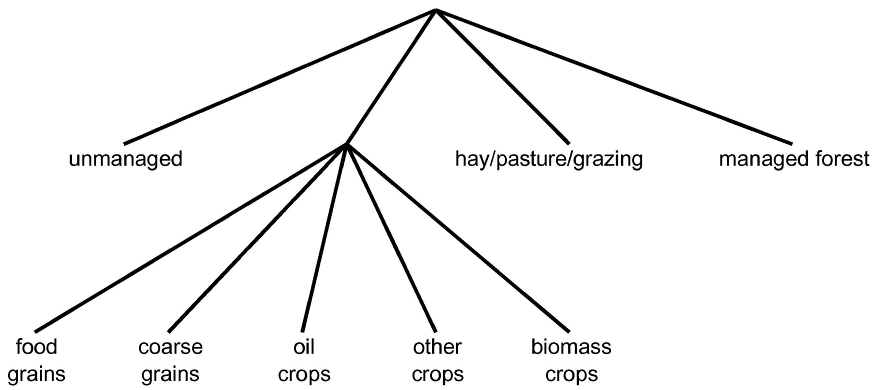


Figure 1. Allocation of land in the AgLU model.

how land is allocated among alternative uses. During any model time step, some land is already committed to trees previously planted. Other land is allocated among food and biomass crops, pasture, and newly planted trees. Crops and commercial biomass are grouped in a separate nest because we assume that land for growing commercial biomass competes directly with land for growing crops.

Selection of land use is based on maximizing economic return per hectare, calculated as revenue less production cost, at each location. Profit per hectare is equal to revenue (yield per hectare times price received) less production cost (yield per hectare times non-land cost per unit of output). An average profit rate, in dollars per hectare, is calculated for each land use as

$$\bar{\pi}_i = \bar{y}_i(P_i - G_i), \quad i = \text{crops, biomass, pasture, forest} \tag{3}$$

where $\bar{y}_i$ is the intrinsic yield for land use i, P_i is the price received for the product produced by land use i, and G_i is the non-land cost per unit of output in land use i. Intrinsic yield is an average yield across all possible locations where a crop could be grown, regardless of the actual land use selected by profit-maximizing land owners. The yield distribution within an AgLU region implicitly represents variation across temperature, precipitation, available sunlight, soil quality, and topography. Between regions, the yield distribution also captures differences in technology and management practice.

Given a joint probability distribution of yield, information on prices received, and non-land costs of production, it is possible to calculate the share of land allocated to each use and the average yield within each land use. With specific assumptions on the functional form of the yield distribution, the share of land allocated to use i is given by

$$s_i = \frac{\bar{\pi}_i^{1/\lambda}}{\sum_k \bar{\pi}_k^{1/\lambda}}, \tag{4}$$

where λ is a positive parameter that determines the distribution of return rates over all lands. This distribution has the desirable properties that greater profit rates imply greater shares of land; it can be calculated quickly; and the shares sum to one.

The profit rate calculation for pasture requires a price for pasture-based feed P_{pasture}. The price of pasture is calculated indirectly through the price of animal products and crops, both of which are solved for within the model. Given these two prices, P_{pasture} is found by solving:

$$P_{\text{animal}} = P_{\text{crops}} \times \mathit{FeedOut} + P_{\text{pasture}} \times \mathit{PastOut} + G_{\text{animal}}. \tag{5}$$

FeedOut is the ratio of crop-based feed calories needed per calorie of animal product; *PastOut* is the ratio of pasture-based feed calories needed per calorie of animal product. As before, G is the non-land cost per unit of output.

The share of land allocated to new forests depends on the profit rate for trees, which depends on the price received for forest products harvested in the future. This future price is determined by equating supply and demand in a market for forest products three model time steps (45 yr) in the future. The profit rate calculation for land allocated to forest products is analogous to Equation (3) and is given by

$$\bar{\pi}_{\text{forest}} = \frac{r}{(1+r)^{45}-1}\bar{y}_{\text{forest}}(\tilde{P}_{\text{forest}} - G_{\text{forest}}), \tag{6}$$

where r is the interest rate and $\tilde{P}_{\text{forest}}$ is the price per cubic meter of forest products three model time steps ahead. Two markets for forest products are brought into equilibrium within each AgLU time step. One market is for trees cut today and another market is for trees planted today for future harvest. The current market determines today's price of forest products and the forward market determines a future price of forest products, which is needed to determine today's allocation of land.

An observed average profit rate for all land within a region is written as a function of the profit rates evaluated at intrinsic yields. This is shown in Equation (7) where k is an index across land use types. The observed average profit rate is greater than any of the individual (unobserved) profit rates.

$$\hat{\pi} = \left[\sum_k \bar{\pi}_k^{1/\lambda}\right]^{\lambda}. \tag{7}$$

An interesting result is that observed average profit rates are equal across land use types as indicated in Equation (8). This result is not derived here, but is a consequence of assuming economic optimization. Clarke and Edmonds (1993) derive a similar result in the context of selecting a set of cost-minimizing energy technologies.

$$\hat{\pi}_i = \hat{\pi}, \quad i = \text{crops, biomass, pasture, forest.} \tag{8}$$

We exploit this result to calculate an observed average yield for each land use analogous to Equation (3). The observed average yield for crops, biomass, and pasture is given by

$$\hat{y}_i = \frac{\hat{\pi}_i}{P_i - G_i}, \quad i = \text{crops, biomass, pasture.} \tag{9}$$

Therefore, the observed average yield is defined to be the yield at which the profit rate is equal to $\hat{\pi}_i$. Average yield is multiplied by the amount of land, given by the land share from Equation (4), to determine supply.

An important feature of this land allocation mechanism is that, for any given land use, average yield may fall as the amount of land allocated to that use increases. For example, if the most productive land is first allocated to crops, crop land can only expand into land less suitable for crops. Sands and Leimbach (2003) provide a more complete description of the land allocation methodology in AgLU and an interpretation of λ as a function of the standard deviation of the profit rate distribution.

2.3. GLOBAL LAND USE SCENARIO

Over time, crop yields should increase in the absence of climate change or CO_2 fertilization. The AgLU baseline scenario assumes that yields in the United States and elsewhere increase at an annual rate of 1.0% between 2005 and 2035, and by 0.5% per year thereafter. Climate change scenarios considered in this study, when superimposed on this autonomous rate of increase, still allow for increased crop yields in 2080 in the United States. Other key drivers of the baseline scenario are population and income. Population projections are from the United Nations medium long-range population projections (United Nations, 2001). Projections of per-capita income are derived from the B2 scenario of the Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios (IPCC, 2001).

Figure 2 provides a view of global land use over time in AgLU. Even with increasing crop yields, the amount of crop land increases until around 2050 to feed an increasing population that is also consuming more animal products as incomes rise. After 2050, the amount of crop land is relatively stable as population growth slows. Global crop land in Figure 2 includes land used for each of the four AgLU crop types, but does not include hay or non-food crops. The pasture land use includes hay and rangeland. Managed forests include forests for production of industrial wood and fuel wood. Unmanaged land is primarily unmanaged forest, but also includes unmanaged rangeland and grassland. Total world land area is about 13 billion hectares, which includes four billion hectares of land that is not usable for any agricultural purpose, leaving nine billion hectares of land for other uses. Pasture land increases over time in response to the increased demand for animal products.

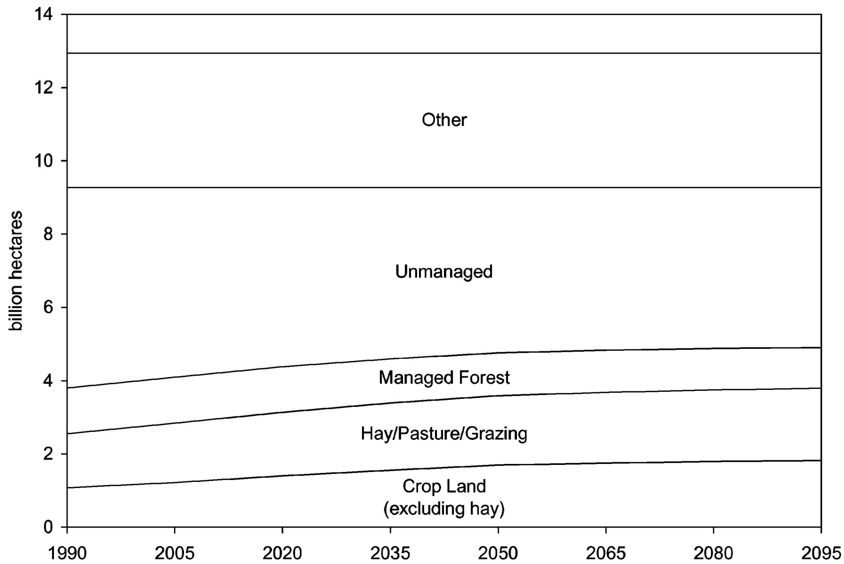


Figure 2. Baseline global land use scenario.

3. Climate Drivers for Field Crops and Land Use

This section describes how results on dryland crops, irrigated crops, hydrology, and unmanaged ecosystems from other papers in this issue are integrated into an economic analysis of climate change using the AgLU model. One challenge is to combine results from EPIC simulations into a national productivity index by crop that varies by climate scenario. The 204 representative EPIC farms scattered throughout the United States provide broad geographical coverage, but the United States is represented within AgLU at a national scale only, and we must choose some method of collapsing yield information for 204 locations into a yield index by crop. Another challenge is that results on dryland crops in Thomson et al. (2004b) cover only corn, winter wheat, soybeans, and hay in the United States. These crops are the major uses of crop land in the United States, but no coverage is provided outside of the United States. Further, the yield simulations are static: they simulate the response of crop yield to climate change as if a new climate were imposed on current agricultural practice instead of future agriculture.

Twelve climate scenarios are derived from three climate models and two climate sensitivities; they are further distinguished by the presence or absence of CO_2 fertilization. The three climate models are from the Australian Bureau of Meteorology Research Center (BMRC), the University of Illinois at Urbana-Champagne (UIUC), and UIUC with a sulfate effect (UIUC + Sulfates). The two climate sensitivities, which represent an increase in global mean temperature by mid-century, are 1.0 °C and 2.5 °C.

We describe methods for creating a national yield index for dryland field crops in the United States in Section 3.1. In Section 3.2, information on water supply and water demand for irrigation is used to construct a yield index with idealized, but restricted, irrigation. In Section 3.3, the BIOME model is used as a tool to represent productivity for forests in each climate scenario. Finally, Section 3.4 provides a discussion of the timing of yield changes brought about by climate change, and how these yield changes interact with autonomous increases in yield that would occur with or without climate change.

3.1. DRYLAND AGRICULTURE

Thomson et al. (2004b) describe dryland yields, from EPIC farm simulations, across 204 hydrologic unit areas (HUAs) for major field crops in the United States, for the case of a baseline climate and twelve climate scenarios. Yield estimates from these simulations represent typical yield in the agricultural land area of each HUA. Agricultural land area, by HUA, is obtained from a land use and land cover data set of the National Oceanic and Atmospheric Administration (NOAA, 2003). Agricultural land in the NOAA data set is defined as in Anderson et al. (1976) and is equal to about one-third of U.S. land area. We use agricultural area as

TABLE I
Simulated yield from EPIC (tons per hectare) and BIOME (tons per hectare of carbon) models without irrigation for the United States

	EPIC				
Scenario	Corn	Soybeans	Winter wheat	Hay	BIOME Woody NPP
Baseline	4.95	1.56	2.88	5.60	5.84
Without CO_2 effect					
BMRC 1.0	4.77	1.45	2.73	5.05	5.72
BMRC 2.5	4.19	1.23	2.60	4.70	0.86
UIUC 1.0	5.00	1.53	2.82	5.38	5.07
UIUC 2.5	4.92	1.44	2.70	5.21	5.76
UIUC 1.0 + Sulfates	4.98	1.53	2.82	5.42	4.26
UIUC 2.5 + Sulfates	4.87	1.43	2.68	5.18	5.76
With CO_2 effect					
BMRC 1.0	5.34	1.76	3.34	5.84	8.21
BMRC 2.5	4.82	1.49	3.20	5.52	1.34
UIUC 1.0	5.59	1.84	3.41	6.20	7.41
UIUC 2.5	5.42	1.72	3.25	6.03	8.35
UIUC 1.0 + Sulfates	5.58	1.84	3.41	6.23	6.35
UIUC 2.5 + Sulfates	5.39	1.72	3.23	6.02	7.49

Note. The CO_2 fertilization effect corresponds to a CO_2 concentration of 560 ppmv.

weights to calculate national dryland yield indexes for corn, winter wheat, soybeans, and hay. The yield indexes are presented in Table I for each crop and climate scenario.

Yield indexes in Table I are somewhat below current practice for two reasons. The first is that many of the yield simulations from EPIC are closer to historical yields in the 1972–1994 time frame (Thomson et al., 2004a) than have been observed recently. The second reason is the use of agricultural area as weights instead of area harvested. Agricultural area is used as weights to represent average yield over a large area where a crop can potentially be grown. If we had instead used historical area harvested, historical patterns of land use by crop would be built into the yield index. The corn baseline yield would have been 5.62 tons per hectare, instead of 4.95 tons per hectare, if area harvested had been used as weights. The soybean baseline yield would have been 1.92 tons per hectare instead of 1.56, and the winter wheat yield would have been 2.99 tons per hectare instead of 2.88.

Average yield is lowest in the BMRC 2.5 °C scenario, with or without CO_2 fertilization. In all scenarios except BMRC 2.5 °C, dryland yields with CO_2 fertilization exceed baseline yield. Dryland yields for the UIUC scenarios are equal to or slightly greater than the corresponding UIUC + sulfates scenarios.

TABLE II
Simulated EPIC yield with restricted irrigation (metric tons per hectare)

Scenario	Corn	Soybeans	Winter wheat
Baseline	5.61	1.77	3.11
Without CO_2 effect			
BMRC 1.0	5.49	1.67	3.02
BMRC 2.5	4.95	1.44	2.90
UIUC 1.0	5.57	1.74	3.02
UIUC 2.5	5.35	1.61	2.88
UIUC 1.0 + Sulfates	5.54	1.73	3.00
UIUC 2.5 + Sulfates	5.30	1.60	2.84
With CO_2 effect			
BMRC 1.0	5.92	1.99	3.58
BMRC 2.5	5.43	1.71	3.45
UIUC 1.0	6.02	2.05	3.58
UIUC 2.5	5.75	1.89	3.40
UIUC 1.0 + Sulfates	5.99	2.04	3.56
UIUC 2.5 + Sulfates	5.71	1.88	3.35

3.2. IRRIGATED AGRICULTURE

Thomson et al. (2004d) provide information derived from the EPIC model on irrigation requirements for corn, soybeans, and winter wheat within each of the 204 HUAs. This information, along with EPIC crop yield under irrigation and water supply by climate scenario, is used to derive an alternative yield index labeled “restricted irrigation” in Table II. The amount of water used for irrigation within each HUA is constrained by the water supply derived from HUMUS simulations in Thomson et al. (2004c).

Yield for each HUA under restricted irrigation is calculated for each crop and climate scenario as an average between dryland yield and yield with full irrigation. First, water supply within a HUA is compared with water demand from irrigation. The amount of irrigated water demanded by the crop varies by climate scenario, as does the amount of water supply. If water supply is adequate to irrigate that crop within all agricultural area in that HUA, then the crop yield under irrigation is used. If water supply is not adequate, then the amount of agricultural land that can be irrigated is determined. In this case, average yield for that HUA is an area-weighted average of dryland and irrigated crop yields. This is the same calculation as was used for each HUA in Thomson et al. (2004d). Even this restricted irrigation calculation is idealized in that we have ignored competing demands for water such as electric power generation and management of stream flow to maintain fish populations.

The pattern of yield index under restricted irrigation relative to baseline yield (Table II) is quite similar to that of dryland yield relative to dryland baseline (Table I). Again, the BMRC scenario at 2.5 °C without CO_2 fertilization has the lowest yields relative to baseline. Some of the detail behind the calculation of yield under restricted irrigation is shown in Figures 3a, b, and c, for corn, soybeans, and winter wheat, respectively. Yield is plotted on the vertical axis while area is plotted along the horizontal axis. These figures show the range of crop yields for all agricultural land in the United States and the land area that could support that yield. In each figure, baseline yield is plotted along with yield from two climate scenarios: UIUC at 2.5 °C with CO_2 fertilization, and BMRC at 2.5 °C without CO_2 fertilization. The area under each curve in Figure 3 can be interpreted as the technical potential output for each crop by climate scenario.

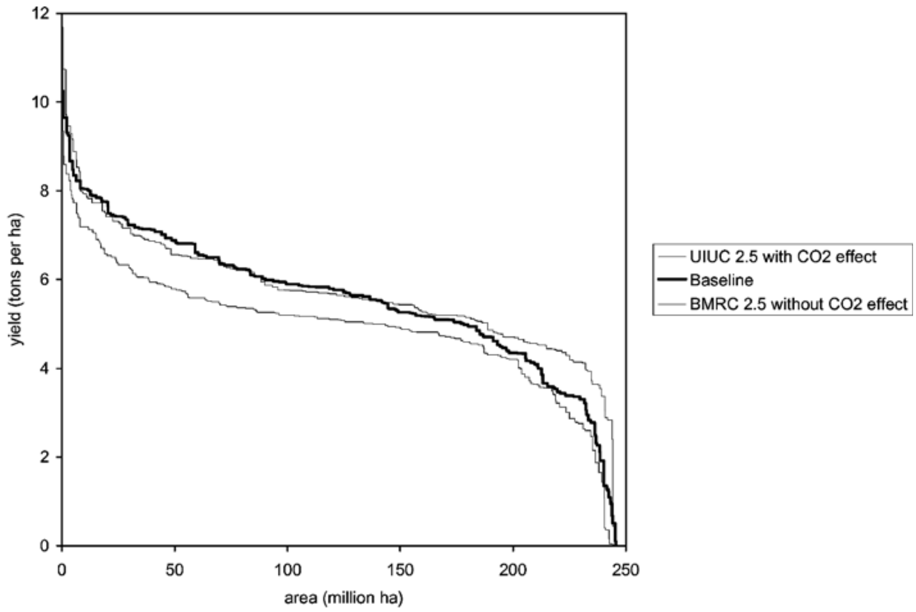
3.3. GRAZING LAND AND FORESTS

An analysis of land use in the United States in response to climate change should cover all major land uses, including grazing land and forests. The pasture component of AgLU is a collection of land used to grow hay, crop land used for pasture, and grazing land. Productivity of this land type across climate scenarios in AgLU is represented by the dryland hay yields in Table I.

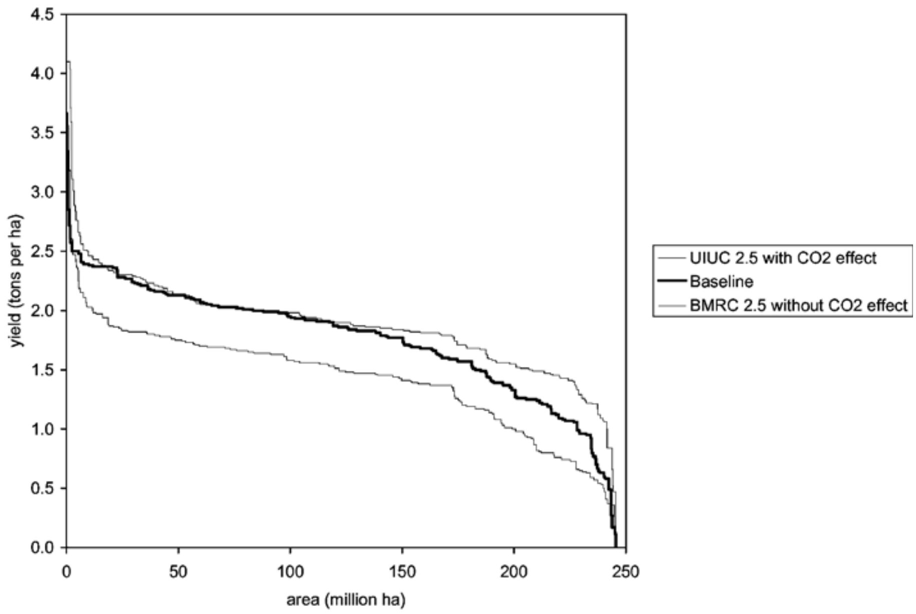
Forest productivity is represented using results from the BIOME3 model, as described in Izaurralde et al. (2004). Yield indexes are created by first calculating average net primary productivity for each four-digit HUA, and then creating a national average using total land area, not just agricultural area, as weights. Results of the yield index calculations are shown in Table I. The most striking result in Table I is the collapse in net primary productivity that occurs when the global mean temperature sensitivity of the BMRC scenario increases from 1.0 to 2.5 °C, regardless of CO_2 fertilization. Izaurralde et al. (2004) also report large geographic shifts in biome type between the BMRC scenarios. Two biome types together, desert arid shrubland/steppe, occupy 19% of United States land area in the baseline scenario, 18% to 22% of land area in the BMRC 1.0 °C scenarios, and 81% to 84% of land in the BMRC 2.5 °C scenarios. This collapse of net primary productivity is reported only for the BMRC scenarios, and not for the UIUC scenarios. Further, no similar collapse in productivity is reported using EPIC for any of the climate scenarios.

3.4. AGRICULTURAL PRODUCTIVITY OVER TIME

Crop yield within AgLU is simulated over time in two ways. First, crop yields will likely increase with improved crop management, more efficient use of water, and improved varieties of seed. Second, crop yields may increase or decrease because of



(a) corn



(b) soybeans

Figure 3. Distribution of crop yield from EPIC model simulations over agricultural land in the United States, for three climate scenarios with restricted irrigation. Simulated yields from EPIC are ranked from high to low for 204 representative farms; the area under each curve equals production in tons if all agricultural land were planted in a single crop: (a) corn; (b) soybeans; (c) winter wheat.

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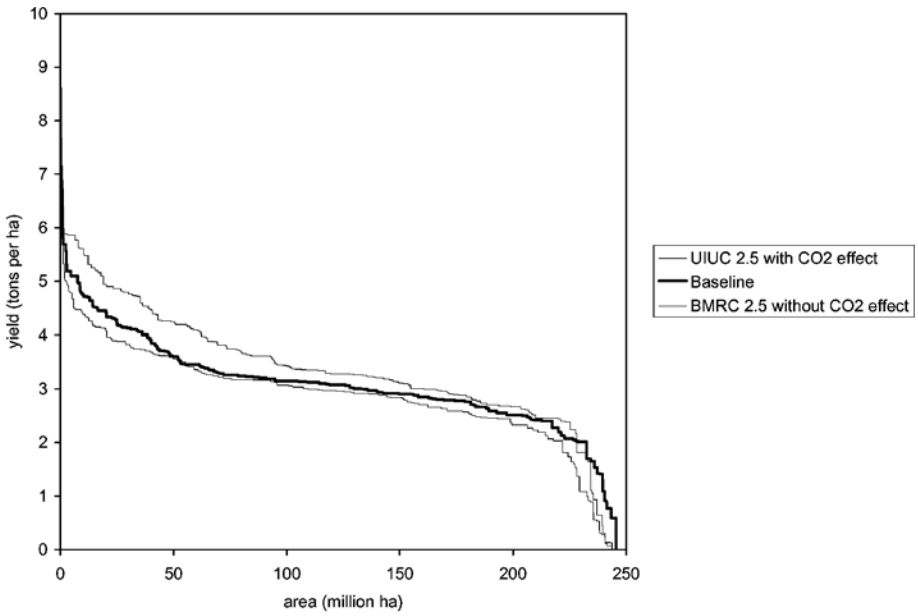


(c) winter wheat

Figure 3. (*Continued*)

climate change. We first describe assumptions in AgLU on autonomous increases in crop yield over time, and then overlay crop yield changes from selected climate-change scenarios. Figure 4 compares trends in historical yields for U.S. corn, wheat, and soybeans with projected trends in AgLU. For each crop, projected trends in yield are linked to historical yield in 1990, the model base year.

Economic activity is simulated from 1990 to 2095 in 15-yr time steps and the reference scenario allows crop yields to increase at 1.0% per year from 2005 through 2035 and 0.5% per year thereafter. At these growth rates, the cumulative increase in yield from 2005 through 2080 is 69%. The increase in crop yield from 1990 to 2005 is set to be the average historical rate of crop yield change from 1981 to 2001. On top of this autonomous trend in yield, we overlay climate change yield indexes based on the average yields in Tables I and II. We allow climate impacts to be phased in gradually between the present and 2080. Table III shows the percent change in yield for three climate scenarios relative to baseline. Simulated crop yields in the AgLU model fully reflect these changes by year 2080. For example, if the change in yield is +10% for a climate scenario, then the projected yield in 2080 is 10% above baseline yield in 2080. The percentage change is gradually phased in between 2005 and 2080.

Yield changes reported in Table III are generally less than our autonomous trend in baseline yield between 2005 and 2080. Results from the BIOME3 model are an exception. Forest productivity in BIOME3 is severely reduced in the BMRC (2.5 °C) scenario.

TABLE III
Yield patterns relative to baseline

AgLU sector	Biophysical model	BMRC 2.5 °C no CO_2 effect	UIUC 2.5 °C no CO_2 effect	UIUC 2.5 °C with CO_2 effect
Food grains	EPIC winter wheat	−6.8%	−7.6%	+10.8%
Coarse grains	EPIC corn	−11.7%	−4.6%	+2.5%
Oil crops	EPIC soybeans	−18.7%	−8.9%	+6.9%
Miscellaneous crops	None			
Pasture	EPIC hay	−16.1%	−7.0%	+7.7%
Forests	BIOME3	−85.3%	−1.4%	+42.9%
Commercial biomass	EPIC hay	−16.1%	−7.0%	+7.7%

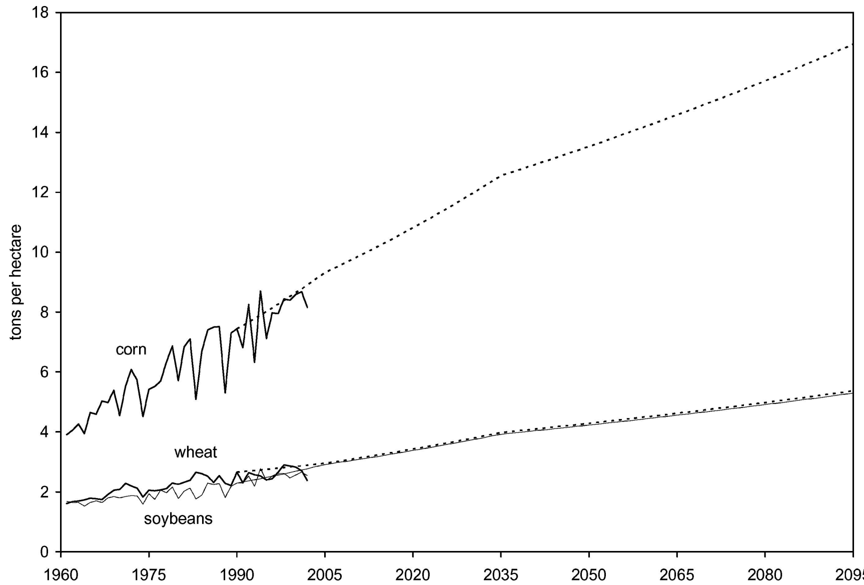


Figure 4. Historical crop yields in the United States (solid lines) and future projections (dashed lines) in the AgLU model. Source for historical yields: FAO (2003).

4. U.S. Analysis

Section 2 of this paper presented the economic framework for this study, a top-down partial equilibrium model with supply and demand for agricultural products in 14 world regions. This framework, the Agriculture and Land Use model, contains production functions for four crop types, and can accept a yield index to scale crop productivity depending on assumptions about technical change and climate change. Section 3 described how climate change impacts on dryland crops, irrigated crops, water supply, and unmanaged ecosystems, derived from other papers in this issue, can be used to vary crop productivity in AgLU. Climate impacts from Table III are applied to the United States; yields in other regions are unchanged. Yield changes due to climate change are fully phased in by 2080. Section 4.1 presents simulations of land use in the United States. Section 4.2 provides a discussion of the economic impacts on producers and consumers. Section 4.3 provides a qualitative discussion of the potential role of biomass energy crops.

4.1. LAND USE CHANGE

Table IV provides a sample of simulated land use change results for the United States. Crop land is increasing over time, even in the absence of climate change, because of a growing world population and increasing incomes. Two climate scenarios, UIUC (2.5 °C) with and without CO_2 fertilization, are used to represent a range of climate impacts on agricultural and forestry production. It is difficult to interpret the land use change results when yield from crops, pasture, and forests all change at the same time. Even among crop types, there are varying rates of change. Therefore, intermediate scenarios are presented where first crop yields only are adjusted, then crop yields and pasture productivity are adjusted, and finally yield adjustments are applied to crops, pasture, and forests simultaneously. In general, the UIUC (2.5 °C) scenario without CO_2 fertilization provides moderate declines in yield. The UIUC (2.5 °C) scenario with CO_2 fertilization provides moderate

TABLE IV
United States land use (million hectares) by climate scenario with a global mean temperature change of 2.5 °C

	Simulation year	Crop land	Hay, pasture grazing	Managed forest	Unmanaged	Wheat & rice	Coarse grains	Oil crops	Misc. crops
Baseline	1990	99.0	249.2	192.4	191.5	29.1	36.5	29.3	4.1
Baseline	2080	157.8	262.2	176.8	135.4	29.6	48.4	74.9	4.9
UIUC 2.5 (without CO_2 effect) applied to:									
Crops only	2080	147.1	266.7	180.3	138.0	26.0	50.1	65.1	5.8
Crops and pasture	2080	151.0	255.2	184.3	141.5	26.6	51.9	66.6	5.9
Crops, pasture, forest	2080	151.8	256.3	181.7	142.2	26.8	52.1	66.9	6.0
UIUC 2.5 (with CO_2 effect) applied to:									
Crops only	2080	167.4	258.1	173.6	132.9	35.5	46.5	81.1	4.2
Crops and pasture	2080	163.1	269.4	169.8	129.7	34.7	44.9	79.4	4.1
Crops, pasture, forest	2080	143.0	241.4	234.7	113.0	30.0	40.0	69.5	3.5

increases in crop and pasture yield, but a very large increase in forest productivity. If only crop yields decline, then crops are less able to compete with other U.S. land uses, and land area for crops declines. If only crop yields increase, then land area for U.S. crops increases, crowding out land area for pasture, forests, and unmanaged land. In the UIUC (2.5 °C) scenario with CO_2 fertilization, the large increase in forest productivity dominates land use change.

4.2. CONSUMER AND PRODUCER WELFARE

Indexes of consumption and output can be constructed for each climate scenario. Each percentage change in Table V for consumption and net output shows the change in an index relative to baseline, using model output from year 2080. The consumption and net output indexes include agricultural and forestry goods, with prices as weights. The concept of net output used in Table V is gross output less that used in other agricultural processes. For example, grains used as animal feed are part of gross output, but not part of net output. Net output for U.S. agriculture varies much more across climate scenario than consumption; international trade patterns adjust so that consumption remains close to baseline.

Changes in net output from Table V refer to primary agriculture: the production of crops, animal products, and forest products. Primary agriculture is a small fraction of national gross domestic product in the United States, and the implied impact on national welfare in an open economy is small, less than one percent.

The change in net output of U.S. primary agriculture represents a change in welfare that can be allocated across domestic consumers, domestic producers, and international trade partners. See the Appendix to this paper for a description of the methodology. Percentages in the last three columns of Table V sum exactly

TABLE V
Changes in consumption and net output of U.S. primary agriculture relative to baseline in 2080

Scenario	Change in consumption	Change in net output	Components of change in net output		
			Consumer	Producer	Trade
Without CO_2 effect					
BMRC 2.5	−1.0%	−16.6%	−4.3%	−12.1%	−0.2%
UIUC 2.5	−0.4%	−6.8%	−2.3%	−4.2%	−0.3%
UIUC 2.5 + Sulfates	−0.5%	−7.3%	−2.5%	−4.5%	−0.3%
With CO_2 effect					
BMRC 2.5	0.0%	−2.5%	0.4%	−3.2%	0.3%
UIUC 2.5	0.4%	9.0%	1.8%	6.8%	0.4%
UIUC 2.5 + Sulfates	0.4%	8.0%	1.9%	5.8%	0.2%

to the change in net output; they are interpreted as the change in U.S. net output of agricultural and forestry products absorbed by domestic consumers, domestic producers, and international trade partners.

In most of the scenarios, changes in consumer and producer welfare have the same sign. All results in Table V are for the case where climate impacts are applied to U.S. agricultural and forestry, but not to other countries. The pattern of change in net output, across climate scenarios, is similar to the percentage change in crop yield.

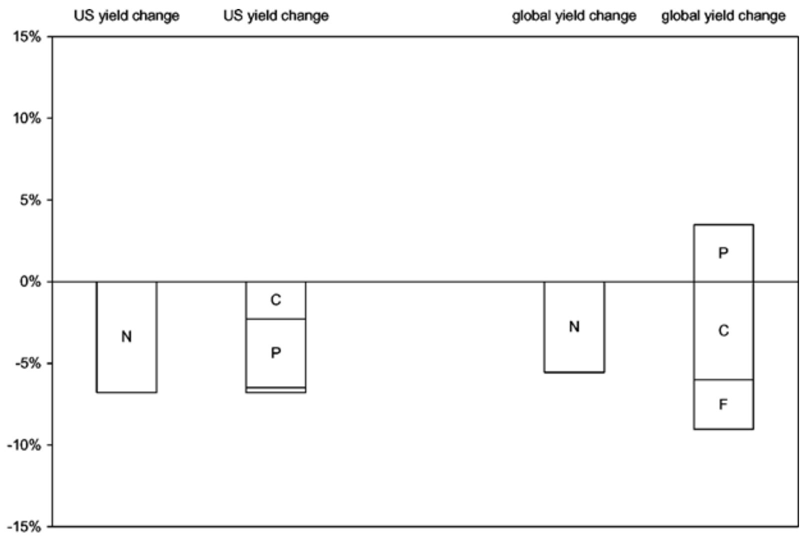
4.3. ROLE OF BIOMASS ENERGY CROPS

The focus of this study has been on climate impacts, but biomass energy crops may become a major land use, especially if the price of oil were substantially higher or if a carbon policy provided incentives for biofuel production. Sands and Leimbach (2003) presented scenarios where biomass energy crops became major land users under a global carbon policy. One could consider future scenarios with both a changing climate and a climate policy designed to stabilize concentrations of greenhouse gases. In this case, biomass energy crops become a link between the agricultural and energy systems. The amount of land devoted to biomass energy crops depends on several factors, including the future productivity of competing food crops, the future productivity of biomass energy crops, the price of fossil fuels, and the magnitude of a carbon price. For any given greenhouse gas concentration target under a climate policy, the cost of meeting that target depends in part on the availability of biomass energy crops, which in turn depends on the productivity of global agriculture. Increasing crop yields, either due to improved technology or changes in climate, reduce the cost of meeting a concentration target. A decline in crop yields increases the cost of meeting that target.

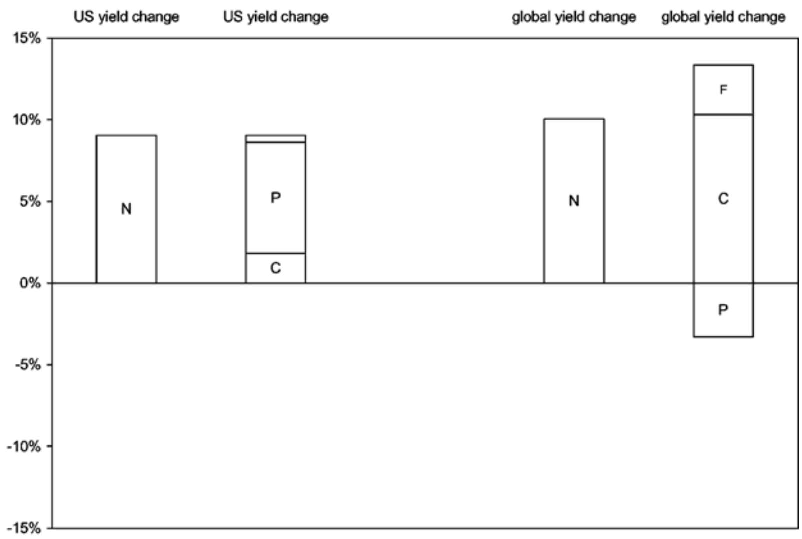
5. Sensitivity to Global Yield Change

Analysis in the previous section covered the case where United States crops, pasture, and managed forests are affected by specific climate change scenarios, but yields in other countries are unchanged. This section covers additional cases where crop yields in the rest of the world are assumed to change in the same direction and to the same extent as in the United States.

Results from Table V on net output and its decomposition are plotted on the left side of Figure 5a for the UIUC (2.5 °C) climate scenario without CO_2 fertilization. The overall loss in welfare of 6.8% is shared by domestic consumers and domestic producers, with a small amount allocated to international trade partners. However, the welfare results change if yield changes outside the U.S. in the same way that it changes within the U.S. In this case, shown on the right side of Figure 5a, producers



(a) UIUC (2.5 °C) without CO_2 effect



(b) UIUC (2.5 °C) with CO_2 effect

Figure 5. Change in net output (N) for primary agriculture in the United States under two climate scenarios relative to baseline: (a) UIUC (2.5 °C) without CO_2 effect; (b) UIUC (2.5 °C) with CO_2 effect. The percentage change in net output from the agricultural and forestry system is decomposed into three welfare components: change in surplus for domestic consumers (C); change in producer surplus (P); and change in surplus for foreign consumers (F). Columns on the left side represent the case where changes in yield are applied to the U.S. only, while yield in other countries is unchanged. Columns on the right side represent the case where changes in yield for the U.S. are applied globally.

TABLE VI
United States summary by sensitivity scenario

Scenario	Simulation year	Total U.S. crops: Production (Pcal)	Total U.S. crops: Land use (million ha)	U.S. Land rent (1990 = 100)
Baseline	1990	1,143	99.0	100
Baseline	2080	2,770	157.8	123
Change in U.S. yields				
UIUC 2.5 without CO_2 effect	2080	2,645	151.8	120
UIUC 2.5 with CO_2 effect	2080	2,717	143.0	137
U.S. yield change applied globally				
UIUC 2.5 without CO_2 effect	2080	2,942	178.4	125
UIUC 2.5 with CO_2 effect	2080	2,605	144.8	119

gain in welfare, while both domestic and foreign consumers have a loss in welfare. Producer welfare is tied to the price of land; if yield falls in only the U.S., then domestic producers are at a disadvantage relative to foreign producers. If yield falls everywhere, then the price of land is bid up everywhere to keep consumption of agricultural goods closer to where it was without climate change.

Figure 5b provides the same type of results as Figure 5a, except that the UIUC (2.5 °C) climate scenario now includes a CO_2 fertilization effect. All welfare components change in sign relative to Figure 5a. An overall gain in welfare of 9.0% is allocated across domestic consumers, domestic producers, and foreign consumers.

Consumer welfare is tied to the price of consumption goods: prices fall when yields rise and consumers are better off. If yield increases occur globally instead of just in the U.S., then prices fall even further and U.S. consumers are even better off. Producer welfare is tied to the price of land. If yields increase in the U.S. only, then U.S. producers have an advantage relative to foreign producers. If yields increase everywhere, then land is less scarce as a resource and land rents fall everywhere. Table VI provides additional model output, including U.S. land rents, across scenarios.

6. Summary

The impact of climate change and CO_2 fertilization on U.S. agriculture is the focus of this exploratory study. PNNL's Agriculture and Land Use model is used to integrate results on crop yields, water demand for irrigation, water supply and productivity of unmanaged ecosystems in the framework of an economic analysis. This study incorporates the full impact of climate change by year 2080, when population growth, a wealthier population, and higher crop yields create an agricultural system larger in scale than today.

Two climate scenarios, UIUC (2.5 °C) *without* CO_2 fertilization and UIUC (2.5 °C) C *with* CO_2 fertilization, are used to represent a range of impacts on U.S. agricultural production. Crop yields are generally lower than they would be otherwise in the UIUC (2.5 °C) without CO_2 fertilization scenario, and higher with UIUC (2.5 °C) and CO_2 fertilization. Therefore, the presence or absence of the CO_2 fertilization effect is a primary determinant of changes in yield and economic welfare. One difficulty is that results from other papers in this issue provide broad geographic coverage of the United States, but no coverage for other countries that trade agricultural goods with the United States. We circumvent this difficulty through scenarios where crop yields outside the United States are assumed to be either unchanged, or to move in the same direction as in the United States.

U.S. consumers of agricultural and forestry products are better off when yields increase, and worse off when yields decline; consumer welfare depends on the prices paid for agricultural and forestry products. A global change in yield has a greater effect on prices, and therefore consumer welfare, than does a local change in yield. U.S producers of agricultural and forestry products could be better or worse off, depending on whether the change in yield is local or global. Producer welfare is tied directly to land rent, which moves in the opposite direction of a global change in yield. However, a local increase (decrease) in yield can result in a local increase (decrease) in land rent.

We address major uncertainties in this paper using scenarios that vary along three dimensions: choice of climate model, effect of CO_2 fertilization, and treatment of international trade. Even though this study addresses important determinants of future agricultural systems, there remain opportunities for further analysis and model improvement. Our single distribution of land quality for the United States masks geographical variation that may limit the amount of possible land use change; splitting the U.S. into regions should be considered. Better treatment of resource constraints beyond land, especially labor in countries with subsistence agriculture, and water in all countries, would be especially helpful for a more realistic evaluation of maintaining agricultural production under conditions of climate change. Another aspect of future agricultural and land use scenarios that should be addressed is the presence or absence of a climate policy, and the corresponding economic incentives for production of commercial biofuels and maintenance of forest land to store carbon.

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Appendix

The purpose of this Appendix is to create a quantity index to measure the change in economic output between climate scenarios, and decompose this change into various welfare measures. If there is an economic gain or loss from climate change, how is the gain or loss distributed among consumers and producers? This methodology depends on placing model results for United States agriculture and forestry within an input-output framework, where land is the primary factor of production. The input-output structure creates an accounting boundary around U.S. agriculture and forestry, where capital, labor, and other non-agricultural inputs are considered "imports" to the agricultural and forestry system. Net output, or final demand, is consumption plus exports minus imports.

A quantity index of net output, which is also equal to gross output less its uses in other domestic agricultural production processes, is used to compare economic output across climate scenarios at a point in time. For example, net output of coarse grains is total production less that used to feed animals and to produce sweeteners and oils. A quantity index of net output is created with prices as weights, where the prices vary by product but are fixed across scenarios under comparison. The change in this quantity index of net output from a baseline scenario 0 to a climate scenario 1 is calculated as:

$$\frac{1}{2}\sum_i \left(P_0^i + P_1^i\right)\left(C_1^i + X_1^i\right) - \frac{1}{2}\sum_i \left(P_0^i + P_1^i\right)\left(C_0^i + X_0^i\right), \tag{A1}$$

where i is an index over agricultural and forestry products, P_k^i is the price of product i in scenario k, C_k^i is consumption of product i in scenario k, and X_k^i is the net export (exports minus imports) of product i in scenario k. We have constructed a quantity index to measure change in output between scenarios, with average prices $\frac{1}{2}(P_0^i + P_1^i)$ as weights. With these prices as weights, the change in the quantity of net output from Equation (1) can be decomposed into the sum of three terms: change in consumer surplus, change in surplus for trade partners, and change in payments to primary factors of production (landowners). The change in consumer surplus is written as:

$$\frac{1}{2}\sum_i \left(P_0^i - P_1^i\right)\left(C_0^i + C_1^i\right) \tag{A2}$$

Equation (2) is interpreted as a change in price multiplied by average consumption. The change in consumer surplus is positive if prices decline. A similar term is constructed for the change in surplus for countries that import agricultural products from the United States.

$$\frac{1}{2}\sum_i \left(P_0^i - P_1^i\right)\left(X_0^i + X_1^i\right) \tag{A3}$$

The third welfare component is the change in payments to primary factors of production. This relies on the accounting identity that the value of payments to primary factors equals the value of final demand. The change in value of final demand is written as:

$$\sum_i P_1^i\left(C_1^i + X_1^i\right) - \sum_i P_0^i\left(C_0^i + X_0^i\right) \tag{A4}$$

Equation (1) can be written as the sum of Equations (2), (3), and (4) by combining like terms. With this exercise, we have constructed an expression for a change in the quantity of net output that is equal to the sum of three welfare measures.

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CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT SUMMARY

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Abstract. This special issue of *Climatic Change* describes an effort to improve methodology for integrated assessment of impacts and consequences of climatic change. Highlights of the seven foregoing Parts (papers) that constitute this special issue are summarized here. The methodology developed involves construction of scenarios of climate change that are used to drive individual sectoral models for simulating impacts on crop production, irrigation demand, water supply and change in productivity and geography of unmanaged ecosystems. Economic impacts of the changes predicted by integrating the results of the several sectoral simulation models are calculated through an agricultural land-use model. While these analyses were conducted for the conterminous United States alone, their global implications are also considered in this summary as is the need for further improvements in integrated assessment methodology.

1. Introduction

In this special issue of *Climatic Change*, a group of analysts in the Joint Global Change Research Institute (JGCRI) report an effort to improve methodology for integrated assessment of the impacts of climatic change. More specifically, our objective has been to develop methods for integrating results from general circulation models with dynamic process-level understanding of agriculture, hydrology and economic behavior in a state-of-the-art integrated assessment model. To accomplish this, we undertook to develop techniques for modeling the interactive impacts of climate on agriculture, water resources and the economy of the conterminous U.S.A. This required that five issues be addressed: (1) climate change mapping; (2) potential agricultural production; (3) irrigation demand; (4) quantifying changes in the balance of water demand and supply at the regional scale and (5) the economic response to changes in potential agricultural supplies and demands against a background of evolving demographic, economic, and climatic circumstances. Agriculture in our study involved simulating the production of food and feed grains and forage. Emphasis in the water sector was on simulating the availability of surface supplies. However, as the research proceeded we recognized the need to link changes in agricultural productivity and/or water supply for irrigation, driven by our scenarios of climate change, to changes in biogeography and productivity of

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unmanaged ecosystems, driven by the same forces. Accordingly Issue 4 was broadened to provide information on what will happen to specific areas of land lost to agriculture, i.e., will they revert to grassland, shrubland or forest ecosystems such as the new climate determines? Under unmanaged ecosystems, we considered climate change impacts on the geography and productivity of 17 categories of forest and grassland vegetation. Additionally, we assumed that rising demand for food, feed and fiber will require that at least some land now in unmanaged ecosystems be converted to agricultural production. Our treatment of Issue 5 was also expanded by consideration of the economic consequences of reallocations of land driven by climate change impacts and changing demand for agricultural products.

2. Scenarios

The scenarios selected for this study were intended to bracket a wide range of possible climate futures. Regional distributions from two different GCMs were used. To further broaden the range of scenarios two levels of climate sensitivity were used for each GCM using the SCENGEN methodology (Wigley, 1994; Hulme et al., 1995). Finally, the scenarios were modified to reflect the effects of sulfur aerosol forcing in addition to greenhouse gas accumulations. All of this results in a range of temperature change over the 48 conterminous states relative to 1990 that varies from a mean increase of 0.4–3.6 °C. Sub-regions of the United States can show even wider variation. The regional distributions of climate change employed here are probably realistic, not in specific detail, but in the notion that change will not be uniform but, rather, regionally complex.

This analysis recognizes the fact that the climate changes considered here are set in a future time. While we do not associate the changes with specific time periods, the projected climate changes can be put into context. Part 1 estimates that, in the absence of explicit measures to limit the concentrations of greenhouse gases in the atmosphere, a 1 °C increase in global mean temperature relative to 1990 is almost certain to occur before the end of this century. An increase of 2.5 °C is not likely to occur before 2050. However, the possibility exists that this temperature increase may be exceeded or that it may not be reached within this century.

Our study began before GCMs were chosen for the U.S. National Assessment of the Potential Consequences of Climate Variability and Change (USGCRP, 2000). Those were the Canadian Global Coupled Model (CGCM) and the British Hadley Centre Coupled Model (version 2) (HadCM2 model). In terms of climate patterns, the former is much like BMRC (Bureau of Meteorology Research Center) in that its changes to climate in the mid-North American continent are adverse to agricultural productivity; the latter is much like UIUC (University of Illinois Urbana-Champagne) in projecting relatively moderate warming and increased precipitation for much of the U.S. A study such as ours is in danger of obsolescence almost before it begins because of the constant rush of new GCMs or new runs of older ones. We argue, however, that selection of GCM is not a very critical matter in assessments of climate change impacts since the uncertainties associated with them overwhelm the uncertainties associated with the kinds of crop, ecosystem and hydrology process models that we and other assessors use. The latter models are verifiable under the natural range of variability that exists in current climate. Put another way, while commonly used crop models given the same climate, soils, and management input data will produce a range of yields that may differ by 20 or 30%, GCMs may produce climate changes that are very much larger and that for particular regions often disagree with respect to sign as well as magnitude of the projected changes. This 'mismatch of confidence' in assessment models will continue until a new generation of GCMs provides considerably better agreement with regard to the regional distribution of climate change. Suffice to say here that the scenarios constructed for this exercise provide for a wide range of possible future climate changes.

Our choice of the UIUC model was influenced by two factors: first, that Stanford University's Energy Modeling Forum had commissioned UIUC to produce a large set of GCM outputs needed by the IA community. Also, at the time, UIUC was one of very few GCMs that dealt with the effects of aerosols. Actually, as it turned out, differences due to inclusion of aerosol effects in these studies were not dramatic, especially when results are aggregated to the national level. And, in the meanwhile, a significant change has occurred in thinking about sulfate aerosol effects, in that the newest emission scenarios generally show a decrease in their importance particularly in the developed nations of the world. Impacts due to the climate effects of sulfate aerosols are likely to be most important over the next half century. Thereafter, the pattern of global change will likely be one dominated by greenhouse gases that warm the atmosphere rather than by aerosols that cool it.

3. Agricultural Modeling Results

With the EPIC model described in Part 2, we simulated agricultural production under dryland conditions in the United States in response to the suite of 12 climate change scenarios developed. The total production of corn, soybean, winter wheat, alfalfa and clover hay was calculated "full-out" as if each crop were grown over all arable land in the country. It was also calculated for the actual current core production areas of these crops (Part 3). The full-out analysis provides a means of identifying new areas that climate change may make available. Some generalities stemming from this analysis are that production tends to be lower in the scenarios associated with higher global mean temperature and that the manifestation of a "CO_2-fertilization effect" raises production and offsets losses. Because of its great extent, its variable soils, typography and climate, the overall *national* production of the several crops studied is not greatly affected by the climatic change scenarios used, since gains and losses in the different producing regions tend to offset one another. However, because we modeled the country in 204 distinct geographic units, we were able to identify important differences in regional impacts. Study of the "Currently Possible Production Areas" indicates that the regions most likely to be affected by climate change are those on the margins of the areas in which they are currently grown. The EPIC model also provided information used in Part 5 on changes in the amounts of water needed for irrigation for all crops and regions.

4. Water Modeling Results

Using the HUMUS model (described in Part 2), which treats the hydrologic cycle in a comprehensive manner, we simulated changes in the hydrology of the conterminous United States to determine, under each of the climate change scenarios, whether the needed irrigation water will be available (Part 4). Of the several parameters modeled by HUMUS we take the changes in "water yield", an approximation of streamflow, to indicate within-basin water supply. The GCMs used to provide climate change scenarios for this study disagree on whether the US as a whole or any of its constituent regions will receive more or less precipitation as the globe warms. Therefore, the scenarios provide a wide range of possible outcomes. Under all scenarios change will likely be most consequential in the semi-arid and arid western U.S. Increases and decreases in water yields may be greater than 50% in the Midwest and Southwest. Interannual variability is likely to increase where water yield is reduced and to decrease with wetter conditions. Because of its transpiration suppression effect on the vegetation covering the modeled basins, the CO_2-fertilization effect causes a small but significant increase in water yields.

5. The Irrigation Fix (An Adaptation)

It is as certain as anything can be in this arena that land and water resource managers will adapt to the impacts of climate change to the extent that economics and available resources allow. We did not, in this study, simulate the effects of such well-known adaptations as changing cultivar maturity (although planting date was automatically adjusted to the climate scenario) since the merits of these and other such simple and relatively inexpensive adaptations have been amply demonstrated in the literature of the past two decades (e.g., Easterling et al., 1992; Rosenzweig et al., 2000; Reilly et al., 2003). Since higher temperatures and certainly reduced precipitation, were they to occur, would lower crop yield in most regions, we use irrigation as a prime example of a contingent adaptation.

Climate change will alter not only crop yields but water availability as well. A previous effort to integrate the agricultural water demand from EPIC and the water supply from HUMUS was made by Rosenberg et al. (2004) and Izaurralde et al. (2003) based on modeling results from the National Assessment. There, a ratio of water supply to water demand was calculated to examine the regional variation in water availability under climate change as projected by the HadCM2 model. In contrast, the approach here uses the projected water supply simulated by HUMUS as a constraint on the agricultural production aggregated from the EPIC model results. By comparing change in the demand of grain crops for irrigation water with change in available supply under the same set of climate change scenarios, we were able to identify regions in which climate change makes irrigation more or less feasible, impossible or unnecessary. In addition, we assess the overall impacts of changes in water supply on national grain production.

Drawing on data from Parts 3 and 4, we calculate national production in current crop growing regions by applying irrigation where it improves crop yields. Irrigation is applied regionally and only over as much land area as can be supported by the projected water supply. For the purposes of this analysis we arbitrarily assume that, neglecting other potential demands, all water in a watershed is available for irrigation within that watershed and that no inter-basin transfers occur. This allows us to set an upper limit on the extent of the impact of irrigation within each of the climate change scenarios. In what is perhaps one of the more counter-intuitive findings, total irrigation in the continental US (under the assumptions and constraints applied) declines under all climate change scenarios employed in this study. In certain regions and scenarios, precipitation declines so much that water supplies are limited and very little cropland can be irrigated; in other scenarios precipitation is so plentiful that crop yields do not increase with irrigation so that it is not applied. Total crop production, aggregated from the regional to the national scale, is greater under irrigation than under dryland conditions at the baseline and under all climate change scenarios. With irrigation simulated, we found corn and soybean production to be lower than baseline under most of the climate change scenarios. Production of winter wheat under irrigation responds significantly to elevated atmospheric CO_2 concentration and appears likely to increase under climate change.

The degree to which we have coupled and integrated results of the crop and water models in Parts 3–5 represents an advance in integrated assessment technique. Our analysis shows that the availability of water for irrigation is an important factor in determining overall agricultural production in the U.S. Agriculture is tightly constrained by water in many regions of the country and the world, especially so in the drier regions where conflicts over water are intensified as the result of climatic change. Integrated assessment would be advanced and agricultural production estimates be more realistic were water availability for irrigation not assumed, but constrained by competing societal demands in the form of withdrawals for municipal water supply, minimum streamflows for navigation, ecosystem management, power plant cooling and other important consumptive and non-consumptive uses.

6. Unmanaged Ecosystems

In addition to our modeling of agricultural crops and water resources, we also characterized the range in response of unmanaged ecosystems in the conterminous U.S.

to the 12 climate change scenarios used throughout this study. Responses were identified in terms of changes in net primary productivity (NPP) and in identification of the areas of the country where land cover changes would be most likely for any particular scenario of climate change. We found with the BIOME 3 model that changes in NPP would be most severe under the BMRC climates in which the rise in regional temperatures is most extreme and is coupled with a decrease in precipitation. In contrast, the UIUC and UIUC + Sulfate scenarios lead to increases in NPP, especially in the West where precipitation increases most. Simulated changes in NPP under greenhouse warming were significant and at times drastic. For example, most scenarios predicted a significant reduction or even disappearance of the Temperate/Boreal Mixed Forests. As well, two other forest biomes (Temperate Conifer and Temperate Deciduous) showed increases in areal extent under the UIUC and UIUC + Sulfate scenarios. Under current climate, the Arid Shrubland/Steppe could potentially occupy 18% of the conterminous U.S. while under the BMRC scenario it would cover almost half of the country. Such striking changes would certainly bring severe consequences for the functioning of ecosystems and people. The inclusion of sulfate aerosols in the climate change scenarios of the UIUC GCM did not produce consistent responses in the distribution of biomes across the conterminous U.S. While in general the differences in biome distribution were small, the area covered by Temperate Conifer Forests under the UIUC + Sulfate scenario decreased by 9% with respect to the same UIUC scenario without sulfates. CO_2-fertilization either favored an increase or alleviated the loss in NPP caused by the climate change scenarios.

Thus, our land-cover modeling employed a simple but consistent way to examine the interactive response of unmanaged and agricultural ecosystems to climate change. The GIS-based methodology allowed for the identification of regions under natural vegetation that, because of climate change, might become available for crop production as well as regions where native ecosystems might expand as a result of agricultural abandonment. The analysis demonstrated the complexity of environmental change and the challenges we face in developing consistent scenarios with which to examine the best paths toward sustainable development, a task difficult enough under a presumable static climate state but likely even more so under changing climatic conditions.

In future work, we will include more realistic representations of land-use change. There is also need to incorporate feedbacks describing soil nutrient dynamics into the simulations, since these will affect plant response to climate change and especially to atmospheric CO_2 concentration.

7. Economics

Agriculture takes place in an economic environment and farmers and other land-users make decisions in response to the circumstances they face. As those circumstances change, so too do their decisions and actions. Climate change adds another source of change and therefore would be expected to result in altered behavior on the part of those using land. We have explored the implication of changes described in Parts 1 through 6 for the agricultural markets and land-use in Part 7.

In Parts 2 through 6 EPIC, HUMUS and BIOME 3 were exercised to provide a large amount of process detail on crops, pastures, forests, and unmanaged ecosystems. This information has been incorporated into an energy-economy-agricultural model with a time scale appropriate for climate studies (one century). The AgLU model also allowed consideration of key global drivers of agriculture and land-use such as technological change and changing demands for food. A link to the energy system through commercial biomass was also explored.

Future changes in productivity could not be taken directly from the process models as exercised in Parts 2 through 6, because agricultural productivity has shown a strong historical tendency to change with time and the timing of climate changes is uncertain (Part 1). Therefore, in Parts 2 through 6 we ignored technological change. However, the economic analysis explicitly addressed the fact that climate change is set in the future and not in the present. That future includes significant changes in many dimensions including demographics, general economic well being, and technology across a wide spectrum of human endeavors. Changes in agricultural productivity from the EPIC model were treated as relative changes when introduced into the AgLU model.

To facilitate comparison with a well- known quantitative description of developments during the new century, one of the cases articulated in the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakicenovic et al., 2000), the B2 scenario as described using the JGCRI integrated assessment model, MiniCAM, was selected as a reference baseline (no climate change) case. This scenario can be described as "Dynamics-as-Usual" (Riahi and Roehrl, 2000) in which innovation proceeds with no drastic changes in socio-economic and energy system assumptions. Emissions levels from this scenario are intermediate with the SRES scenarios, with industrial carbon dioxide emissions nearly tripling over the 21st century.

The MiniCAM B2 scenario has a global population that stabilizes at 9.4 billion people. Gross world product increases by an order of magnitude. Both primary energy and final energy more than triple during the 21st century. Land-use change emissions increase initially, but decline to zero in the second half of the 21st century and then go negative as reforestation exceeds deforestation. Finally, fossil fuel carbon emissions grow from six billion tons of carbon per year in 1990 to more than 20 billion tons of carbon per year by the end of the 21st century, implying a CO_2 concentration that exceeds 700 vppm. In the reference scenario, agricultural yields were assumed to increase during the period 1990 to 2095 at a fixed rate of 1% per year from 1990 to 2035 and at 0.5% per year thereafter. This allowed the AgLU model to calculate global food, feed, and forest-product requirements over time and the changes in U.S. land-use that would be required under alternative climate change scenarios so as to accommodate increasing demands both domestically and internationally. Inferences concerning the possible productivity of biomass crops in the U.S. were drawn from the EPIC and BIOME 3 modeling in earlier papers of ours (e.g. Brown et al., 2000) and scenarios of biomass demand based on its competitiveness under various credible energy futures also affected the AgLU calculations of global land-use under each of the 12 climate change scenarios. Assumptions about changes in agricultural productivity outside the United States are treated on a scenario basis, either responding in the same way as in the United States, or not responding at all. Commercial biomass is considered as an option for displacing fossil fuels in scenarios with limits on carbon emissions.

The presence or absence of a CO_2-fertilization effect strongly affects results. Climate change yields welfare gains for the United States when the CO_2-fertilization effect is operative, while losses are experienced when it is not. Agriculture and land-use markets act to dampen impacts. If yields decline globally, the price of agricultural products will rise, causing marginal land to enter production. If cropland expands to meet demand it will do so at the expense of unmanaged land and marginal productivity will decline; declines in crop productivity will require proportionately larger increases in cropland. To the extent that those marginal lands retain more carbon as unmanaged than as managed ecosystems, the potential is raised for an additional net release of carbon to the atmosphere.

At this point in the evolution of our integrated assessment approach we recognize the need both to further refine the detail with which we study the United States and the need to apply the biophysical models to other important agricultural regions if not, indeed, to the rest of the world. We are, in fact, now doing both. For the United States, we would like an improved understanding of the potential for increasing biomass and crop production beyond just agricultural land, as defined in our study. Other questions needing answers: Will water supplies suffice as populations and affluence grow under stable and changing climates? Are there physical (let alone societal) obstacles to expansion of commercial biomass onto non-agricultural lands?

8. Some Final Thoughts

So, what are the big lessons, technical and strategic, learned from this extensive analysis? The research reported here builds on the approach taken by Rosenberg et al. (1991, 1993). As such, it is complementary to the approach forged by the IMAGE (Integrated Model to Assess the Greenhouse Effect modeling team (Alcamo et al., 1994) and by the AIM (Asia-Pacific Integrated Modeling) team (Morita et al., 1993). Where these approaches yield similar answers to a common question, the insight has a robustness that would not otherwise be available. Where these approaches yield contradictory insights, further research is clearly needed.

The impacts of changing climate will not be experienced in the present but, rather, in the future. One of the first and most obvious, but nonetheless critical, lessons is the importance of setting the analysis of potential impacts of climate change in their appropriate place and time. The future will bring with it both potential advantages in dealing with climate change as well as potential stresses which could exacerbate impacts of climate change. We have seen examples of both in this study. For example, our results show that negative impacts of climate change on crop yields could be mitigated by elevated CO_2 concentrations. On the other hand, the stress of climate change on unmanaged ecosystems could be increased by the effects of increasing human population and its associated activities.

Our examination of agriculture in this study highlights the importance of the CO_2 -fertilization effect. For agriculture in the United States in the year 2080 the CO_2-fertilization effect has an impact as large or larger than that attributable to the difference in climate models used. That is, the difference in agricultural productivity observed when we compared a case that considered climate change alone with one that considered the combined effects of climate change and CO_2-fertilization were larger than the aggregate productivity difference we observed between the UIUC model and the BMRC model. We note, of course, that both the UIUC and BMRC models were employed at Global Mean Temperatures of 1 and 2.5 °C – somewhat less that the 4.5–5.5 °C that could possibly occur in this century. And our point is not to downplay the value of improved climate model prediction for analysis of the impact of climate change on agriculture, but rather to remind ourselves that CO_2-fertilization plays a non-trivial role and that a better understanding of its long-term effects for agriculture can also be powerful.

Furthermore, the future of agriculture is strongly affected by the rate of technological change in the reference case. In fact, this fundamental uncertainty is associated with a far larger uncertainty in future production than climate change with or without the CO_2-fertilization effect. To the extent that climate change occurs against a background of high productivity growth, the effects of climate change on welfare are modest. But, to the extent that climate change takes place against a background of low productivity growth climate change worsens an already stressed system. Our analysis of potential net loss to society is relatively modest in the year 2080 when climate change is 2.5 °C for both the UIUC and BMRC models – a few tenths of a percent when compared with GDP. But substantial local changes – both positive and negative – in economic well-being are observed. And these changes affect producers and consumers differently.

A real surprise to us was the decline in the demand for irrigation under the climate change scenarios we studied. In some regions and scenarios, precipitation declines so much that water supplies are limited and very little cropland can be irrigated; in other scenarios precipitation is so plentiful that no benefit is derived from crop irrigation.

Whereas consumers are relatively well buffered from the negative impacts of climate change, individual producers and ecosystems are not. Very substantial changes in ecosystem productivity are observed for some cases. Depending on whether the UIUC or BMRC climate model was assumed to predict future climate, the forestry sector in the United States either flourishes or is virtually destroyed. Given the enormous variation in the potential magnitude, timing and character of climate change noted above, our analysis highlights the need for advances in general circulation models and no less in regionalization of the distribution of change in climatic variables of importance to natural processes such as photosynthesis and evapotranspiration. These include means and extremes of temperature, precipitation amounts and distributions and features of the wind and humidity regimes. Lacking credible predictions of changes in climate, impact models cannot be used to their full capability. If we could know with any degree of certainty what the climate of the Corn Belt will be 50 yr from now, we could begin to model specific adaptations to those changes.

So, as we look to the future with this project complete, we see great value in pursuing improvements in scenario development and a fuller and more integrated assessment. It is not only the physical systems of concern that are affected by climate change. Markets and economies are also affected. We have begun the work of mapping the full set of interactions between the climate change, CO_2-fertilization, energy and agricultural markets and land-use. But much work remains before us. If nothing else, the analysis presented here can be expanded to a truly global and truly integrated assessment. By that we mean not only coverage of the world's lands, but also all of the relevant human activities and markets.

Were that done, many questions could then be brought into sharper focus. For example, how will emissions mitigation activities and impacts interact? If hydrogen production creates a large new demand for water, and biomass farms expand into currently unmanaged lands, mitigation could have adverse effects on ecosystems. Are there insights that can help define the proper balance over time and space between emissions mitigation and adaptation to climate change? Technological change in agriculture could be the most critical factor affecting agriculture in the century ahead and is, therefore, a prime candidate for further research.

Other research is also indicated. In this study, we implicitly assume that the statistical distribution of climate variables on a day-to-day basis is identical across time, with changes only in the mean monthly distribution. Changes in the distribution of climatic variables can have a significant impact on agricultural production. Improved information on the statistical distribution of climate variables under climate change could, when coupled to an integrated assessment framework, yield significant insights.

The wide variation in potential future climate change, CO_2-fertilization effects, and rates of technological progress in agriculture, noted above, argues for the development of yet another approach to integrated assessment. Rather than ask the question, "what climate changes will occur and what could their consequences be?" one might ask the complementary question, "where, when, how and how much must climate change before the consequences are of various prescribed magnitudes. The latter approach is not intended as a substitute for the former, but rather an approach that could yield valuable knowledge. But perhaps the most important methodological advance that we can propose is the application and extension of our integrated assessment methodology combining impacts on crop yield, water supply, irrigation prospects and land-use change to the world scale. While our approach is demanding, it appears to be feasible, and if successful would provide insights heretofore unavailable. So, it seems fitting to conclude our second installment of the saga of integrated assessment of the impacts climate change with the thought "Today the Lower 48, on to the world and the world of tomorrow!"

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