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CLIMATE CHANGE IMPACTS ON THE POTENTIAL PRODUCTIVITY OF CORN AND WINTER WHEAT IN THEIR PRIMARY UNITED STATES GROWING REGIONS

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Abstract. We calculate the impacts of climate effects inferred from three atmospheric general circulation models (GCMs) at three levels of climate change severity associated with change in global mean temperature (GMT) of 1.0, 2.5 and 5.0 °C and three levels of atmospheric CO_2 concentration ($[CO_2]$) – 365 (no CO_2 fertilization effect), 560 and 750 ppm – on the potential production of dryland winter wheat (Triticum aestivum L.) and corn (Zea mays L.) for the primary (current) U.S. growing regions of each crop. This analysis is a subset of the Global Change Assessment Model (GCAM) which has the goal of integrating the linkages and feedbacks among human activities and resulting greenhouse gas emissions, changes in atmospheric composition and resulting climate change, and impacts on terrestrial systems. A set of representative farms was designed for each of the primary production regions studied and the Erosion Productivity Impact Calculator (EPIC) was used to simulate crop response to climate change. The GCMs applied were the Goddard Institute of Space Studies (GISS), the United Kingdom Meteorological Transient (UKTR) and the Australian Bureau of Meteorological Research Center (BMRC), each regionalized by means of a scenario generator (SCENGEN). The GISS scenarios have the least impact on corn and wheat production, reducing national potential production for corn by 6% and wheat by 7% at a GMT of 2.5 °C and no CO_2 fertilization effect; the UKTR scenario had the most severe impact on wheat, reducing production by 18% under the same conditions; BMRC had the greatest negative impact on corn, reducing production by 20%. A GMT increase of 1.0 °C marginally decreased corn and wheat production. Increasing GMT had a detrimental impact on both corn and wheat production, with wheat production suffering the greatest losses. Decreases for wheat production at GMT 5.0 and $[CO_2] = 365$ ppm range from 36% for the GISS to 76% for the UKTR scenario. Increases in atmospheric $[CO_2]$ had a positive impact on both corn and wheat production. AT GMT 1.0, an increase in $[CO_2]$ to 560 ppm resulted in a net increase in corn and wheat production above baseline levels (from 18 to 29% for wheat and 2 to 5% for corn). Increases in $[CO_2]$ help to offset yield reductions at higher GMT levels; in most cases, however, these increases are not sufficient to return crop production to baseline levels.

1. Introduction

Climatic change will, to a greater or lesser degree, affect virtually every natural resource and economic sector. The Pacific Northwest National Laboratory (PNNL) is developing a system for integrated assessment of the causes and effects of anthropogenically-driven climatic change. That system, the Global Change Assessment Model (Edmonds et al., 1994) or GCAM, calculates emissions of greenhouse gases on the basis of economic activity (by means of the Second Generation Model (Edmonds et al., 1995)), determines the degree of warming that results from these

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and other anthropogenically-driven emissions (by means of the MAGICC model (Wigley, 1994)), scales the output of general circulation models (GCMs) to the severity of global warming, distributing the changes in GCM grid-boxes to regions of varying size and/or shape required by impact simulation models (by means of the SCENGEN system of Hulme et al., 1995) and calculates the effects of these regional climate changes on agriculture, forests, water resources and unmanaged ecosystems by means of appropriate process models. As its name indicates, GCAM deals with the globe as a whole. Also, it is useful to think of the GMT as a surrogate for time. The further along we go on any emissions path that increases the atmospheric content of greenhouse gases (and other substances that affect the global radiation balance), the greater becomes the GMT. Despite this linear characterization of GCAM, it should be understood that feedbacks and interactions occur among all of its components.

A major part of the GCAM modeling activities includes an evaluation of the potential impact of climate change on agricultural production and consequent changes in land use. Within the confines of an integrated assessment, such an evaluation must address the impacts that climate change will have on crop growth and productivity and then link the changes in crop growth into an economics model. This paper addresses the first step in this process and reports on the response of winter wheat (Triticum aestivum L.) and corn (Zea mays L.) production to three GCM scenarios set at three levels of severity and three levels of CO_2 fertilization. In its full application GCAM will simulate the growth and yield of major grain crops over all the arable land in the conterminous United States. We do this since, regardless of whether any particular region is currently capable of supporting a particular crop, climate change may be great enough at some point to make it possible. Thus, the application of a particular GCM may show corn growing well under dryland conditions in the Great Basin, where today that would not be possible. A typical ‘full-out’ run of this kind (Figure 1) shows changes in corn yield simulated under the BMRC GCM at a level of severity associated with a global mean temperature change of 2.5 °C and no CO_2 fertilization effect (see Section III.B below for details. The origin of the geographic units shown in the figure are also explained below).

As an aide to those concerned with the more likely and nearer-term impacts of climate change, we select for this paper data from the ‘full-out’ set national-coverage simulations data to represent the current U.S. growing regions for corn and winter wheat. Policy and decision makers in these regions are most immediately concerned with the questions of how the crops that currently underpin their economies might fare. Also in this preliminary set of analyses we do not consider adaptation, not for lack of belief that adaptations to changing climate will be made and will be important. But the suite of appropriate adaptations is very great and would require a much more extensive set of simulations if both ‘on the shelf’ adaptations (e.g. changing cultivars, planting dates) and ‘policy-driven’ adaptations (e.g. irrigation, increased heat and drought resistance, greater photosynthetic efficiency) are to be dealt with. Indeed, the notion of the ‘dumb farmer’ who fails

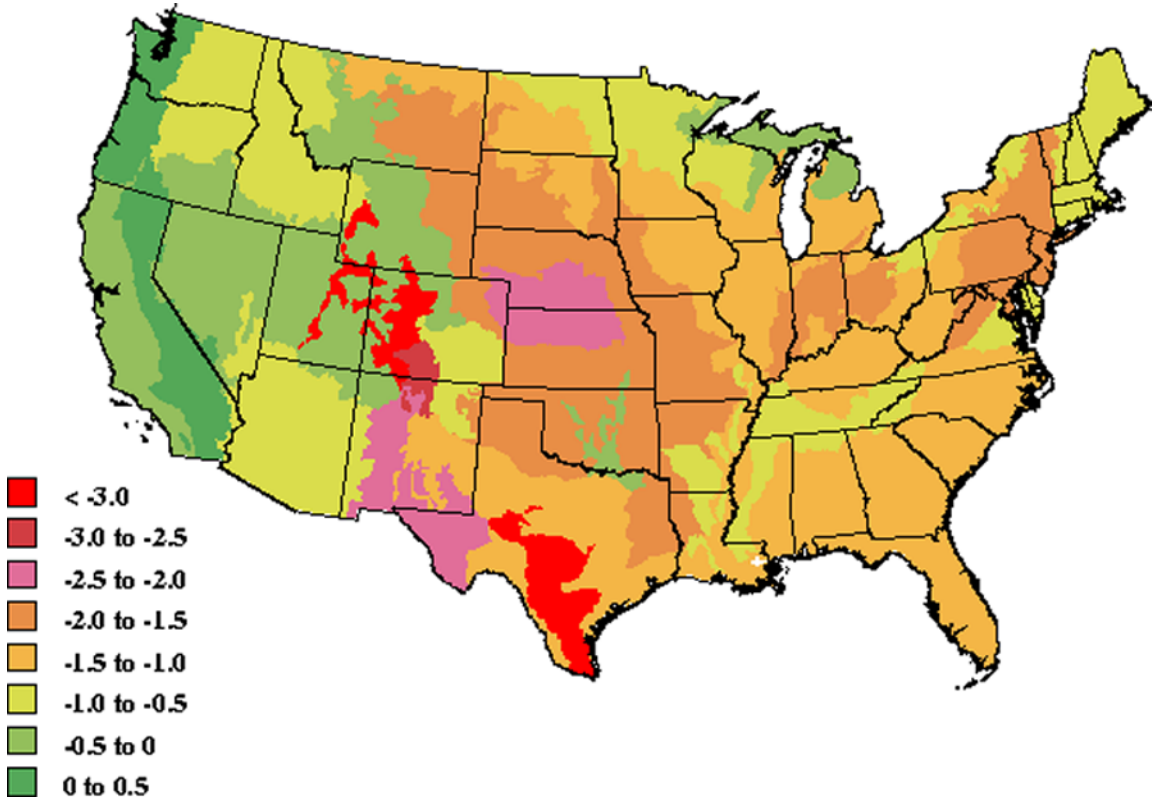

Figure 1. Change in dryland corn yield from baseline for the BMRC GCM at a global mean temperature of 2.5 °C and atmosheric [CO_2] set at 365 ppm: an example of GCAM 'full-out' production analysis.

to adapt and the ‘smart farmer’ who does was formally introduced in integrated assessment by one of us (NJR) in a study of climate change impacts on natural resources in the central U.S. (the MINK Study, Rosenberg, ed. 1992, 1993).

2. Literature

Since 1958, the rising concentration of CO_2 in the atmosphere, documented in the Mauna Loa record (Keeling, 1984) and at other observatories throughout the world, began to generate concern that the troposphere might warm enough to induce significant changes in global climate. This concern has stimulated the study of potential impacts of climatic change on all sectors of human activity and interests. Early studies devoted to agriculture used ‘off the shelf’ regression models (e.g., Bach, 1979; Newman, 1982; Blasing and Solomon, 1982). But as Katz (1977) and Rosenberg (1982) have shown, such models are useful only within the climatic range in which they are calibrated and cannot be reliably extrapolated beyond the range in which the statistical relationship applies.

Regression models have given way to process-level crop simulation models in assessments of climate change impacts on agriculture. Largely, the development of these models has been motivated by the need to anticipate yields and potential regional or national production as the growing season progresses and to guide farm-level management (planting date, fertilization, pesticide application and irrigation). The Erosion Productivity Impact Calculator (EPIC, Williams et al., 1984), used in this study, is one such model. It was developed for the U.S. Department of Agriculture, Natural Resources Conservation Service, in order to assess potential erodability of U.S. lands as affected by weather, crop rotation, tillage and other management practices. Because of its focus on soil erosion and its application to the entire United States, EPIC was required to simulate the growth of virtually all major crops. In that way it differs from other prominent modeling systems such as CERES (Ritchie et al., 1985) and SOYGRO (Wilkerson et al., 1985; Jones et al., 1988) and others that focus on one or, at most, a few crops.

Process-based models are better equipped than regression models to extrapolate beyond the range of current climatic conditions because crop responses to varying temperature, humidity, soil moisture and irradiance can be established through experimentation at the leaf and whole plant levels in controlled climates. The whole plant response can then be evaluated in terms of the causal plant physiological processes such as photosynthesis, respiration, transpiration and translocation. The effects of CO_2 fertilization on crop yields and water use (summarized in reviews e.g. Kimball, 1983; Cure, 1985; Rosenberg et al., 1990; Idso and Idso, 1994) can also be simulated on the basis of abundant experimentation relating CO_2 concentration to photosynthesis and evapotranspiration.

Process-level simulation models are now widely used in studies of climate change impacts. Some recent examples include Rosenzweig (1989), Rosenberg, ed. (1992), Easterling et al. (1992), Mearns et al. (1992), Butterfield and Morison (1992), Rosenzweig et al. (1994), Semenov and Porter (1995), Peiris et al. (1995), Yin et al. (1995), and Wang and Conner (1996). The use of crop yield simulation models for the study of climate change impacts is not without problems, however, as their critics and users (often the same persons) are quick to proclaim and/or admit. A recent symposium on the 'Use and Abuse of Crop Simulation Models' (Baker, 1996) provides good perspective on this question. The contribution to this symposium by Passioura (1996) is particularly critical of the use of simulation models to project effects of climate change on crop growth. He reasons that such models cannot be extrapolated beyond the calibrating data set and that the processes being modeled are generally non-linear '. . . so that interactions between them can often lead to unexpected results'.

Most users of simulation models for purposes of climate impacts analysis recognize this weakness. Yet policy development in the face of what most scientists believe to be a real threat of climatic change (e.g., IPCC, 1995) requires estimates of its possible impacts on agriculture and other sectors – estimates, in other words, of what is at risk. Such estimates can be based on the best – albeit imperfect – tools available or on other, less scientific approaches. Well-designed simulation models, it can be argued, do at least deal with the important crop physiological processes and incorporate experimentally established data on physiological, morphological and yield response to the environmental factors thought likely to change over a range exceeding current experience. All crop simulations models, admittedly, rely on empiricism to a greater or lesser extent. However, the alternative to their use is the extension of empirical regression models beyond the range of climatic conditions within which they have been established and that do not treat with process at all. Imperfect as they are, process models permit not only a regional but a global view (e.g. Rosenzweig and Iglesias, 1994) of climate change impacts on agriculture and permit systematic assessment of adaptation opportunities. The results of process crop models have been successfully incorporated in economic analyses, e.g.. Adams et al. (1990), Kaiser et al. (1993), Rosenzweig and Parry (1994), and Bowes and Crosson (1993).

All models used to study crop response to climate change require information on expected changes in temperature and precipitation. But crop yields are affected as well by changes in other controlling climatic parameters – humidity and solar radiation, for example – and in such important physiological parameters affected by atmospheric carbon dioxide concentration ([CO_2]) – as leaf area index and stomatal resistance. In a recent study Brown and Rosenberg (1997) used EPIC to estimate the sensitivity of crop yields to each of the factors mentioned above, individually and in combination. Production of corn, soybean, winter wheat and sorghum was simulated with EPIC on five representative Midwestern farms over a range of temperature, precipitation, solar radiation, humidity and [CO_2] conditions. Stomatal resistance and leaf area index were also varied in some of the simulations. Changes in each of these variables altered crop yields and water use. The direct effects of each climatic and plant (LAI, stomatal resistance) variable and their interactions indicate that future studies of climate change impacts should consider the full spectrum of climate variables and changes in atmospheric CO_2 and not just temperature and precipitation. In this study we do not directly apply the GCM projections of change in solar radiation and relative humidity; rather these parameters are treated endogenously and are varied in response to GCM-projected temperature and precipitation changes by the weather generator embedded in EPIC.

3. Methods and Materials

3.1. THE EPIC MODEL

EPIC (version 3090) is the crop growth simulator used in this study. EPIC models agricultural production on the scale of single fields or 'representative farms' and simulates photosynthesis, evapotranspiration, and other major plant and soil processes. The representative farm is an entity that typifies agriculture in large coherent regions. It is characterized by its soil type, topography, rotation and management practices such as tillage, fertilization, irrigation, etc. Soil series and properties for each farm were derived from the STATSGO soils database (USDA-SCS, 1992). Climatic conditions on each representative farm were derived from the daily records of the nearest National Weather Service Cooperative Climate Network station (Reek et al., 1992). For the purposes of the current study the 1960–1989 climate record provides a no-climate-change 'baseline'. In order that climate effects on yields not be unduly confounded by other factors, EPIC was configured to model optimal farm management. Planting date and growing season length were allowed to vary based on heat units required for a crop to attain maturity, and fertilizer was applied 'on demand' up to a maximum of 150 kg N/ha annually. By setting an upper boundary of 150 kg N/ha, fertilizer levels were kept within reasonable bounds for a modern farm operation. For many of the farms, N stress was reduced to virtually zero. However, it should be noted that imposing an upper limit to 'on demand' fertilization does not guarantee the absence of N stress and for a number of corn farms, N stress is still present.

EPIC runs on a daily time step requiring the input of daily weather data. Records of actual daily weather may be used or EPIC can simulate daily weather with the aid of a stochastic weather generator, WXGEN (Richardson and Nicks, 1990). For this study the historical daily climate record of precipitation and min/max temperature from 1960–1989 was used as the baseline climate. The climate change cases were developed by applying the GCM monthly changes in temperature and precipitation provided by SCENGEN to the daily climate record. WXGEN was used to generate daily values of solar radiation, relative humidity and wind speed for both the baseline climate and the climate change scenarios, scaling these values according to daily temperature and precipitation.

EPIC calculates the maximum daily increase in plant biomass made possible by the daily total of solar radiation incident on the field. The algorithms used to model potential plant growth (biomass accumulation) are driven by photosynthetically active radiation (PAR). The amount of solar radiation captured by the crop is a function of PAR and leaf area index (LAI). The amount of solar radiation converted into photosynthate (biomass) is a function of a crop-specific radiation use efficiency. Solar radiation also provides the energy that drives evapotranspiration. Temperature affects rates of photosynthesis, respiration and transpiration in EPIC and determines (via heat units) the rate of plant phenological development and duration of the growing season. EPIC counts the days on which temperature stress (heat or cold) occurs. A stress day reduces potential crop yield by a fixed amount. Changes in timing or amount of precipitation affect soil moisture supply and crop yield. EPIC counts days on which atmospheric demand for soil moisture exceeds supply as a water-stress day. Atmospheric humidity modulates evapotranspiration and affects radiation use efficiency in photosynthesis. Stockle and Kiniry (1991) adjusted the radiation use efficiency in EPIC to account for the influence of vapor pressure deficit. Elevated concentrations of CO_2 increase the rate of photosynthesis in C_3 plant species (small grains, legumes, most trees and root crops) grown under controlled conditions and reduce water use in both C_3 and C_4 species (tropical grasses such as corn, sorghum, sugar cane, millet). In EPIC the effects of rising $[CO_2]$ are expressed through increases in radiation use efficiency. This, among other effects, results in increased leaf area index (LAI) and increases in stomatal resistance that reduce transpiration. The EPIC algorithms that relate LAI and stomatal resistance to photosynthesis and transpiration were altered by Stockle et al. (1992a) and Stockle et al. (1992b) to accommodate the effects of changes in atmospheric $[CO_2]$. Nitrogen stress also limits crop growth. Nitrogen is applied in our simulations in quantities consistent with optimal farming practices in the regions studied, but these quantities are not always large enough to preclude the occurrence of some nitrogen stress, often driven by climatic conditions (mineralization of N is affected by temperature and soil moisture; precipitation determines the amounts of nitrogen lost to the crop by leaching and runoff). Demand for N is affected by the daily rate of plant growth, phenological stage and duration of the growing season – factors also controlled by climate. Thus, in EPIC, climate change can affect the number of nitrogen-stress days by altering both the availability and demand for nitrogen.

3.2. THE REGIONS AND REPRESENTATIVE FARMS

Fifty-five regions have been defined for the GCAM analysis of U.S. agriculture by superimposing the Soil Conservation Service Land Resource Regions (USDA/SCS, 1981) onto the 18 U.S. Geological Survey Water Resource Regions (USGS, 1987) of the coterminous states. Twenty-four of the 82 regions covering most of the

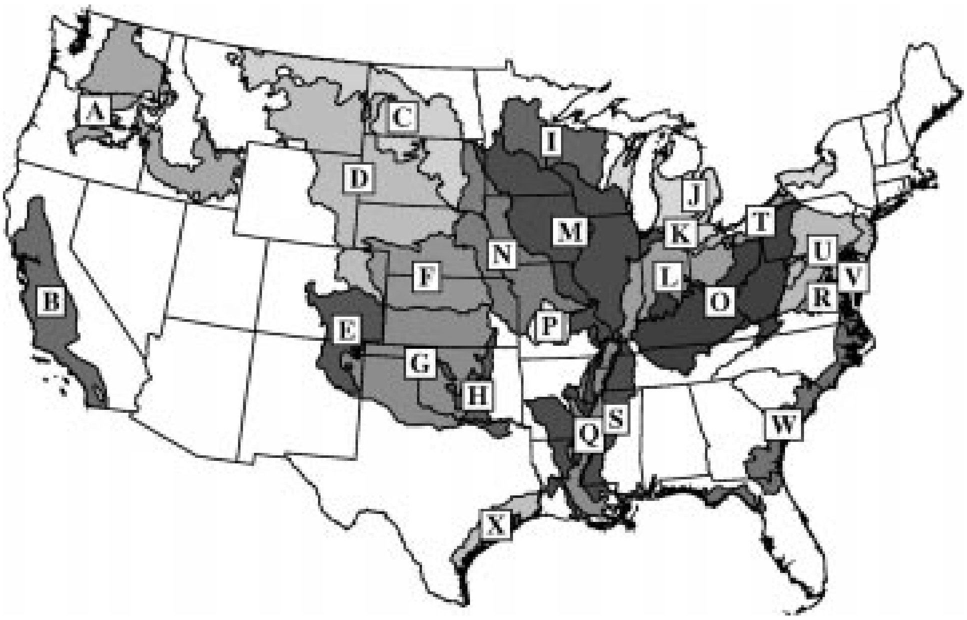

Figure 2. The twenty-four land units used in EPIC modeling of the corn and wheat growing regions.

primary and secondary winter wheat and corn production in the U.S. were used in this analysis (Figure 2). These regions are identified by block letters in the figure.

Figure 3 shows the production regions studied for winter wheat and corn, respectively. Information on the farms shown in Figure 3, their locations, soil series and associated climatological stations is given in Appendix I. The primary winter wheat production regions are in the central Midwest, the central and northern Great Plains, the Palouse of the Pacific Northwest and the Central Valley of California. The primary production region for corn is the Cornbelt which includes the eastern Great Plains and most of the U.S. Midwest. The corn region also includes the Mississippi Delta, the mid-Atlantic states and the Southern coastal plain. Small areas of production in New England and South Florida are not included in our analysis. The winter wheat regions defined in Figure 3 cover 16% of the United States but account for 68% of total winter wheat production and 70% of the total area harvested. The corn regions cover 26% of the United States and account for 88% of the total corn production and 87% of the total area harvested. This paper deals only with dryland production. However, we include currently irrigated regions in our coverage since the range of climate change conditions in our simulations could conceivably make dryland production necessary and/or possible in these regions.

3.3. VALIDATION OF EPIC BASELINE CROP YIELDS

The aim of the validation exercise reported below was modest – to establish whether EPIC treatment of the processes controlling crop yield in combination

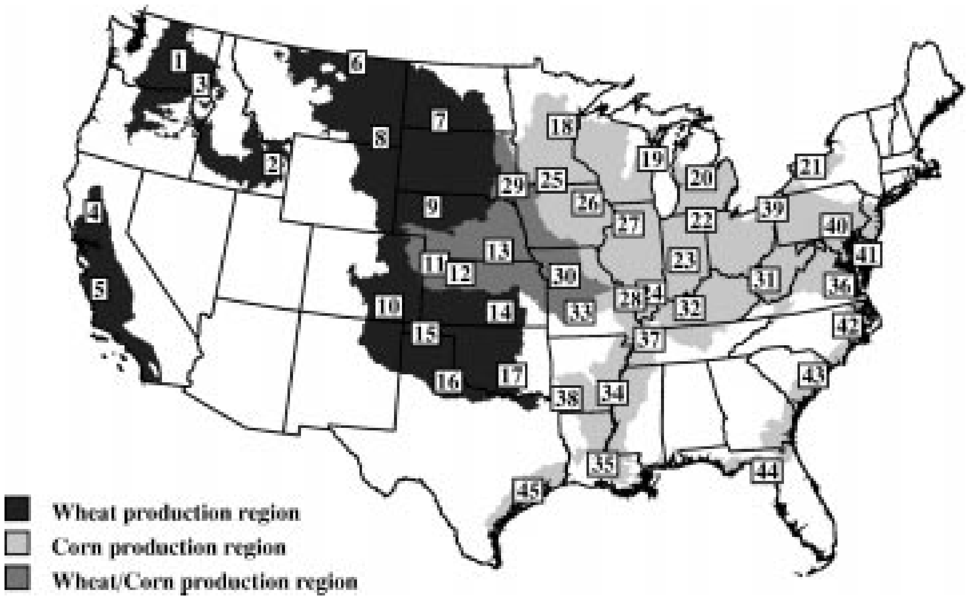

Figure 3. The major corn and winter wheat growing regions of the U.S. and location of the representative farms modeled.

with our parameterizations of the representative farms allow for ‘ballpark’ agreement with historic yields obtained for the regions studied. Following procedures developed by Rosenberg et al. (1992), the simulated yields were compared with yield data from three sources: the NASS county crops database (USDA-NASS, 1972–1994); state-average yields published in USDA (1995); and reports of agronomic experiments and crop variety trials. EPIC yields were simulated using daily historic climate from 1960 through 1989. NASS yields are for the period 1972–1994 and are county averages of yield/harvested acre (USDA-NASS, 1972–1994); state-wide yields of corn are from 1971–1993; the period for wheat is 1988–1993 (USDA, 1995). The experimental yields are from the late 1980’s and early 1990’s. The EPIC simulations are derived from a much longer time period than the actual yields. We recognize that this difference may bias the comparison of simulated and observed data. However, the lack of synchrony among data sets may be less of a problem than might first appear since the simulations employ current management practices for the entire period modeled. Simulated and actual yields are compared in Table I and summarized for each crop and GCAM region.

Table I also presents the root mean square error (RMSE), which measures the agreement between simulated yields and observed yields. The RMSE shows that both simulated corn and wheat yields agree best with experimental yields and least well with NASS yields. EPIC yields exceed NASS yields in most of the regions studied. The difference between NASS and EPIC is particularly great for corn in regions Q, S, W, X (Mississippi Delta and southeastern U.S.) and for wheat in

TABLE I

Ranges of EPIC simulated, experimental, NASS county crops database, and historic state average yields

GCAM	Crop	EPIC		Experiments	NASS	State totals
region		# of Farms	Range (t/ha)	Range (t/ha)	Range (t/ha)	Range (t/ha)
A,B	Wheat	5	1.5–4.3	5.9	1.5–3.2	3.9–5.2
C,D	Wheat	4	2.5–4.2	2.2–3.9	1.6–1.8	2.1–2.0
E,F,G,H	Wheat	11	1.0–4.3	1.9–3.3	1.1–2.5	1.9–2.9
EPIC Mean and RMSE from observed yields (wheat for all regions)			**3.2**	**1.2**	**1.7**	**1.4**
F	Corn	3	4.8–7.8	2.1–8.7	2.8–4.2	8.0–8.3
I,M,N,P	Corn	8	6.4–8.7	6.7–11.1	4.2–7.3	4.6–7.5
J,K,L,O,R,T,U,V	Corn	14	6.3–8.6	6.5–10.0	4.4–6.7	6.0–7.4
Q,S,W,X	Corn	6	6.9–8.6	10.4	2.5–5.3	6.7
EPIC Mean and RMSE from observed yields (corn for all regions)			**7.6**	**1.6**	**3.0**	**1.7**

regions C and D (northern Great Plains). A combination of factors explains the tendency for EPIC to overestimate yields. First, EPIC is not able to capture the impact of extreme climatic events such as hail storms, floods and late or early frosts on yields. Second, EPIC does not capture the impact of disease or pest outbreaks on crop yields. Third, as has been explained in Section III.A, EPIC, as we have used it, assumes a high level of technology and optimal crop management with regard to harvest efficiency, fertilizer application and tillage operations. One or all of these factors may combine to cause EPIC to overestimate historic yields in any particular region.

In regions A, B (Pacific Northwest and California) for wheat and region F (central Great Plains) for corn, EPIC underestimates state average yields because irrigated crops predominate in these regions. In the remaining regions, EPIC overestimates state average yields. However, for both corn and wheat the RMSE between EPIC and state average yields is smaller than for the NASS comparison. The agreement between EPIC yields and experimental yields is further explored in Figure 4. The majority of the experimental corn yields exceed EPIC yields. Wheat yields, on the other hand, slightly overestimate experimental yields. Some differences between EPIC yields and experimental yields are to be expected, since we did not parameterize the model to mimic the environmental conditions for each experiment or crop trial and only used experimental yields as a surrogate for potential yields for a region. Even though the EPIC yields are not able to match historic county crop yields and in some cases state average yields, the agreement between EPIC yields and experimental yields is sufficiently good for the purposes of this study.

3.4. THE CLIMATE CHANGE ENVELOPE

We proceed on the assumption that climate will change if greenhouse gases continue to increase in concentration in the atmosphere (Houghton et al., 1996). But uncertainties regarding the regional distribution of climate change and the severity of change remain substantial. In addition, as stated above, evidence for a CO_2 fertilization effect is strong but uncertainties remain about how it will manifest itself. In this paper, therefore, we array the results of our simulations of potential climate change effects on crop production in the U.S. in an ‘envelope’ designed to capture the three sources of uncertainty:

1. Regional distribution of climate change as projected by a set of general circulation models (GCMs). Since we cannot be confident that any one of the available GCMs is closer to truth than any other, we have chosen to use three that project considerably different changes for the major agricultural regions of the country. These are the Goddard Institute for Space Studies (GISS; Hansen et al., 1984), UK Meteorological Office Transient (UKTR; Murphy, 1995) and

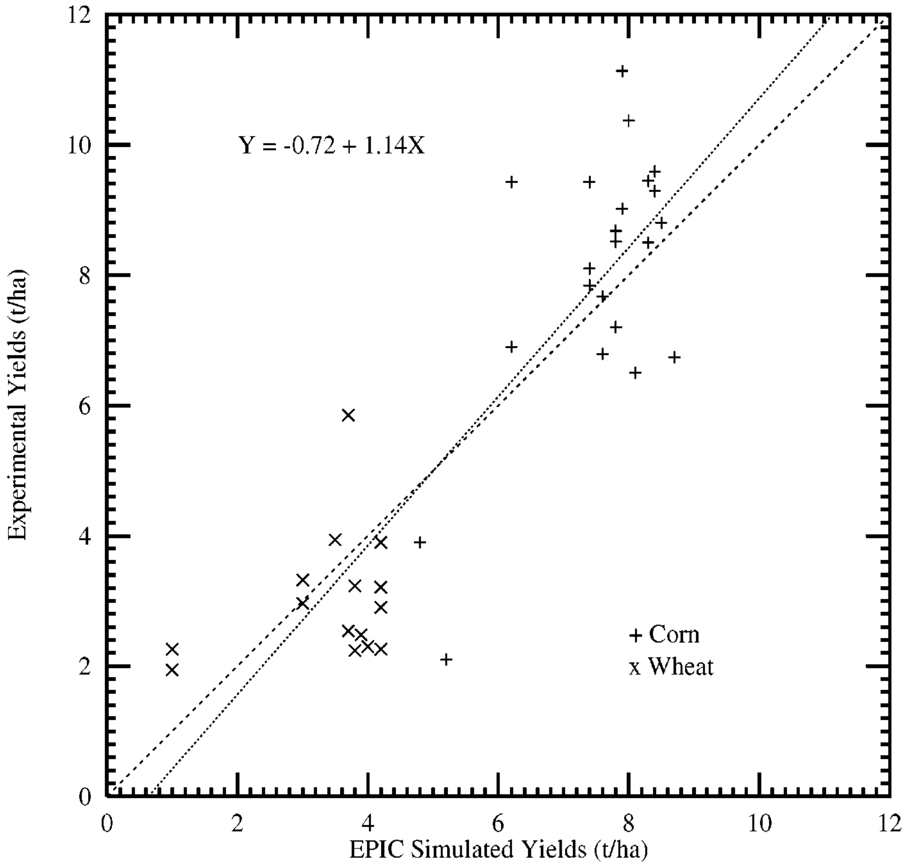

Figure 4. Comparison of EPIC-simulated corn and winter wheat yield with experimental yields in the vicinity of the EPIC representative farms.

the Australian Bureau of Meteorology Research Center (BMRC; McAveny et al., 1991) models;*

2. Severity of regional climate change determined by the extent of greenhouse warming (indicated by global mean temperature change, GMT);
3. Direct effects of the rising atmospheric carbon dioxide concentration on plant growth and yield.

Both GMT and [CO_2] can be thought of as surrogates for time. The date at which any particular [CO_2] or GMT will be reached depends on the emissions scenarios and atmospheric chemistry models employed. For example, IPCC emissions scenarios (Houghton et al., 1996) are frequently used in climate change analyses.

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* Each GCM projects the regional distribution of climate changes that would occur at a doubling of the pre-industrial carbon dioxide concentration. A unique increase in global mean temperature (GMT) occurs at this so-called ‘2 × CO_2’ concentration. SCENGEN permits us to scale the severity of the regionally distributed changes in climate consistent with larger or smaller GMTs.

TABLE II

Factorial design of climate change scenarios applied to the EPIC simulations

Scenario	Change in GMT (°C)	Atmospheric [CO_2] (ppm)
1 (baseline)	0.0	365
2	1.0	365
3		560
4		750
5	2.5	365
6		560
7		750
8	5.0	365
9		560
10		750

One such, IS92a, describes a pathway consistent with ‘business as usual’ (no efforts to mitigate emissions). When applied through the MAGICC model (Wigley, 1994) IS92a projects atmospheric [CO_2] of 560 ppm by 2060 and 750 ppm by 2100. Under that same scenario MAGICC projects that GMT will increase 1.0 °C by about 2045, 2.5 °C by 2105 and 5.0 °C by 2150.

Mean yields and standard deviations of corn and winter wheat crops were simulated under rainfed conditions for each representative farm listed in Appendix 1. The factorial design shown in Table II is applied to each farm. In addition, baseline yields are simulated with no climate change and at the near-current CO_2 concentration of 365 ppm. This requires 10 scenarios per farm. The design is employed with each of the three GCMs so that the total number of simulations required for corn in this analysis is:

for corn: 31 farms $\times$ 9 simulations per GCM $\times$ 3 GCMs $=$ 837 simulations plus 31 baseline runs $=$ 868 simulations; for winter wheat with a total of 20 farms, 560 simulations are required.

4. Results

4.1. CLIMATE CHANGE SCENARIOS

The three GCMs employed in this study project climate changes of differing severity for the major U.S. corn and winter wheat growing regions. Annual changes in mean temperature and precipitation projected by the three GCMs normalized to a

TABLE III

Range of changes in annual mean temperature and precipitation projected for the U.S. corn and winter wheat producing regions by three GCMs at GMT = 1.0 °C

GCM	GISS		UKTR		BMRC	
region	Temp. change (°C)	PPT change (%)	Temp. change (°C)	PPT change (%)	Temp. change (°C)	PPT change (%)
Northern Corn Belt	0.8–1.2	2.5–7.5	1.6–2.0	2.5–7.5	1.6–2.0	–2.5–2.5
Southern Corn Belt	0.8–1.2	–2.5–2.5	1.6–2.0	7.5–12.5	1.6–2.0	–2.5– –7.5
Northern Wheat Belt	0.8–1.2	2.5–7.5	1.6–2.4	2.5–7.5	1.2–1.6	–2.5–2.5
Southern Wheat Belt	0.8–1.2	–2.5–2.5	1.6–2.4	2.5–7.5	1.2–1.6	–2.5–2.5

global mean temperature (GMT) of 1.0 °C are shown in Table III. GISS warms both regions from 0.8 to 1.2 °C. UKTR and BMRC warm the corn region by as much as 2.0 °C, while UKTR warms the wheat region by as much as 2.4 °C, more than either of the other GCMs. Precipitation projections differ within the regions. GISS increases precipitation in the northern portions of the corn and wheat regions and decreases it in parts of the southern portion. UKTR increases precipitation overall, but most in parts of the southern corn region. Precipitation is decreased most by BMRC in the southern portion of the corn region.

Table III deals only with changes in annual means of temperature and precipitation. Seasonal changes are likely to be more meaningful in terms of the plant responses they evoke. Therefore, in Table IV we present data on seasonal climate changes projected by each of the GCMs at a GMT of 1.0 °C for a select number of the representative farms. As was shown in Table III, the GISS scenario is the most moderate with the least warming of any GCM in all seasons. Its greatest precipitation increases occur in winter. UKTR temperatures are highest in all seasons with the least degree of warming in spring. The seasonal distribution of precipitation shifts with increases in winter and decreases in summer. The BMRC scenario projects the most severe climate changes with the largest of any GCM decreases in precipitation coupled with the greatest temperature increase. Increases in precipitation under BMRC generally occur only in winter; summer precipitation is generally reduced. The seasonal patterns of change described above apply primarily to the large contiguous corn and wheat regions. Effects in the Palouse and Central Valley differ slightly.

4.2. CLIMATE CHANGE IMPACTS ON YIELD AND PRODUCTION

The tables and figures that follow provide information on the effects of the various climate change scenarios on yield and production of winter wheat and corn. A subsample of cases from the ‘envelope’ is selected to illustrate the separate effects of GCM, GMT and [CO_2] on individual farm yields in Tables V–VII for wheat and VIII–X for corn. The factors that explain the resulting yields are documented in these tables. Figures 5 and 6 are used to show effects of the entire envelope and illustrate factorially the interactions of GMT and [CO_2] within GCM. The measure applied in the figures is percentage change in the aggregated national production of the two crops.

4.2.1. *Farm Level Yields of Winter Wheat*

Effects of Climate Change Scenario (GCM)

Table V displays yields of winter wheat, length of the growing season and numbers of stress days at a set of representative farms under the baseline climate and for the three GCMs at their most moderate (GMT = 1.0 °C) and with no CO_2-fertilization effect ([CO_2] = 365 ppm). On many of the farms yields are unaffected or increase

TABLE IV

GCM projected deviations from baseline seasonal means of temperature and precipitation. Baseline climate contains the 1960–1989 daily record with baseline temperature units in (C) and precipitation units in (mm). For GCM, temperature changes in (C) and precipitation changes in percent

GCAM	Climate	Temperature (°C)				Precipitation (mm)			
region	scenario	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
A	Baseline	**–0.8**	**9.9**	**20.8**	**10**	**83**	**61**	**37**	**60**
	GISS	1.3	0.9	0.9	1.2	9	5	4	2
	UKTR	1.4	1.3	2.1	2.1	8	2	–6	4
	BMRC	1.4	0.9	1.5	1	–1	0	–11	2
B	Baseline	**8.6**	**13.2**	**21**	**15.7**	**229**	**127**	**16**	**89**
	GISS	1	0.9	1	1	2	4	3	3
	UKTR	1.1	1.1	1.3	1.3	14	–8	2	–4
	BMRC	1.1	1.1	1.1	0.9	–5	–3	–12	–12
C	Baseline	**–10.3**	**5.3**	**19.9**	**6.6**	**34**	**146**	**210**	**79**
	GISS	1.4	1.1	0.8	1.2	7	3	2	–2
	UKTR	2.3	1.8	1.7	2	14	12	1	5
	BMRC	1.8	1.2	1.6	1.3	4	4	–7	–1
G	Baseline	**1**	**10.6**	**22.2**	**12.1**	**31**	**135**	**218**	**93**
	GISS	1.1	1	0.9	1.2	3	2	3	0
	UKTR	1.9	1.3	1.9	1.7	9	5	–4	2
	BMRC	1.6	1.7	1.6	1.3	–4	–3	–7	–10
J	Baseline	**–5.1**	**7.2**	**20.4**	**9.8**	**125**	**214**	**255**	**232**
	GISS	1.3	1	0.8	1.1	3	2	1	–5
	UKTR	2.1	1.6	1.9	1.8	12	5	–5	–5
	BMRC	2.2	1.6	1.5	1.6	4	–1	–3	–1
L	Baseline	**–2.7**	**10.2**	**22.3**	**12.1**	**190**	**300**	**315**	**231**
	GISS	1.3	1.1	0.8	1.4	2	1	1	–3
	UKTR	2.3	1.5	1.7	1.8	12	3	0	–5
	BMRC	2	1.5	1.5	1.5	1	–4	–4	–2
Q	Baseline	**10.7**	**19.1**	**25.9**	**19.2**	**403**	**399**	**478**	**354**
	GISS	1	1	0.9	1.1	–2	–3	0	6
	UKTR	1.7	1	1.5	1.6	0	1	–3	–5
	BMRC	1.2	1.5	0.9	1.1	–7	–6	–8	–2
U	Baseline	**–1.1**	**10.4**	**22.4**	**12.4**	**222**	**287**	**295**	**262**
	GISS	1.3	1	0.8	1	2	1	3	–7
	UKTR	2.4	1.6	2	1.8	12	1	1	0
	BMRC	2.2	1.7	1.4	1.6	1	–2	–5	–3

TABLE V

Simulated winter wheat yields under baseline conditions and under three GCM-derived climate change scenarios at a GMT of 1.0 with no CO_2-fertilization (365 ppm). Length of growing season and numbers of stress days are also shown

GCAM region	Farm #	Baseline					GISS					UKTR					BMRC				
		Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)		
				Water	Temp.	N			Water	Temp.	N			Water	Temp.	N			Water	Temp.	N
A	1	1.5	276	29	32	0	1.6	270	30	28	0	1.6	268	26	25	0	1.5	269	31	27	0
A	2	2.5	325	35	47	0	2.8	319	39	41	0	2.6	315	41	39	0	2.2	315	40	41	0
A	3	3.7	257	21	26	0	3.7	249	18	25	0	3.7	248	15	22	0	3.7	248	18	24	0
B	4	3.2	196	5	11	0	3.0	191	4	9	0	3.0	191	4	8	0	2.9	190	5	9	0
B	5	4.3	212	7	7	0	4.0	205	5	6	0	4.0	205	4	6	0	4.0	204	5	6	0
C	6	2.5	321	35	54	0	2.4	316	40	49	0	2.4	312	44	46	0	2.1	315	41	49	0
C	7	4.2	322	27	57	0	4.2	317	28	53	0	4.3	314	31	49	0	4.0	315	30	53	0
D	8	3.5	320	32	50	0	3.6	314	36	45	0	3.5	311	41	41	0	3.0	312	39	44	0
D	9	4.2	294	27	45	0	4.1	281	27	42	0	3.9	267	28	40	0	3.7	279	30	42	0
E	10	0.9	277	44	25	0	0.9	274	49	20	0	0.9	271	53	18	0	0.8	269	50	19	0
F	11	3.0	273	21	36	0	3.0	273	23	31	0	2.9	273	25	29	0	2.6	272	26	31	0
F	12	3.7	269	20	36	0	3.5	269	23	31	0	3.4	267	26	28	0	3.2	266	25	31	0
F	13	3.8	275	11	45	0	3.9	272	10	41	0	3.9	271	10	38	0	3.8	272	10	41	0
G	14	3.9	257	8	37	0	4.0	256	7	34	0	4.1	253	6	31	0	3.9	253	7	34	0
G	15	2.2	264	17	28	0	2.0	260	19	23	0	1.9	258	21	19	0	1.6	257	22	22	0
G	16	2.4	216	5	20	0	2.2	215	4	18	0	2.4	214	3	17	0	2.0	212	4	19	0
H	17	2.1	216	5	19	0	1.9	213	4	17	0	1.9	211	3	16	0	1.9	212	4	18	0
N	29	4.3	309	15	57	0	4.5	304	15	54	0	4.6	302	16	52	0	4.4	302	15	54	0
N	30	4.0	270	6	42	0	3.9	266	4	39	0	3.9	263	3	38	0	3.8	263	4	41	0
P	33	3.1	242	8	32	0	3.1	240	7	29	0	3.1	238	6	26	0	3.0	238	6	30	0

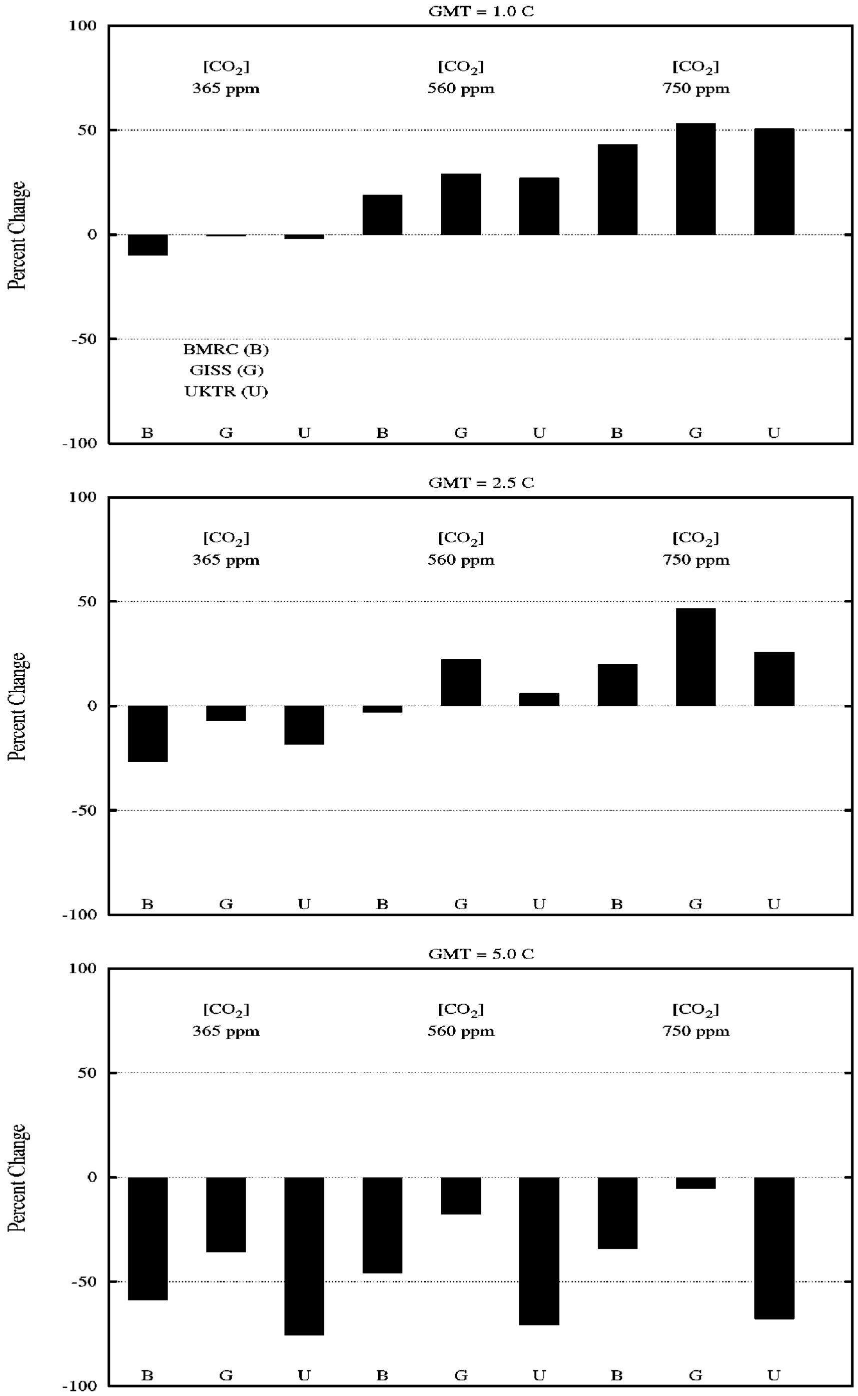

Figure 5. Changes in potential U.S. winter wheat production as a function of climate change scenario (GCM), climate change severity (GMT) and atmospheric carbon dioxide concentration ([CO$_2$]).

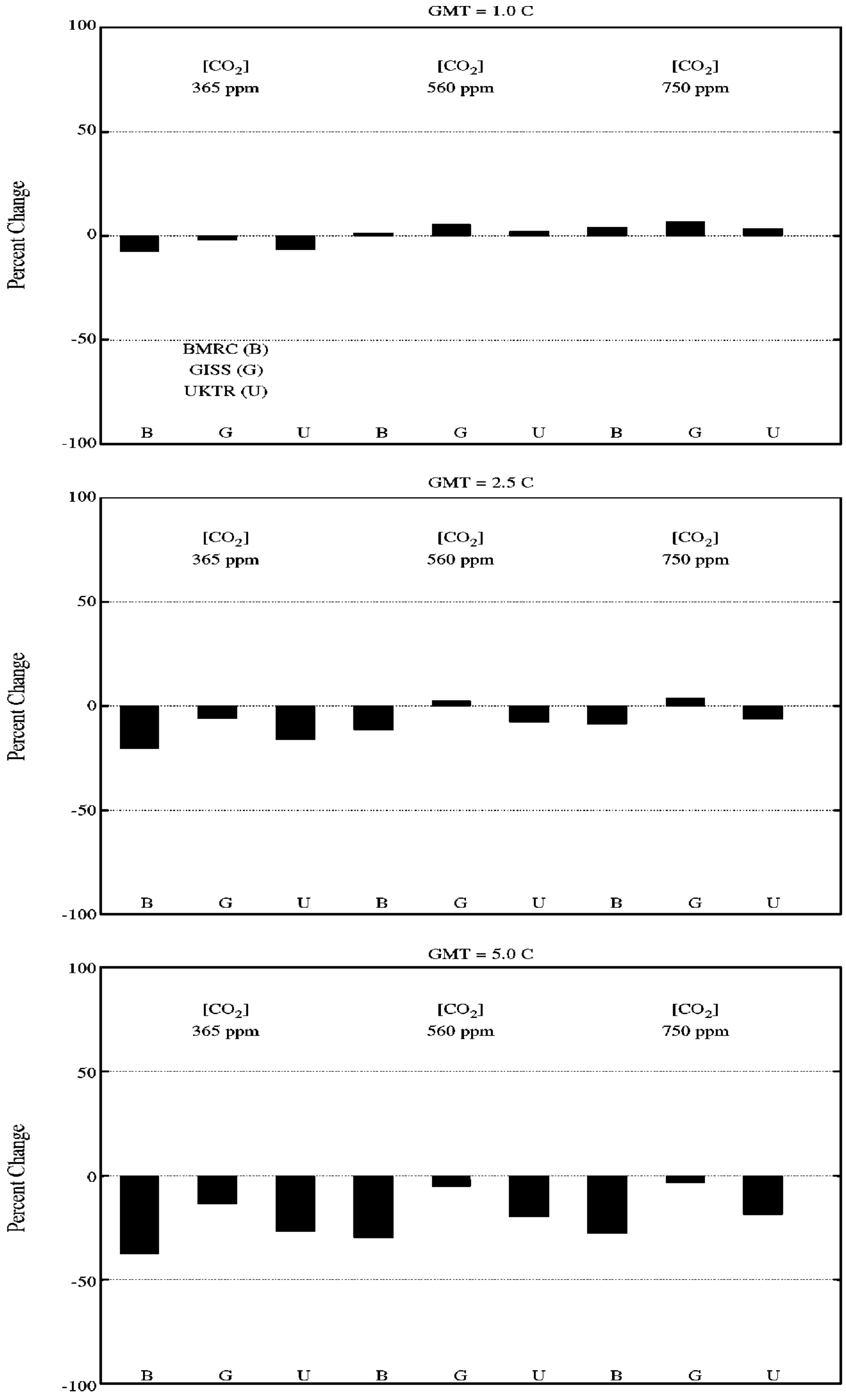

Figure 6. Changes in U.S. corn production as a function of climate change scenario (GCM), climate change severity (GMT) and atmospheric carbon dioxide concentration ([CO$_2$]).

slightly. On a few farms the BMRC climate changes cause losses of up to 0.6 t/ha to occur. Temperatures increase under each GCM at all farms studied. This increase causes the crop to mature sooner which should, all other factors being constant, lower yields. At GMT = 1.0 °C, however, the loss of growing season is relatively minor. Increased temperature during the wheat growing season reduces the total number of temperature stress days by decreasing cold stress. This effect is most notable in the Palouse region and northern Great Plains (farms 1, 2, 3, 6, 7, 8 and 29) and may offset the effects of more frequent heat stress later in the growing season. In cases where precipitation also increases or is unchanged, yields may increase above baseline or decreases may be moderated. Winter wheat yields rise with increasing precipitation in fall and winter, while changes in summer precipitation have less impact. Nitrogen stress is not a factor since the model applied fertilizer 'on demand' up to a maximum of 150 kg N/ha annually. Fertilizer applications were properly timed and in sufficient quantity to preclude N stress under baseline climate and the 'climate change envelope'.

Increased precipitation in the semi-arid Palouse under the GISS scenario holds yields at baseline or increases them slightly, despite a shortened growing season. Yield responses in the Great Plains are more variable. Temperature effects are more pronounced for the southern than for the northern farms, probably because of the higher baseline temperatures there. The UKTR scenario increases wheat yields in this region because of the increase in winter precipitation (farms 14 in Kansas and 29 in S. Dakota). Across the board, reductions in yield, when they occur, are most severe under the BMRC scenario.

Effects of Climate Change Severity (GMT)

The mechanisms by which climate change affects wheat yield, reducing it in most scenarios and locations, are apparent even when GMT is set to only 1.0 °C. In SCENGEN the climate change scenario becomes linearly more severe (or benign if precipitation is increased) as GMT is increased (a 2 °C temperature increase at GMT =1.0 °C becomes a 5 °C increase at GMT =2.5 °C). However, the effects of these changes on the simulation of photosynthesis, respiration, evapotranspiration, and hence on yield, are non-linear. This is illustrated in Table VI using the UKTR GCM to provide scenarios with GMTs set at 1.0, 2.5 and 5.0 °C and [CO_2] held at 365 ppm. Except in the Palouse region, winter wheat yields decrease at the higher GMTs even where yields are above baseline levels at GMT = 1.0 °C. In these cases, the higher temperatures shorten the growing season and increase heat stress, overwhelming even the effects of increased precipitation. Yields drop only slightly at 14 farm locations and increase slightly at the remaining 6 sites (farms 1, 2, 7, 13, 14 and 29) at GMT 1.0 °C. Yields decrease much more on most of the farms at the 2.5 °C GMT level and dramatically in some cases at GMT = 5 °C. Farms 9 (Nebraska) and 29 (S. Dakota) show particularly severe yield loses at GMT = 5.0 °C for the UKTR scenario. Early crop maturation is the primary cause of the lowered yields. The shorter season decreases numbers of temperature and water stress days

TABLE VI

Response of winter wheat to three levels of severity of the UKTR climate change scenario with $[CO_2]$ held at 365 ppm

GCAM region	Farm #	Baseline yield (t/ha)	GMT = 1.0 °C				GMT = 2.5 °C				GMT = 5.0 °C			
			Yield (t/ha)	Growing season (d)	Stress days (d)		Yield (t/ha)	Growing season (d)	Stress days (d)		Yield (t/ha)	Growing season (d)	Stress days (d)	
					Water	Temp.			Water	Temp.			Water	Temp.
A	1	1.5	1.6	268	26	25	1.8	256	18	17	1.9	237	10	7
A	2	2.5	2.6	315	41	39	2.6	302	45	32	1.9	217	14	28
A	3	3.7	3.7	248	15	22	2.7	211	6	17	1.4	182	3	8
B	4	3.2	3.0	191	4	8	2.5	182	3	5	1.7	103	1	5
B	5	4.3	4.0	205	4	6	3.5	194	2	4	2.3	173	1	3
C	6	2.5	2.4	312	44	46	2.1	223	34	39	0.5	136	0	34
C	7	4.2	4.3	314	31	49	4.1	295	35	41	0.7	127	2	33
D	8	3.5	3.5	311	41	41	3.5	278	43	35	0.6	127	1	32
D	9	4.2	3.9	267	28	40	1.2	128	4	29	0.1	123	0	34
E	10	0.9	0.9	271	53	18	0.9	242	60	16	0.6	117	23	25
F	11	3.0	2.9	273	25	29	2.6	252	25	25	1.0	127	2	28
F	12	3.7	3.4	267	26	28	2.7	233	25	24	0.9	130	2	28
F	13	3.8	3.9	271	10	38	3.5	241	8	32	0.6	111	0	30
G	14	3.9	4.1	253	6	31	3.6	235	2	27	0.3	101	0	34
G	15	2.2	1.9	258	21	19	1.4	246	29	12	0.7	120	27	16
G	16	2.4	2.4	214	3	17	2.3	207	2	15	0.8	118	1	23
H	17	2.1	1.9	211	3	16	1.7	198	1	15	1.4	85	1	30
N	29	4.3	4.6	302	16	52	4.0	283	13	49	0.2	125	0	35
N	30	4.0	3.9	263	3	38	1.5	137	1	35	0.3	111	0	38
P	33	3.1	3.1	238	6	26	2.5	204	3	22	1.1	95	2	28

despite higher temperatures or reduced precipitation. Interestingly, on farm 1 in eastern Washington yields at GMT = 5.0 °C exceed baseline as water stress days decrease because of greater precipitation, despite a 31-day shorter growing season.

Effects of CO_2 Concentration

Winter wheat yields increase with increasing [CO_2] under all GCMs and GMTs. This effect is illustrated for the UKTR scenario at 2.5 °C GMT in Table VII. The climate change alone ([CO_2] = 365 ppm) reduces yield below baseline except on farms 1 and 2 in the Palouse. The first increment of CO_2 (550 ppm) restores yields to baseline levels or above on many of the farms. This does not happen on farms 3 (eastern Washington), 4 and 5 (Central Valley), 9 (Nebraska), or 30 and 33 (Missouri). The second increment of CO_2 (750 ppm) increases yields still further; yet even at this level yields fail to fully recover on three of the farms (3, 9 and 33). Winter wheat is a C_3 crop and increases in CO_2 improve its photosynthetic efficiency. This occurs despite increased stomatal resistance, which has a much smaller effect on photosynthesis than on transpiration. The impact of CO_2 is greatest in the arid and semi-arid regions where water stress is frequent and severe. Temperature, which controls growing season length, is invariable in Table VII, yet the number of temperature stress days increases with increasing CO_2. This is an artifact of EPIC, in which only one stress can be assigned to a particular day. The relief of water stress on a particular day allows temperature stress, if it occurs, to be counted. Figure 5 illustrates the interaction of climate change (GCM and GMT) and [CO_2] on wheat yield.

4.2.2. *Farm Level Yields of Corn*

Effect of Climate Change Scenario (GCM)

Table VIII displays simulated dryland corn yields, crop stress days and growing season length for the baseline climate and three GCMs at GMT = 1.0 °C and [CO_2] = 365 ppm. Corn production was simulated for the traditional Corn Belt of the Central Midwest, the Great Lakes region and portions of eastern and southern United States. Only in the Midwest do the corn and winter wheat growing regions overlap. Yields decrease moderately on most of the farms under the three scenarios, but most under the increased temperature and decreased precipitation that occurs in all seasons under BMRC. However, even under this most moderate expression of climate change (GMT = 1.0 °C), yields are either unchanged or increase slightly on 8, 5 and 4 farms under the GISS, UKTR and BMRC scenarios, respectively. Corn yield losses are generally associated with early maturation and/or with increases in one or another type of stress day. In an effort to keep management inputs realistic, annual fertilizer applications in the simulations were limited to 150 kg/ha. Nitrogen stress occurs in some of the southern and southeastern farms (# s 31, 32, 34, 36, 37 and 38) at baseline and under the three GCM scenarios. Favorable climate changes

TABLE VII

Response of winter wheat to three atmospheric CO_2 concentrations under the UKTR scenario at GMT of 2.5 °C

GCAM region	Farm #	Baseline yield (t/ha)	$[CO_2] = 365$ ppm				$[CO_2] = 560$ ppm				$[CO_2] = 750$ ppm			
			Yield (t/ha)	Growing season (d)	Stress days (d)		Yield (t/ha)	Growing season (d)	Stress days (d)		Yield (t/ha)	Growing season (d)	Stress days (d)	
					Water	Temp.			Water	Temp.			Water	Temp.
A	1	1.5	1.8	256	18	17	2.5	237	9	7	3.3	251	16	18
A	2	2.5	2.6	302	45	32	3.7	302	42	33	5.1	302	36	36
A	3	3.7	2.7	211	6	17	3.0	205	6	18	3.2	200	6	18
B	4	3.2	2.5	182	3	5	3.0	182	2	5	3.2	182	2	5
B	5	4.3	3.5	194	2	4	4.0	194	2	4	4.3	194	2	4
C	6	2.5	2.1	223	34	39	3.0	223	27	40	4.1	223	17	43
C	7	4.2	4.1	295	35	41	5.3	295	29	43	5.8	295	23	45
D	8	3.5	3.5	278	43	35	4.9	278	34	37	6.1	278	20	42
D	9	4.2	1.2	128	4	29	1.4	128	3	29	1.5	128	3	30
E	10	0.9	0.9	242	60	16	1.3	242	56	17	1.8	237	51	18
F	11	3.0	2.6	252	25	25	3.4	252	19	27	4.2	252	12	29
F	12	3.7	2.7	233	25	24	3.8	233	17	27	4.5	233	10	29
F	13	3.8	3.5	241	8	32	4.1	241	5	34	4.3	241	3	35
G	14	3.9	3.6	235	2	27	4.4	235	2	28	4.7	235	1	28
G	15	2.2	1.4	246	29	12	2.1	246	26	13	3.2	246	16	15
G	16	2.4	2.3	207	2	15	3.1	207	1	15	3.6	207	1	15
H	17	2.1	1.7	198	1	15	2.0	198	1	15	2.2	198	1	15
N	29	4.3	4.0	283	13	49	4.7	283	11	51	5.0	283	9	52
N	30	4.0	1.5	137	1	35	1.7	137	1	35	1.8	137	1	35
P	33	3.1	2.5	204	3	22	2.9	204	3	22	3.1	204	3	22

TABLE VIII

Simulated corn yields under baseline conditions and under three GCM-derived climate change scenarios at a GMT of 1.0 °C with no CO_2-fertilization. Length of growing season and numbers of stress days are also shown

GCAM region	Farm #	Baseline					GISS					UKTR					BMRC				
		Yield	Growing	Stress days (d)			Yield	Growing	Stress days (d)			Yield	Growing	Stress days (d)			Yield	Growing	Stress days (d)		
		(t/ha)	season (d)	Water	Temp.	N	(t/ha)	season (d)	Water	Temp.	N	(t/ha)	season (d)	Water	Temp.	N	(t/ha)	season (d)	Water	Temp.	N
F	11	4.8	164	31	15	0	4.8	151	29	18	1	4.4	138	30	17	0	3.6	143	33	16	0
F	12	5.2	148	26	22	1	4.7	135	26	22	1	4.2	125	28	16	0	3.8	129	31	17	0
F	13	7.8	159	14	21	2	7.6	143	14	27	3	7.3	131	14	27	1	7.1	134	15	28	1
I	18	6.4	141	7	34	1	6.3	119	7	43	1	6.1	108	6	45	1	6.0	110	7	45	1
J	19	6.2	137	6	27	1	6.2	117	5	36	1	5.9	104	5	37	1	6.0	107	5	38	1
J	20	7.2	161	16	25	1	7.0	153	15	19	1	6.5	138	15	28	1	6.7	145	14	25	1
J	21	6.8	156	13	18	1	6.5	155	13	16	1	5.9	132	14	29	1	6.1	144	15	24	1
K	22	7.6	155	8	20	2	7.3	135	8	31	2	6.9	121	9	34	1	7.0	126	9	33	2
L	23	7.7	149	7	19	2	7.3	131	8	27	3	7.0	121	9	27	2	6.9	125	10	28	2
L	24	8.4	151	8	19	7	8.1	138	9	22	5	7.7	129	9	23	3	7.6	132	10	23	3
M	25	8.3	168	12	32	5	8.4	165	5	17	11	7.9	160	11	18	2	8.0	164	12	16	1
M	26	7.4	156	7	20	1	7.3	139	6	31	2	6.9	123	6	35	2	7.0	128	6	34	2
M	27	7.9	159	4	17	2	7.6	144	3	26	2	7.2	130	3	30	2	7.3	135	3	30	2
M	28	8.7	154	5	16	9	8.6	141	5	19	6	8.2	132	6	21	4	8.2	135	7	20	4
N	29	7.4	157	12	19	1	7.2	142	11	27	1	6.9	121	10	35	1	6.8	128	11	35	1
N	30	8.1	132	5	29	3	7.8	124	4	22	3	7.5	118	3	16	2	7.4	120	4	18	2
O	31	7.5	169	1	18	20	7.4	169	1	12	18	7.5	164	2	13	15	7.7	122	2	23	9
O	32	8.3	161	2	13	15	8.5	145	1	16	18	8.7	136	2	16	18	7.6	107	2	8	4
P	33	7.4	140	14	19	4	7.1	128	15	19	3	6.7	119	15	16	2	6.6	122	16	17	2
Q	34	8.6	130	1	10	15	8.3	124	1	9	8	8.0	119	2	8	5	8.2	122	2	8	6
Q	35	7.9	132	1	7	4	7.7	127	1	6	4	7.5	125	1	7	4	7.6	125	1	6	4
R	36	8.5	149	1	19	16	8.6	140	2	16	17	8.5	135	2	15	16	8.5	136	2	16	14
S	37	8.9	145	2	19	20	9.1	137	2	14	23	9.0	132	2	14	16	8.9	133	2	14	16
S	38	6.9	132	14	9	14	6.6	127	15	7	10	6.2	122	15	6	7	6.5	125	16	5	7
T	39	7.6	149	6	24	1	7.4	129	5	35	2	7.0	116	5	35	2	7.2	122	5	36	2
U	40	6.2	161	16	14	2	5.9	145	15	22	2	5.3	130	15	25	2	5.4	138	16	24	2
V	41	8.1	165	4	13	9	8.2	155	3	15	10	8.3	146	4	18	7	8.3	148	5	18	6
V	42	8.4	132	1	16	7	8.2	126	1	11	5	8.0	122	1	9	4	8.0	123	1	10	3
V	43	8.6	133	1	10	12	8.4	128	1	7	7	8.3	125	1	7	7	8.2	125	1	8	4
W	44	8.0	131	12	4	4	7.7	126	13	3	3	7.6	126	14	3	2	7.5	126	14	3	2
X	45	8.6	128	6	6	17	8.6	124	7	6	14	8.5	123	7	6	14	8.5	123	7	5	14

actually increase the incidence of N-stress, even when shortages are minor, since EPIC allows only one stress to be counted on any particular day.

Effects of Climate Change Severity (GMT)

Table IX displays corn yields at the representative farms under the UKTR scenario at three levels of severity. Generally, the higher the GMT the greater the decrease in corn yield. An exception is farm 31, which experiences an increase in yield at GMT = 2.5 °C because of the effects of increased precipitation. At GMT = 5.0 °C the negative impacts of a shortened growing season and higher temperatures overwhelm the effects of the increased precipitation. Temperature stress days are fewer at GMT = 2.5 °C than at GMT = 1.0 °C or at baseline because of the reduction in cold stress and/or shortening of the growing season. Yields decrease nonetheless because of the negative impact of the latter factor. On farm 29, temperature stress days decrease from 35 at baseline to 12 at GMT = 2.5 °C. They then increase to 19 at GMT = 5.0 °C indicating that the beneficial effects of cold stress reduction are overcome by the further increase in heat stress at the higher temperatures. Water stress days decrease in number at GMT = 5.0 °C (see farms 11 and 12), an artifact caused by the greater severity of heat stress overwhelming all other stresses. In general, the loss of corn yield at the highest GMT is not as severe as for winter wheat, whose length of growing season is more sharply curtailed at the higher GMT of 5.0 °C.

Effects of CO_2 Concentration

Table X provides data on dryland corn yields, growing season length and occurrence of stress days as affected by [CO_2] under the UKTR scenario at a GMT of 2.5 °C. In 6 of 31 locations, the CO_2-fertilization effect raises yields above baseline; in the remainder it substantially offsets losses caused by the climatic change. That fewer corn than wheat farms show yields above baseline is due to the different photosynthetic response of C_4 and C_3 species to elevated [CO_2] as captured in EPIC. Both the C_3 and C_4 species respond with increased stomatal resistance and reduced transpiration. Hence, the strongest yield response to CO_2 for corn occurs under moisture stress, either under baseline or GCM-projected climate change. Farm 12 has a baseline yield of 5.2 t/ha. With no CO_2 fertilization the 25 days of moisture stress under the UKTR scenario reduce yield to 3.7 t/ha. Water stress days decrease to 20 at [CO_2] = 560 ppm and yield increases to 5.3 t/ha. Stress days decrease to 9 and yield rises to 6.5 t/ha at [CO_2] = 750 ppm. For corn farms experiencing little water stress the highest [CO_2] has little additional effect on yields. Interactions of [CO_2] with GCM and GMT on corn production are shown in Figure 7.

4.3. STATISTICAL ANALYSIS OF EPIC SIMULATIONS

Analysis of variance was used to test for statistical differences between baseline and the ‘climate change envelope’ for each GCM/crop combination. Results are

TABLE IX

Response of corn to three levels of severity of the UKTR climate change scenario with $[CO_2]$ held at 365 ppm

GCAM region	Farm #	Baseline Yield (t/ha)	GMT = 1.0 °C					GMT = 2.5 °C					GMT = 5.0 °C				
			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)		
					Water	Temp.	N			Water	Temp.	N			Water	Temp.	N
F	11	4.8	4.4	138	30	17	0	4.2	115	26	13	0	3.9	98	14	19	0
F	12	5.2	4.2	125	28	16	0	3.7	111	25	9	0	3.4	99	14	21	0
F	13	7.8	7.3	131	14	27	1	6.8	116	13	13	1	6.1	105	6	25	1
I	18	6.4	6.1	108	6	45	1	5.6	91	4	13	1	5.1	79	2	9	1
J	19	6.2	5.9	104	5	37	1	5.4	87	4	8	1	4.6	75	2	9	1
J	20	7.2	6.5	138	15	28	1	5.8	106	13	20	1	4.9	91	11	13	0
J	21	6.8	5.9	132	14	29	1	4.7	103	15	15	0	3.8	89	11	16	0
K	22	7.6	6.9	121	9	34	1	5.9	104	10	9	1	4.9	91	8	13	1
L	23	7.7	7.0	121	9	27	2	6.1	106	9	8	1	5.1	95	7	15	1
L	24	8.4	7.7	129	9	23	3	6.9	117	7	11	2	6.1	108	6	21	1
M	25	8.3	7.9	160	11	18	2	7.1	120	10	31	2	6.1	101	6	18	1
M	26	7.4	6.9	123	6	35	2	6.2	103	5	11	1	5.4	91	4	16	1
M	27	7.9	7.2	130	3	30	2	6.4	111	2	15	2	5.4	98	1	20	1
M	28	8.7	8.2	132	6	21	4	7.2	118	6	15	2	6.3	109	3	28	1
N	29	7.4	6.9	121	10	35	1	6.4	101	8	12	1	5.7	90	3	19	1
N	30	8.1	7.5	118	3	16	2	6.7	107	2	15	2	6.1	99	1	24	1
O	31	7.5	7.5	164	2	13	15	8.3	135	2	15	19	7.3	118	3	15	5
O	32	8.3	8.7	136	2	16	18	8.3	121	2	10	9	7.2	110	2	22	3
P	33	7.4	6.7	119	15	16	2	6.2	104	13	7	2	5.5	93	7	22	1
Q	34	8.6	8.0	119	2	8	5	7.1	109	2	14	2	5.5	97	2	28	1
Q	35	7.9	7.5	125	1	7	4	6.9	116	1	9	3	5.8	104	1	15	2
R	36	8.5	8.5	135	2	15	16	8.0	125	2	12	4	7.4	116	2	22	3
S	37	8.9	9.0	132	2	14	16	8.4	122	1	13	7	7.7	113	1	23	6
S	38	6.9	6.2	122	15	6	7	5.5	112	15	8	4	4.5	100	13	18	1
T	39	7.6	7.0	116	5	35	2	6.3	99	5	10	1	5.3	86	3	14	1
U	40	6.2	5.3	130	15	25	2	4.5	112	15	10	2	4.0	101	11	18	1
V	41	8.1	8.3	146	4	18	7	7.7	129	5	16	3	6.8	118	4	21	2
V	42	8.4	8.0	122	1	9	4	7.4	113	1	11	1	6.7	105	1	19	1
V	43	8.6	8.3	125	1	7	7	7.8	117	1	8	2	6.8	107	1	17	1
W	44	8.0	7.6	126	14	3	2	6.9	119	13	5	2	5.8	109	14	9	2
X	45	8.6	8.5	123	7	6	14	7.8	116	7	9	7	6.2	106	8	15	1

TABLE X

Response of corn to three atmospheric CO_2 concentrations under the UKTR scenario at a GMT of 2.5 °C

GCAM region	Farm #	Baseline Yield (t/ha)	GMT = 1.0 °C					GMT = 2.5 °C					GMT = 5.0 °C				
			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)			Yield (t/ha)	Growing season (d)	Stress days (d)		
					Water	Temp.	N			Water	Temp.	N			Water	Temp.	N
F	11	4.8	4.2	115	26	13	0	5.5	115	21	15	1	6.3	115	10	18	1
F	12	5.2	3.7	111	25	9	0	5.3	111	20	11	1	6.5	111	9	14	1
F	13	7.8	6.8	116	13	13	1	7.7	116	7	15	2	7.8	116	3	15	2
I	18	6.4	5.6	91	4	13	1	6.1	91	3	13	1	6.1	91	2	13	1
J	19	6.2	5.4	87	4	8	1	5.8	87	2	8	1	5.8	87	1	8	1
J	20	7.2	5.8	106	13	20	1	6.6	106	9	21	1	6.9	106	5	22	1
J	21	6.8	4.7	103	15	15	0	5.5	103	12	16	1	5.8	103	8	18	1
K	22	7.6	5.9	104	10	9	1	6.6	104	7	10	1	6.8	104	3	10	2
L	23	7.7	6.1	106	9	8	1	6.7	106	6	9	2	6.9	106	4	9	2
L	24	8.4	6.9	117	7	11	2	7.6	117	5	11	2	7.7	117	3	12	2
M	25	8.3	7.1	120	10	31	2	7.8	120	6	31	2	8.0	120	3	32	2
M	26	7.4	6.2	103	5	11	1	6.8	103	3	12	2	6.8	103	2	12	2
M	27	7.9	6.4	111	2	15	2	6.8	111	2	15	2	6.8	111	1	15	2
M	28	8.7	7.2	118	6	15	2	7.9	118	4	15	3	7.9	118	2	16	3
N	29	7.4	6.4	101	8	12	1	7.0	101	5	13	2	7.0	101	2	13	2
N	30	8.1	6.7	107	2	15	2	7.2	107	1	15	2	7.2	107	1	15	2
O	31	7.5	8.3	135	2	15	19	8.3	135	1	15	24	8.3	135	1	15	24
O	32	8.3	8.3	121	2	10	9	8.6	121	1	9	15	8.6	121	1	9	14
P	33	7.4	6.2	104	13	7	2	7.0	104	10	8	3	7.3	104	6	9	4
Q	34	8.6	7.1	109	2	14	2	7.5	109	1	13	3	7.5	109	1	13	3
Q	35	7.9	6.9	116	1	9	3	7.3	116	1	9	4	7.3	116	1	9	4
R	36	8.5	8.0	125	2	12	4	8.5	125	1	12	9	8.4	125	1	12	9
S	37	8.9	8.4	122	1	13	7	8.7	122	1	11	14	8.7	122	1	11	13
S	38	6.9	5.5	112	15	8	4	6.4	112	11	8	8	6.7	112	8	8	12
T	39	7.6	6.3	99	5	10	1	6.8	99	3	10	1	6.9	99	2	10	2
U	40	6.2	4.5	112	15	10	2	5.2	112	12	10	2	5.6	112	10	11	2
V	41	8.1	7.7	129	5	16	3	8.3	129	2	15	8	8.3	129	1	15	8
V	42	8.4	7.4	113	1	11	1	7.9	113	1	11	3	7.8	113	1	11	2
V	43	8.6	7.8	117	1	8	2	8.3	117	1	8	5	8.2	117	1	8	5
W	44	8.0	6.9	119	13	5	2	7.7	119	11	5	6	7.9	119	7	5	8
X	45	8.6	7.8	116	7	9	7	8.4	116	3	7	18	8.4	116	1	7	19

TABLE XI

Scenario means, coefficient of variations, F statistics and least significant differences for simulated corn and winter wheat yields under baseline conditions and ‘climate change envelope’ scenarios

Scenario	[CO_2]	GMT	Corn (t/ha)			Wheat (t/ha)		
	(ppm)	(°C)	BMRC	GISS	UKTR	BMRC	GISS	UKTR
1	365	0.0	7.64	7.64	7.64	3.15	3.15	3.15
2	365	1.0	7.20	7.49	7.21	2.90	3.13	3.10
3	560	1.0	7.84	8.03	7.82	3.73	3.98[a]	3.94[a]
4	750	1.0	8.02	8.15[a]	7.97	4.38[a]	4.63[a]	4.58[a]
5	365	2.5	6.33[a]	7.20[a]	6.58[a]	2.82	2.53[a]	
6	560	2.5	7.04[a]	7.81	7.21	3.01	3.65	3.21
7	750	2.5	7.25	7.95	7.34	3.65	4.30[a]	3.75
8	365	5.0	5.08[a]	6.64[a]	5.70[a]	1.26[a]	1.93[a]	0.95[a]
9	560	5.0	5.72[a]	7.27	6.26[a]	1.62[a]	2.46	1.12[a]
10	750	5.0	5.94[a]	7.41	6.36[a]	1.95[a]	2.80	1.23[a]
		Mean	6.80	7.50	7.01	2.79	3.28	2.75
		CV (%)	14	11	14	36	36	36
		F Ratio	30.67	8.44	16.92	19.42	10.35	32.61
		lsd (0.05)	0.50	0.44	0.51	0.63	0.73	0.62

CV = coefficient of variation.

lsd = least significant difference.

[a] Statistical difference with baseline scenario at p value > 0.05 using lsd.

summarized in Table XI. In all cases the F-statistic was sufficiently large to disprove the null hypothesis at $p > 0.001$. In addition, the least significant difference (lsd) was computed to allow for pairwise comparisons between baseline and any climate change scenario. Table XI presents the lsd at the 0.05 confidence level, highlighting scenarios that are significantly different from baseline. Fifteen of 27 climate change scenarios led to wheat yields significantly different from baseline; this was true of only 12 scenarios in the case of corn. Scenarios involving the highest GMT and the greatest CO_2 concentrations generally caused significant yield deviations from baseline with scenario 8 (GMT 5.0, [CO_2] 365 ppm), showing a significant difference from baseline under all GCMs. Scenarios 3 and 4 (GMT 1.0, [CO_2] 560, 750 ppm) changed wheat yields but not corn yields significantly from baseline under the GISS and UKTR GCMs. That wheat yield is more sensitive to CO_2 may explain this effect. The GISS-based scenarios caused the fewest significant yield differences. This result is to be expected, given that the GISS climate change was the most moderate of those studied.

4.4. IMPACTS ON NATIONAL PRODUCTION

Figures 5 and 6 show percent change in yields from baseline under the 'climate change envelope' for the areas of wheat and corn production. The production estimates were scaled from the simulated yields using historic area of corn and winter wheat harvested as weights. Whenever a region contained two or more farms, the regional yield was calculated by averaging the individual farm yields. The following statistics may help to interpret the production changes from baseline. For corn, the historic area harvested under rainfed management was 25 million ha, while for winter wheat, the historic area harvested was 12 million ha. EPIC-simulated national yields are 3.27 t/ha (range 1.8–4.2) and 7.56 t/ha (range 6.2–8.6) for wheat and corn respectively. USDA (1995) presents actual mean national yields of 2.53 and 7.02 t/ha for wheat and corn. Baseline calculated production from simulated yields is 92 and 469 million tonnes of winter wheat and corn, respectively. This compares with actual current mean annual wheat and corn production of about 44 and 190 million tonnes. The production estimates from simulated yields are 109% and 146% of historic production for wheat and corn, respectively. These overestimates are explained primarily by uniformly high level of management assumed in the simulations (see Section IIC).

Losses of production are least severe and gains are greatest for both crops under the GISS scenario at all levels of $[CO_2]$ and all GMTs. Production is greatest in both crops at GMT $= 1.0\,°C$ and $[CO_2] = 750$ ppm. Under the GISS scenario production of both crops is above baseline even at GMT $= 2.5\,°C$ if $[CO_2] > 560$ ppm. Next to GCM, GMT has the greatest impact on production of both crops. This impact is moderated by CO_2-fertilization at the lower GMTs. At GMT $= 5.0\,°C$, however, the great losses of production caused by the UKTR and BMRC scenarios at $[CO_2] = 365$ ppm, while offset somewhat in corn and in BMRC in wheat, remain well below baseline even at the highest level of CO_2-fertilization.

5. Summary and Conclusions

Regional distributions of climate change derived from three general circulation models, each scaled to three levels of severity, have been applied through the EPIC crop growth simulator to evaluate possible climate change effects on the potential production of winter wheat and corn under dryland conditions in the conterminous United States. The moderating effects of 'CO_2-fertilization' were evaluated by running each of the nine climate change scenarios at three atmospheric CO_2 concentrations. The EPIC model produced crop yields consistent with county and state-level statistics. Agreement was best with experiment station yields. Because a high level of technology was assumed, EPIC yields are generally higher than actual yields.

The GISS scenario has the least severe impacts on wheat and corn production. UKTR at the higher GMTs affects wheat production most severely; BMRC is the most detrimental to corn production at high GMTs. None of the three GCM scenarios applied in this study reduce potential crop production by more than 10% at a severity associated with a GMT increase of 1.0 °C. Wheat production exceeds baseline when [CO_2] is elevated to 560 ppm in conjunction with this GMT and is as much as 50% higher at 750 ppm. Corn production exceeds baseline, but only modestly with CO_2-fertilization. At a GMT of 2.5 °C and no CO_2-fertilization, production of both crops drops sharply. At this GMT wheat production rises above baseline for both the GISS and UKTR scenario with CO_2-fertilization at 560 ppm. At 750-ppm wheat production exceeds baseline for all three GCMs. At GMT of 2.5 °C only the GISS scenario raises corn production above baseline at [CO_2] of 560 ppm and higher. Production of both crops falls radically from 13 to 75% at GMT of 5.0 °C and no increase in [CO_2]. CO_2-fertilization offsets these losses, but even at 750 ppm production remains below baseline in all cases.

The moderating effects of CO_2-fertilization on crop production in the United States had already been modeled at the process level (e.g. Rosenberg, 1993), but only for a limited region and a single climate change scenario. An innovative feature of the present study is the opportunity afforded by the research design to evaluate the effects of CO_2 on a large number of farms, each of which experiences different climatic changes; to scale up the results to the level of major production regions; and to study the interactions of CO_2 enrichment with intensifying severity of climate change. The results of this analysis support the notion that CO_2-fertilization can significantly reduce the negative impacts of climate change on the two major crops studied, especially in the earliest stages of climate change (i.e., the smaller GMTs). The results also indicate that the palliative effects of CO_2 diminish as climate changes become more severe with time and cannot be counted on to offset the reductions in production that such change may bring to these regions.

In their national study of climate change effects on corn, wheat and soybeans in the U.S., Rosenzweig et al. (1994) used three GCMs to provide scenarios (one of these – GISS – we also used). Nineteen locations were studied. One level of CO_2-fertilization (555 ppm) was considered. Even with CO_2 fertilization, yields were decreased in that study in most locations under the scenarios of climate change employed. Losses were attributable mostly to shortened growing seasons.

As should be expected, our results are generally consistent with those of Rosenzweig et al. (1994) in the range of climatic changes wherein they overlap. The study reported here covers a broader range of climatic change because of the GCMs employed. In addition, we scale the severity of climatic change to the accumulating emissions of greenhouse gases in the atmosphere. Effects over time are captured for each GCM through the ‘envelope’ of multiple GMT and CO2-fertilization levels. This approach is in no way limited to the scenarios and assumptions we have used. The reader may draw inferences about the values at risk from permitting greenhouse warming to reach any given level of severity by employing other scenarios and assumptions about the time course of greenhouse gas emissions.

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Appendix I

TABLE A.I

Location, weather station, elevation, soil series and crop modeled for representative farms mapped in Figure 3

Map region	Location	Farm #	Weather station	Latitude (deg)	Longitude (deg)	Elevation (m amsl)	Soil series	Crop modeled	
								Corn	Wheat
A	Pacific Northwest – Palouse	1	Ephrata, WA	47.30	119.53	11	Warden		×
		2	Idaho Falls, ID	43.52	112.07	439	Portneuf		×
		3	Pomeroy, WA	46.48	117.58	177	Athena		×
B	California – Central Valley	4	Willows, CA	39.52	122.18	13	Solano		×
		5	Priest Valley, CA	36.20	120.70	209	Altamont		×
C	Northern Great Plains	6	Glasgow, MT	48.78	107.43	793	Glendive		×
		7	Carson, ND	46.38	101.58	762	Amor		×
D	Western Great Plains	8	Broadus, MT	45.43	105.40	281	Lonna		×
		9	Valentine Lakes, NE	42.37	101.75	320	Otero		×
E	Western Great Plains	10	La Junta, CO	37.67	103.92	449	Wiley		×
F	Central Great Plains	11	McDonald, KS	39.78	101.37	312	Richfield	×	×
		12	Oberlin, KS	39.37	99.83	206	Harney	×	×
		13	Geneva, NE	40.53	97.60	151	Hastings	×	×
G	Central Great Plains	14	Wichita, KS	37.65	97.42	123	Grant		×
		15	Boise City, OK	36.60	101.71	307	Acuff		×
		16	Silverton, TX	34.43	100.28	181	Miles		×
H	Southwestern Prairie Region	17	Okla City, OK	34.78	96.68	95	Stephenville		×
I	Northern Lake States	18	Cambridge, MN	46.25	93.52	120	Santiago-b	×	
J	Southern Lake States	19	West Bend, WI	44.47	87.50	55	Hortonville	×	
		20	Alma, MI	43.38	84.67	69	Marlette-b	×	
		21	Geneva, NY	43.12	77.67	50	Hilton	×	
K	Central Corn Belt	22	Waterloo, IN	41.43	85.03	85	Morley-b	×	
L	Central Corn Belt	23	Indianapolis, IN	39.73	86.27	73	Crosby	×	
L	Central Corn Belt	24	Fairfield, IL	38.38	88.37	42	Cisne	×	

TABLE A.I

(Continued)

Map region	Location	Farm #	Weather station	Latitude (deg)	Longitude (deg)	Elevation (m amsl)	Soil series	Crop modeled	
								Corn	Wheat
M	Central Corn Belt	25	Winnebago, MN	43.77	94.17	338	Clarion	×	
		26	Oelwein, IA	42.67	91.92	96	Kenyon-b	×	
		27	Walnut, IL	41.55	89.58	66	Tama	×	
		28	Jackson, MO	38.13	89.70	50	Tamalco	×	
P	Eastern Corn Belt	33	Lebanon, MO	37.65	92.68	117	Hobson	×	×
Q	Mississippi Delta	34	Tallulah, LA	33.88	91.50	49	Dubbs	×	
		35	Melville, LA	30.68	91.73	3	Sharkey-a	×	
R	Southeastern Piedmont	36	Richmond, VA	37.50	77.33	15	Norfolk-b	×	
S	Southeastern Piedmont	37	Dresden, TN	36.28	88.72	39	Grenada	×	
		38	Fordyce, AR	33.70	92.37	26	Ruston	×	
T	Northeastern Region	39	Jamestown, PA	41.50	80.47	98	Canfield	×	
U	Mid-Atlantic Region	40	Harrisburg, PA	40.22	76.85	104	Penn-b	×	
V	Southeastern Coastal Plain	41	Georgetown, DE	38.63	75.47	5	Sassafras	×	
		42	Greenville, NC	35.62	77.37	9	Norfolk-b	×	
		43	Kingstree, SC	33.67	79.82	38	Suffolk	×	
W	Southeastern Coastal Plain	44	Cross City, FL	29.63	83.12	5	Malbis	×	
X	Southeastern Coastal Plain	45	Thompson, TX	29.50	95.75	149	Segno-b	×	

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