PNWD-2432

Potential Production of Switchgrass and Traditional Crops under Current and Greenhouse-Altered Climate in the 'MINK' Region of the Central United States

Robert A. Brown
Norman J. Rosenberg
William E. Easterling III
Cynthia Hays

April 1998

Report to Texas A&M under subcontract 22023

Primary Contractor
Great Plains Regional Center for Global Environmental Change, National Institute for Global Environmental Change, U.S. Department of Energy under Contract 62-123-6512

Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

GTSP Pubs

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
Operated by
BATTELLE MEMORIAL INSTITUTE
For the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Potential Production of Switchgrass and Traditional Crops under Current and Greenhouse-Altered Climate in the 'MINK' Region of the Central United States

Robert A. Brown
Pacific Northwest National Laboratory
Norman J. Rosenberg
Pacific Northwest National Laboratory
William E. Easterling III
Department of Geography, Pennsylvania State University
Cynthia J. Hays
School of Natural Resource Sciences, University of Nebraska-Lincoln

April 1998

Report to Texas A & M under Subcontract 22023

Report to the Great Plains Regional Center for Global Environmental Change, National Institute for Global Environmental Change, U.S. Department of Energy under Contract 22023

Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

ABSTRACT

This report addresses the feasibility and possible impacts of a land use conversion from traditional agricultural crops to switchgrass, a biomass energy crop, in the Missouri-Iowa-Nebraska-Kansas (MINK) region of the U.S. under both current climatic conditions and a scenario of possible climate change. The production of biomass is intended as a substitute for some portion of the fossil fuels now contributing to greenhouse-forced global warming. In order to reduce carbon emissions substantially, large areas of land including productive agricultural land will have to be converted to biomass feedstock production.

Using the EPIC crop growth model, we simulated production of corn, sorghum, soybean, winter wheat and switchgrass at 302 sites within the MINK region. Daily climate records from 1982-1992 provided data on the baseline climate. For the climate change scenario, we used the CSIRO general circulation model, regionalized to a 50 km^2 grid resolution, and simulated crop yields at two levels of atmospheric CO_2 concentrations: 365 ppm (approximate present day concentration) and 560 ppm (double the pre-industrial CO_2 concentration) to allow consideration of the CO_2-fertilization effect.

EPIC simulations under baseline climate correctly reproduced the geographic patterns of crop yield within the MINK region. Corn and soybean yields were greatest in Iowa and Missouri. Sorghum yields were highest in eastern Nebraska and Kansas. Winter wheat yields were also highest in Iowa and Missouri, but economically viable yields (above 1.0 t/ha) occur at many sites in the central and western portions of the study region. Yields of corn, sorghum and soybean, on the other hand, decreased dramatically in the western zone due to precipitation shortages, temperature extremes and poor soil conditions. Switchgrass yields were highest in the southern and lowest in the northern portions of the MINK region.

Simulated yields of the perennial switchgrass increased at all sites under the CSIRO climate change scenario. Temperature increases ranging from 3.0 to 8.0 C extended the growing season for switchgrass and also diminished the amount of cold stress experienced by the crop. Resultant yield increases ranged from 0.1 to 10.2 t/ha. Conversely, the temperature increases lowered yields for the traditional annual crops, primarily by increasing the frequency of temperature stress and shortening the time to maturity. Precipitation increases in the western zone of the MINK region increased crop yields there. This trend is evident for all crops but most noticeable for corn with increases up to 3.2 t/ha at some sites. Simulated yields increased for all crops and sites under the higher atmospheric concentration of CO_2. Soybeans and winter wheat, C3 crops, responded most to the 'CO_2 fertilization effect.'

Simulations also indicated higher water consumption and less runoff for switchgrass than for any of the traditional crops. This is due to the higher growth rate and longer growing season of switchgrass. Under the CSIRO climate change scenario, higher temperatures increased water use for all crops. Precipitation increases resulted in greater runoff. Simulated soil erosion rates at sites under switchgrass and wheat cultivation were generally less severe than under corn management. However, considerable erosion occurred under switchgrass at a few sites in eastern Iowa due to strong winds during the crop establishment phase.

Acknowledgements

We thank our colleague Cesar Izaurralde for his assistance and advice with regard to preparation of this report. We also thank Jimmy Williams, Jim Kiniry, Georgie Mitchell, Verel Benson and Raghavan Srinivasen of the Blacklands Research Center Temple, TX for their assistance in all matters concerning the EPIC model. Dr. Ken Vogel of the University of Nebraska-Lincoln Agronomy Department provided the experimental data used in model validation. Suzette Hampton and Janine Jakubcik assisted in editing and preparing the report for publication.

CONTENTS

INTRODUCTION **1**

METHODS AND MATERIALS **2**

DESCRIPTION OF EPIC CROP GROWTH ALGORITHM 2
DESCRIPTION OF CROP STRESS DAYS AND CO_2 FERTILIZATION 2
DELINEATION OF STUDY AREA AND DEVELOPMENT OF EPIC INPUT DATASETS 4
VALIDATION OF EPIC RESULTS 9

RESULTS AND DISCUSSION **14**

THE CLIMATE SCENARIOS 14
CLIMATE AND CHANGE ON THE FARM 15
CROP YIELDS UNDER BASELINE CLIMATE 27
CROP YIELDS UNDER THE CSIRO CLIMATE CHANGE SCENARIO WITH NO CO_2-FERTILIZATION 28
CLIMATE CHANGE WITH THE CO_2-FERTILIZATION EFFECT 30
REGIONAL CROP PRODUCTION UNDER THE BASELINE AND CSIRO CLIMATE SCENARIOS 49
EVAPOTRANSPIRATION, RUNOFF AND SOIL EROSION UNDER THE BASELINE CLIMATE AND CSIRO CLIMATE SCENARIOS 53

SUMMARY AND DISCUSSION **59**

CONCLUSIONS **63**

WORKS CITED **65**

APPENDIX **70**

List of Figures

FIGURE		PAGE
1	The RegCM grid network and its orientation with respect to the MINK region.	7
2	Scatterplot of historic yields and EPIC simulated yields for corn, sorghum, soybean and winter wheat under dryland management	10
3	Scatterplot of experimental switchgrass yields and EPIC simulated yields. The experimental yields are classified by the 'harvest date' and 'fertilizer' experiments	12
4 (a-d)	Seasonal mean temperatures for baseline climate	17
5 (a-d)	Seasonal mean temperature deviations from baseline for CSIRO climate change scenario	19
6 (a-d)	Seasonal precipitation totals for baseline climate	21
7 (a-d)	Seasonal precipitation deviations from baseline for CSIRO climate scenario	23
8 (a-b)	Baseline yields of dryland corn and deviations from baseline under the CSIRO climate scenario (no CO_2 fertilization effect).	39
9 (a-b)	Baseline yields of dryland sorghum and deviations from baseline under the CSIRO climate scenario (no CO_2 fertilization).	41
10 (a-b)	Baseline yields of dryland soybeans and deviations from baseline under the CSIRO climate scenario (no CO_2 fertilization).	43
11 (a-b)	Baseline yields of dryland winter wheat and deviations from baseline under the CSIRO climate scenario (no CO_2 fertilization).	45
12 (a-b)	Baseline yields of switchgrass and deviations from baseline under the CSIRO climate scenario (no CO_2 fertilization).	47
13 (a-e)	Expected yield for corn, sorghum, soybean, winter wheat and switchgrass for the MINK region under baseline climate, CSIRO climate ([CO_2] = 365 ppm) and CSIRO climate ([CO_2] = 560 ppm).	50

List of Tables

TABLE		PAGE
1	Data sources used in building the EPIC representative farms	5
2	Location and background information for the switchgrass experimental sites used in Vogel (1996a)	12
3	Mean yields, standard deviations and root mean square error for switchgrass experiments and EPIC simulations subdivided by experiment, location and year	13
4	Experimental and modeled switchgrass yields at Ames, IA and Mead, NE by fertilizer treatment. Data are 2 year (1994-1995) means. EPIC stress days are also shown	13
5	Location and climate of the subset of representative farms	16
6	Mean seasonal baseline temperatures and deviations from baseline under the CSIRO climate change scenario	25
7	Mean seasonal baseline precipitation and deviations under the CSIRO climate change scenario	26
8	EPIC-simulated yields of dryland corn under baseline and the CSIRO climate change with CO_2 of 365 and 560 ppm	33
9	EPIC-simulated yields for dryland sorghum under baseline and the CSIRO climate change with CO_2 of 365 and 560 ppm	34
10	EPIC-simulated yields for dryland soybeans under baseline and the CSIRO climate change with CO_2 of 365 and 560 ppm	35
11	EPIC-simulated yields for dryland winter wheat under baseline and the CSIRO climate change with CO_2 of 365 and 560 ppm	36
12	EPIC-simulated yields for dryland switchgrass under baseline and the CSIRO climate change with CO_2 of 365 and 560 ppm	37
13	Potential Evapotranspiration (PET), actual evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under corn cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm	55
14	Potential Evapotranspiration (PET), actual evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under winter wheat cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm	56
15	Potential Evapotranspiration (PET), actual evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under switchgrass cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm	57

Introduction

Biomass based energy systems have been proposed as a means of reducing greenhouse gas emissions (Hall et al, 1990; Graham et al, 1992; Hall et al, 1993). Biomass energy systems are carbon neutral as compared to fossil fuel-based energy systems since, upon combustion, the former release CO_2 only recently withdrawn from the atmosphere. Biomass production may also provide a stable base for rural economies in industrialized countries and provide opportunities for economic growth in less-developed countries. Biomass energy production research has focused on two sources of biomass: short rotation woody crops (SWRC) and herbaceous forage crops (McLaughlin, 1993; Wright, 1994; Sanderson et al, 1995).

Biomass production on a scale that will permit a significant substitution for fossil fuels cannot be accomplished on marginal lands alone but will require large areas of land. Graham (1994) classified 159 Mha of US land now in traditional forestry and agricultural production as capable of supporting biomass energy crops. Of this land, 79% is currently classified as cropland. In another analysis, Graham et al (1992) projected a 'future' scenario in which 28 Mha of land would be required for the production of enough biomass energy feedstock to replace up to 20% of the US fossil fuel carbon emissions and 4% of the world fossil fuel carbon emissions. We report here on a research project supported by the Great Plains Regional Center of the National Institutes for Global Environmental Change (NIGEC) that has been devoted to the study of the physical potential for production of herbaceous biomass in the Missouri-Iowa-Nebraska-Kansas (MINK) region of the central U.S. and of the economic consequences of a large scale conversion of land to this purpose. We present results of a simulation study in which we compare the yield potentials of an herbaceous biomass crop, switchgrass (*Panicum virgatum*), and the region's dominant agricultural crops -- corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), soybeans (*Glycine max* L.) and winter wheat (*Triticum aestivum* L.) -- under current climatic conditions and under a scenario of greenhouse-forced climate change.

Methods and Materials

In this section, we describe the Erosion Productivity Impact Calculator (EPIC) a crop growth simulator used for this study, the approach used in developing the input datasets or 'representative farms' for use with EPIC and the validation of a subset of the EPIC results with actual agronomic data.

A. Description of EPIC crop growth algorithm

EPIC (ver. 5320) is a process-based model that simulates agricultural production and related environmental phenomena such as runoff, soil erosion and nutrient cycling. The model runs on a daily time step at the scale of a single farm field. EPIC inputs include daily climate, soil properties and crop management (e.g. fertilizer, crop variety, tillage.). The algorithms which constitute EPIC are described in detail in Williams (1995). A brief explanation of EPIC's crop growth component, focusing on the how EPIC incorporates climate and other environmental conditions in simulating crop growth, follows.

EPIC calculates the maximum daily increase in plant biomass made possible by the daily amount of solar radiation incident on the field. The algorithms used to model potential plant growth are driven by photosynthetically 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). The amount of solar radiation converted into plant biomass is a function of a crop specific radiation use efficiency. Solar radiation also provides the energy which drives evapotranspiration

EPIC considers the effects of temperature extremes and moisture and nutrient shortages to scale potential plant growth to actual growth. EPIC tallies temperature, water and nutrient stress daily and then determines the extent to which the most severe stress of the day reduces potential growth according to the severity of that stress. Stress day statistics are useful for interpreting and diagnosing the effects of changes in climatic and environmental variables on yield. In addition, EPIC is able to simulate the 'CO_2-fertilization' effect on plant photosynthesis and transpiration. More detail on the operation of EPIC follows.

B. Description of Crop Stress Days and CO_2-fertilization

Temperature

Temperature influences rates of physiological processes that govern plant growth (see Abrol and Ingram, 1996 for review of effects of rising temperatures on crop growth). Photosynthesis increases with increasing temperature until a crop specific optimum temperature is reached. Increases beyond this optimum decrease photosynthesis. EPIC models the impact of temperature extremes by calculating temperature stress based on how far the temperature deviates from optimal. Because the temperature response to plant processes is parabolic, EPIC will indicate cold stress from temperatures below optimum and heat stress from temperatures above optimum.

Temperature also determines the rate of crop phenological development and the duration of the growing season, the latter defined by crop heat units. Heat units are accumulated as the number of degree days above a specified base temperature. The base temperature represents a threshold below which the plant will not develop and grow. Crop maturity is reached when a crop/cultivar attains a specific number of heat units.

Precipitation

Plants extract almost all of their moisture from the soil. At times of low precipitation, soil moisture may be insufficient to meet the evaporative demand imposed by the atmosphere. Plant leaves lose turgor and stomata close to prevent further dehydration of the plant. The entry of CO_2 into the leaf is inhibited and photosynthesis, crop growth and yield are reduced. EPIC calculates water stress whenever atmospheric demand for water exceeds the rate at which available water in the rooting zone can be taken up by the plant.

Nutrient uptake and stress

Nutrient stress is also important in limiting crop growth. Shortages of either nitrogen (N) or phosphorus (P) stress the plant. Crop demand for nutrients is determined by the rate of plant growth, the phenological stage of growth and the duration of the growing season. Nutrient supply is determined by the amount of crop-available N or P within the soil-rooting zone. This, in turn, is determined by mineralization and leaching and, in the case of N, by volatilization. Changes in temperature and precipitation influence these chemical and physical processes in soil. For example, increases in soil water limit the availability of nitrogen by increasing the amount lost through surface runoff and percolation, while increases in temperature affect nitrogen availability by increasing rates of mineralization and nitrification.

Atmospheric CO_2 *concentration*

Under controlled conditions, elevated concentrations of CO_2 increase the rate of photosynthesis in C3 plant species (small grains, legumes, most trees and root crops) and reduce water use in both C3 and C4 species (tropical grasses such as corn, sorghum, and switchgrass) (see Kimball 1983; Rosenberg et al. 1990; Kimball et al. eds, 1990 for reviews). The impact of elevated CO_2 concentrations in the field where crop growth may be limited by moisture and nutrient shortages, unfavorable temperature and disease and insect infestations is still in question (e.g. Fajer et al. 1989; Mooney and Koch, 1994). Nonetheless, the preponderance of evidence indicates significant and favorable 'CO_2-fertilization' effects on yield and water use in most cultivated species and in reducing yield restrictions imposed by high temperatures, salinity and perhaps even nutrient shortages (Idso and Idso, 1994). In EPIC, the effects of rising [CO_2] are expressed through increases in radiation use efficiency (photosynthesis per unit of solar radiation absorbed) which, among other effects, results in increased LAI and also, through increases in stomatal resistance, reductions in transpiration. The algorithms that relate LAI and stomatal resistance to photosynthesis and transpiration in EPIC were altered by Stockle et al. (1992a,b) to accommodate the effects of changes in [CO_2].

Water Use and Soil Erosion

EPIC calculates water erosion using the Moderate Rate Universal Soil Loss Equation (MUSS; Williams, 1995). Wind erosion is calculated with the Wind Erosion Continuous Simulation Equation (WECS; Williams 1995). EPIC determines crop water use, both potential (PET) and actual (ET) evapotranspiration, using the Penman-Monteith method (Williams, 1995). Runoff is measured using the Green and Ampt infiltration equation (Williams, 1995).

C. Delineation of study area and development of EPIC input datasets.

The study area was delineated from Giorgi et al (1998) who employed a nested regional climate model (RegCM) to disaggregate general circulation model (GCM) output from large-scale grids, typically 3° to 5° on a side, to a finer resolution of 50 km^2. Their purpose was to resolve output of large-scale climate models with regional or local agricultural models in impact assessment studies. The RegCM fine scale network was superimposed on the MINK states. The region is covered by a network of 302 50 km^2 grids bounded by the coordinates 37° 5' to 44° 4'N latitude and 90° 54' to 104° 09'W longitude. These cover most of the 4-state MINK region (Figure 1). The detail and small spatial scale afforded by the RegCM grid allows us to address our objective of simulating switchgrass and traditional crops within the MINK region with sufficient detail to explore variability due to geography, climate, soils and farm management.

An EPIC 'representative farm' was developed to typify agriculture in each 50 km^2 grid within the RegCM model. The representative farm describes a farm enterprise typical of agricultural production and environmental conditions for a particular region (Easterling et al, 1992). The approach to representative farm design is based on a previous study of the MINK region (Rosenberg, ed, 1993) and subsequent follow-up analyses (Easterling et al, 1998). Table 1 lists the data sources used in building the representative farms and Appendix 1 provides examples of the detail involved in characterizing representative farms.

Information on the tillage practices employed with corn, sorghum, soybean and winter wheat was derived from the Agricultural Sector Model (ASM) crop budgets for 1996 (McCarl, 1982; McCarl et al, 1998). These budgets describe the timing and intensity of farm operations and management specific to a crop and ASM region. Except for Iowa which is divided into four regions, ASM considers Missouri, Nebraska and Kansas as a single model unit each. This results in a single crop budget for Kansas, Missouri and Nebraska while Iowa has different crop budgets for its northern, southern, western and central regions. Budgets for switchgrass were developed from Anderson (1989), Anderson and Shapiro (1990) and Mitchell et al (1994). To maintain consistency, a single switchgrass budget which included a single mid-summer harvest was applied to the entire MINK region even though a two harvest system may be appropriate for the southern locations.

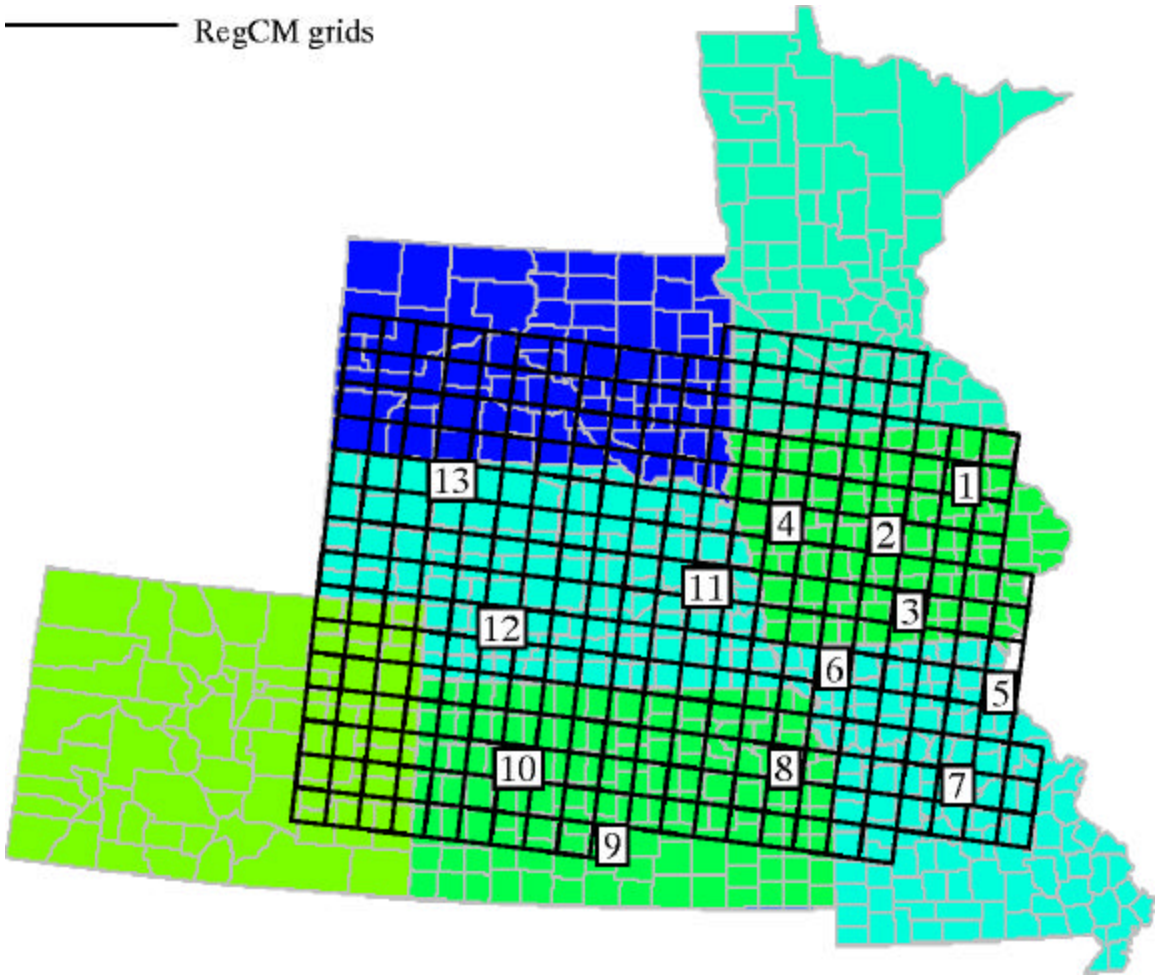
We developed a climate baseline to represent current conditions for each farm using daily records of the National Weather Service (NWS) Cooperative Climatological Network for the period of 1982-1992. The baseline record includes minimum and maximum temperature and precipitation. EPIC also requires daily inputs of solar radiation, relative humidity and windspeed. Since observations of these parameters are not made at the Cooperative Climate stations, we simulated them with the EPIC weather generator, WXGEN, using monthly means of solar radiation, wind speed and relative humidity observed at the nearest NWS First Order station and adjusted on the basis of daily precipitation and temperature at each local site. The result is a 10-year record of daily climate which drives the EPIC crop growth simulations under the baseline climate.

A project designed to develop high resolution climate scenarios for the central Plains of the U.S. (described in Mearns et al, 1996) provided us with the climate change scenario. Mearns, et al used the CSIRO general circulation model (GCM) (Watterson et al, 1995) to generate a high resolution climate change scenario for the United States through the NCAR regional climate model RegCM2 of Giorgi et al, (1993a,b). The CSIRO GCM was chosen because of its ability (relative to other available GCMs) to reproduce historic climate over the central United States. Mearns, et al developed a 10 -year daily record for both the control and a climate change scenario based on an effective doubling of the preindustrial atmospheric CO_2 content ($2xCO_2$ climate). The differences between control and $2xCO_2$ climates were then applied to the baseline to create a climate change scenario for this study.

Table 1: Data sources used in building the EPIC representative farms

Data	Source
Baseline Climate	NWS, Cooperative Climatological Station Network
$2xCO_2$ Climate	Mearns, et al 1996; NCAR RegCM Model (Giorgi, et al, 1998)
Soil Series	STATSGO Soils Database (USDA, 1992)
Crop Budgets (traditional)	Agricultural Sector Model (McCarl, 1982; McCarl et al, 1998)
Crop Budgets (switchgrass)	Anderson (1989); Anderson and Shapiro (1990); Mitchell et al (1994)
EPIC Crop Parameters	Texas Agricultural Experiment Station, Blacklands Research Station, Temple, TX

Figure 1: The RegCM grid network and its orientation with respect to the MINK region. The numbered boxes correspond to the sample farms from accompanying Results Tables



D. Validation of EPIC Results

EPIC simulations of crop yield have been extensively and convincingly validated against actual crop yields. Kiniry et al (1990) found strong agreement between simulated and actual yields of corn, wheat, rice, soybean, barley and sunflower under a variety of management regimes and environmental conditions. As part of the original MINK study, Rosenberg et al (1992) compared EPIC yields favorably with historical county yields (National Agricultural Statistical Service, NASS), yields from agronomic experiments and yield estimates made by local agricultural experts. Easterling et al (1998) in a project to analyze the effect of scale on simulating regional agricultural production found that EPIC simulations of representative farms using climate and soils data on a 0.5° X 0.5° grid scale explained 65% of the variation yields of eastern Iowa corn and 54% of the variation of western Kansas wheat between 1984 – 1992.

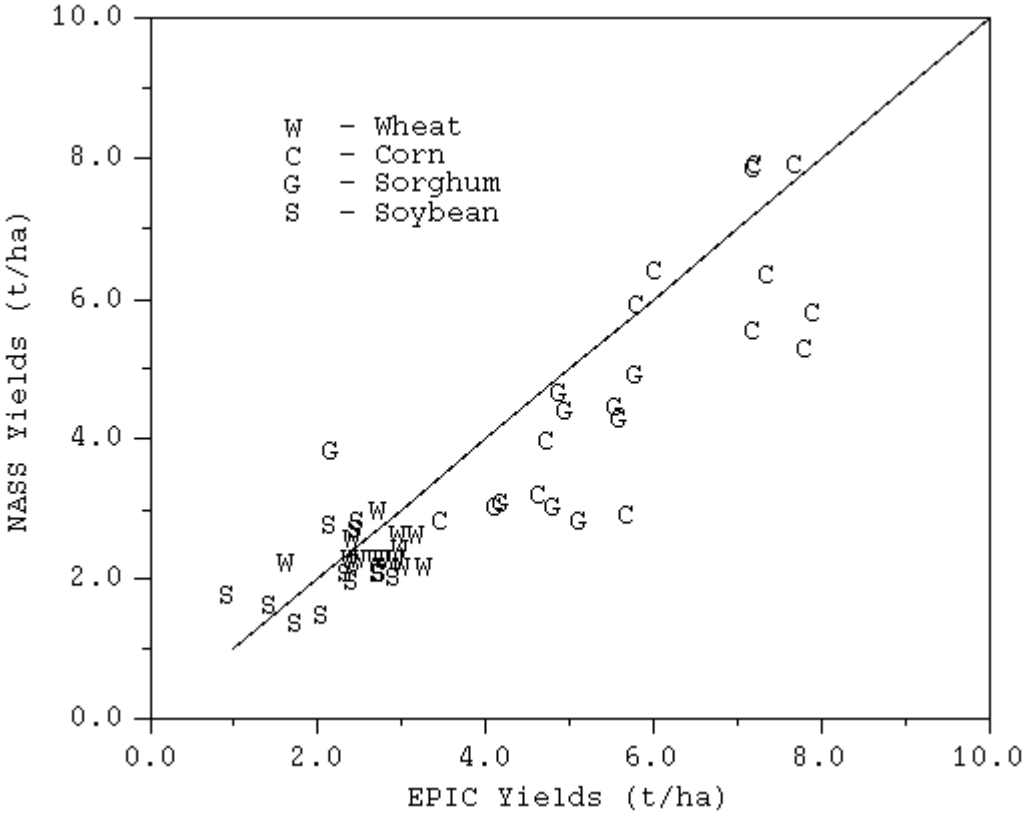
The validation exercises described above employed earlier versions of EPIC and the crop budgets, soils and climates of the representative farms differed slightly from those used here. Therefore, we undertook an additional validation comparing yield results on a sample of 13 representative farms (identified in Figure 1) to NASS county mean crop yields (USDA-NASS, 1982-1994). The 13 farms are those used in the following section to interpret results obtained in modeling the full set of 302 farms. The historic yields are means per harvested acre for the years 1982 – 1994.

Figure 2 is a scatter-plot relating EPIC and NASS yields. The EPIC yields account for 88% of the variability in NASS yields. In most cases, EPIC overestimates NASS yields slightly. This is expected, since EPIC assumes crop management at high levels of technology and harvest efficiency. In addition, EPIC does not account for extreme climatic events (sudden frosts, hail and windstorm damage) and pest outbreaks, all of which can lower real yields. Given these considerations, we judge the EPIC simulations of traditional crops acceptable for the purposes of this study.

Switchgrass has not been cultivated extensively in the MINK region. Thus, no long-term yield records exist for validation purposes. Some recent switchgrass yield trials conducted in the MINK region provide an opportunity for validating our EPIC simulations. Easterling et al (1992) argue that EPIC is best compared with experimental yields since optimal management is usually employed in both. Kiniry et al (1996) validated simulated switchgrass yields from the ALMANAC model – a model closely related to EPIC – against actual yields from agronomic trials in Texas and found generally good agreement.

The agronomic data come from factorial experiments in which the effects of nitrogen fertilization rates and harvest schedule on switchgrass yield were studied at two locations (Ames, IA and Mead, NE) between 1993 and 1995 (Vogel, 1996a). Table 2 gives information on climate and soils for these sites. Switchgrass was planted in 1993 to establish the crop. During 1994 and 1995 the switchgrass was fertilized with 60 kg/ha increments of N from zero to 300 kg/ha and harvested at weekly intervals starting in late June and continuing into September. In addition, a final harvest was made at the end of the growing season in November.

Figure 2: Scatterplot of historic yields and EPIC simulated yields for corn, sorghum, soybean and winter wheat under dryland management



EPIC input datasets were constructed to approximate the environmental conditions of the experiment as detailed in Table 2. Daily climate records for 1993-1995 were obtained from the Automated Weather Data Network (AWDN) for Mead, NE and from the Cooperative Climate Network Station at Ames, IA. The WXGEN daily weather generator was employed, as described above, to provide daily values of solar radiation, humidity and windspeed. Soils data were supplied by the EPIC soils database and then parameterized to match the soil nutrient conditions for each location. Because of previous agronomic experiments conducted at both sites, phosphorus levels were high enough to avoid stressing the crop[1]. The EPIC soil parameter controlling crop available P was adjusted to increase the supply to the plant and virtually eliminate stress. Management parameters were altered to mimic the field experiments with regard to the timing and quantities of fertilizer applications and harvest dates. EPIC was run in each case for 30 years with the daily climate from 1993-1995 repeating 10 times. We discarded results from the first 9 years and averaged results from the remaining 21 years.

Figure 3 shows strong agreement between experimental and simulated yields with EPIC explaining 85% of the variation in experimental yields. Table 3 further explores the validation data presenting means, standard deviations and root mean square error (RMSE) for experimental and simulated yields subdivided by experiment, location and year. The RMSE, a measure of the 'error' between experimental and simulated yields, shows that EPIC is better able to reproduce the larger yields from the primary cutting during the growing season (RMSE 1.9 to 3.5 t/ha; EPIC mean yield 6.0 to 10.6 t/ha) than for the final cutting of the growing season (RMSE 0.6 to 2.6 t/ha; EPIC mean yield 2.1 to

[1] Personal communication with Dr. Ken Vogel, Agronomy Department, University of Nebraska, Lincoln.

4.5 t/ha). EPIC tends to overestimate the fall harvest and generally underestimates the summer harvest. Thus, while annual yields agree, simulation of switchgrass development throughout the growing season was not totally satisfactory. Means to improve the seasonal fidelity of EPIC's switchgrass growth simulation processes will be explored.

Agreement between experimental and EPIC yield response to N-fertilization also needs to be improved. Both at Ames and Mead the EPIC yields are lower than experimental yields with N fertilization rates of zero to 120 kg/ha (Table 4). The large number of N stress days reduce the crop yields. At levels of N fertilization greater than 180 kg/ha, however, the observed yields tend to stabilize while EPIC yields continue to increase. These increases in yields are associated with a decreasing number of N stress days. These results suggest that switchgrass sensitivity to N-fertilization (at all rates) may be overstated in EPIC. Lack of agreement between the antecedent soil nutrient conditions in the simulations as compared to the actual agronomic experiments could explain the switchgrass sensitivity. This is unlikely, however, given work by Kiniry et al (1996) which has shown that for multi-year simulations using the ALMANAC model, the initial soil N is not a factor after the first few years with the model stabilizing crop available nitrogen 1 or 2 years into the simulation. Despite the discrepancies highlighted above we conclude, as did Kiniry et al (1996) in Texas, that, while imperfect, EPIC can be used to represent yields of switchgrass grown at the two experimental sites in the MINK region for which we have experimental data.

Table 2. Location and background information for the switchgrass experimental sites used in Vogel (1996a)

Location	Lat.	Long.	Elev.	Soil Series (Great Group)	Annual Precipitation 1994	1995
	degree. N	degree W	m		mm	
Ames, IA	42.0	93.5	305	Webster (Endoquall)	719	730
Mead, NE	41.3	96.6	366	Sharpsburg (Argiudoll)	644	503

Figure 3: Scatterplot of experimental switchgrass yields and EPIC simulated yields. The experimental yields are classified by the 'harvest date' and 'fertilizer' experiments.

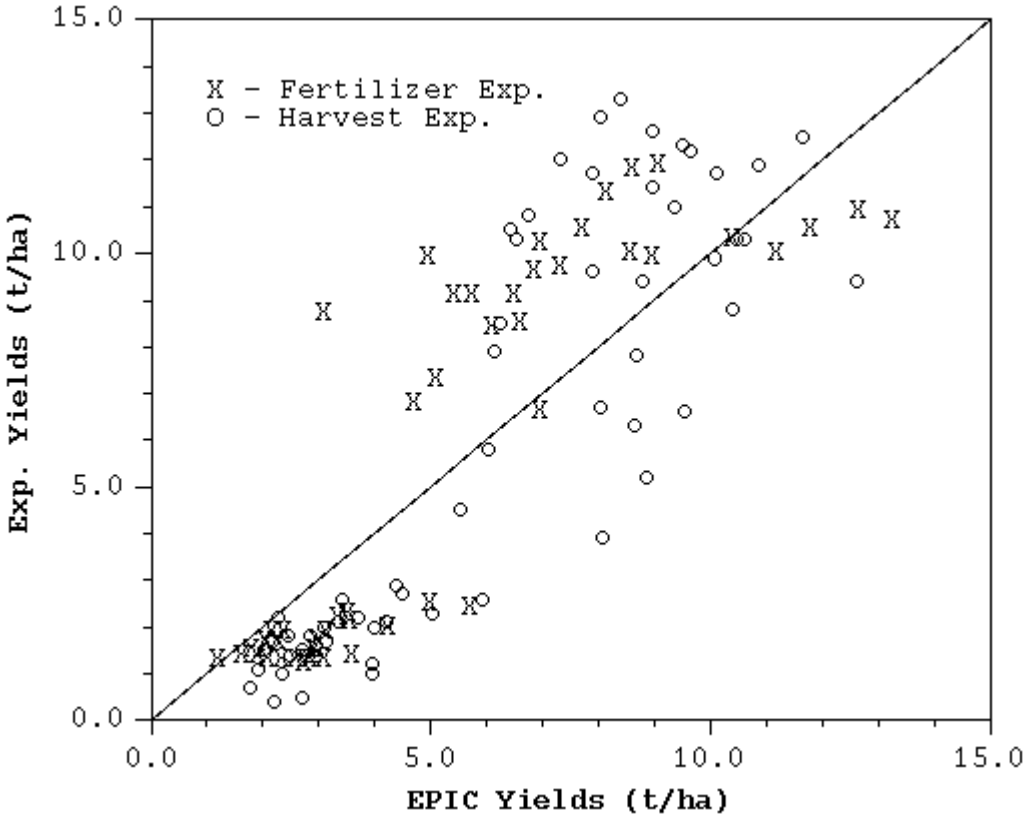


Table 3: Mean yields, standard deviations and root mean square error for switchgrass experiments and EPIC simulations subdivided by experiment, location and year

Experiment Location, Year	# of obs.	Experimental Yield Mean	Experimental Yield Std. dev.	Simulated Yield Mean	Simulated Yield Std. Dev.	RMSE
		----------t/ha----------				
Summer Cutting						
Fertilizer treatment						
Ames, IA, 1994	6	9.5	1.6	9.1	3.1	1.9
Ames, IA, 1995	6	10.3	2.0	8.0	0.8	2.4
Mead, NE, 1994	6	9.9	0.7	8.1	3.8	2.7
Mead, NE 1995	6	8.8	0.8	6.0	0.7	2.5
Harvest treatment						
Ames, IA, 1994	8	9.5	2.5	10.6	1.2	2.1
Ames, IA, 1995	8	10.3	3.4	8.4	0.8	3.5
Mead, NE, 1994	8	9.9	2.2	9.3	0.6	2.0
Mead, NE 1995	8	8.8	2.6	6.4	0.5	3.1
Fall Cutting						
Fertilizer treatment						
Ames, IA, 1994	6	2.0	0.5	4.0	1.3	2.6
Ames, IA, 1995	6	1.8	0.5	3.1	0.3	1.5
Mead, NE, 1994	6	1.3	0.1	2.4	0.9	1.5
Mead, NE 1995	6	1.7	0.2	2.1	0.2	0.6
Harvest date treatment						
Ames, IA, 1994	7	2.0	0.7	4.5	0.7	2.6
Ames, IA, 1995	7	1.8	0.8	3.3	0.6	1.5
Mead, NE, 1994	7	1.4	0.5	2.7	0.3	1.5
Mead, NE 1995	7	1.7	0.6	2.3	0.6	0.7

Table 4: Experimental and modeled switchgrass yields at Ames, IA and Mead, NE by fertilizer treatment. Data are 2 year (1994-1995) means. EPIC stress days are also shown

N Fertilization Rates	Yield Experimental	Yield Simulated	EPIC Stress Days Water	EPIC Stress Days Nitrogen	EPIC Stress Days Temp.
kg/ha	----------t/ha----------		----------d----------		
Ames, IA					
0	8.0	8.4	3	91	167
60	10.5	9.9	4	88	167
120	12.2	11.4	5	84	168
180	12.8	13.0	6	80	168
240	13.5	14.4	7	76	168
300	13.8	15.6	9	71	168
Mead, NE					
0	9.4	5.6	6	94	174
60	10.9	7.0	8	90	174
120	11.2	8.5	9	86	175
180	10.8	9.9	10	83	175
240	11.1	11.6	10	79	175
300	11.8	13.1	11	76	175

Results & Discussion

In this section we do the following: document the baseline and climate change scenarios, present EPIC simulated yields and diagnostic information for traditional agricultural crops and switchgrass on the 13 representative farms (identified in Figure 1) under the baseline and climate change scenarios, and aggregate yield data for the entire set of 302 representative farms into regional production estimates

A. The Climate Scenarios

Figures 4-7 display the temperature and precipitation climate under baseline and climate change conditions. The climate change is calculated by adjusting the baseline with the difference between the CSIRO $2xCO_2$ runs for each 50 km^2 grid in the RegCM. Mean temperatures (Figure 4) in winter range from 1.6 C in the south to –8.8 C in the most northerly region. Spring temperatures range from 13.8 to 5.8 C; summer from 26.1 to 18.5 C; fall from 14.4 to 6.6 C. Temperature increases of 4 to 6 C were the general rule under the CSIRO $2xCO_2$ climate (Figure 5). The greatest increases (as much as 8 C) occur in winter and spring. Deviations increase with a general SW to NE orientation. Deviations due to the climate change in summer and fall range from 3.5 to 5.0 C increasing from W to E. These very large temperature increases in winter and spring are explained in Giorgi et al (1998) as a feedback effect associated with the loss of the region's winter snow cover. The high albedo of snow results in lower temperatures. With the loss of permanent snow cover, temperature increases are intensified under the $2xCO_2$ climate.

Figure 6 shows the baseline precipitation climatology of the study region. Precipitation decreases from E to W in this transition zone from the Prairies into the Great Plains. Precipitation in winter may be as low as 25 mm in the west and as high as 225 mm in the southeast corner of the study region. Precipitation increases across the region in spring to as much as 350 mm in the southeast portion. In summer much of the eastern third of the region receives more than 300 mm, while less than half that amount falls in much of the western region. Fall precipitation in the western two thirds of the region ranges from 50 to 200 mm, is above 200 mm in the eastern third and as high as 350 mm in the southeast corner.

With only a few of the 50 km^2 grids excepted, the study region experiences increased precipitation under the CSIRO GCM. Increases in winter are modest, ranging from zero to 50 mm. In spring increases range from zero to 200 mm with a peak in north central Missouri and south central Iowa. A larger (but still small) number of the grids show modestly decreased precipitation in summer. However, increases ranging from zero to 200 mm are typical and their distribution is more random than in other seasons. Deviations ranging from zero to 200 mm occur in fall, increasing in amount from west to east.

B. Climate and Change on the Farms

The thirteen farms selected for presentation are described in Table 5. Farms 1-7 in Missouri and Iowa typify the highly productive agricultural region now dominated by rainfed corn and soybean. Annual precipitation ranges from 811 to 1064 mm in this region. Precipitation is lower on farms 8 and 11 in eastern Kansas and Nebraska and is sufficient for the production of corn, sorghum and winter wheat under rainfed conditions. Farms 9, 10, 12 and 13 in western Kansas and Nebraska represent the more arid western Great Plains where low precipitation limits the options for dryland agriculture. Only winter wheat and sorghum are grown in this region under rainfed conditions. Irrigated corn is also a major crop here.

The greatest increases in precipitation under the CSIRO climate change scenario occur in the Iowa and Missouri region (farms 1-7) and into eastern Nebraska and south central Kansas (farm 8, 9, 10) with projected annual changes of 155 to 280 mm. The smallest absolute increases occur in the western and north central sections of the study region (farms 11,12, 13) with projected annual changes from 130 to 146 mm. Since the western region is the driest, the relative change in precipitation in this region can be greater than in the eastern zone. Such increases in precipitation could improve its prospects for dryland crop production.

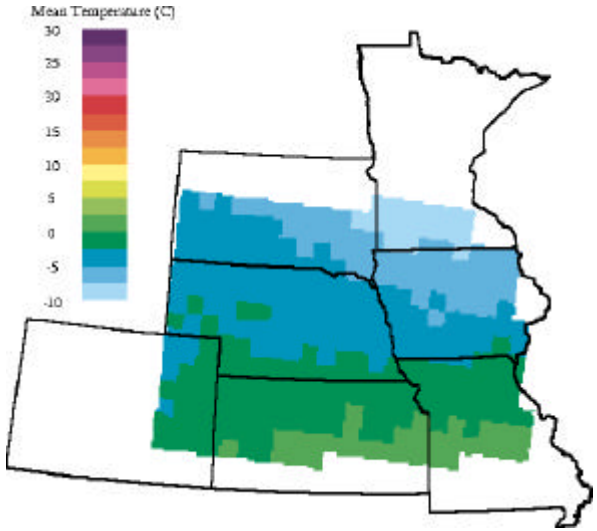
Winter precipitation changes range from –2 to 30 mm with little geographic variation under the CSIRO scenario. Minimal decreases in precipitation occur on a few farms in southern Kansas. Changes in spring precipitation range from -18 to 138 mm with the greatest increases occurring along the Missouri – Iowa border and extending into eastern Kansas (farms 3,6, 8). Small decreases in precipitation occur in sections of Iowa and eastern Nebraska. Changes in summer precipitation are the most spatially variable, ranging from –43 to 168 mm. Scattered throughout the entire MINK region are a few grids with decreased summer precipitation. However, a small concentrated area of precipitation decrease is found in extreme southeastern Iowa, Missouri and east central Kansas. Regions with increases greater than 100 mm are found in northern Iowa, southern Minnesota (farm 1) and in south central Kansas (farm 9). Precipitation changes in fall are more spatially consistent, with the largest increases in eastern Missouri and Iowa (farms 1-3,7). A large area centered in western Kansas shows little increase in precipitation and even some slight decrease in a few of the grids.

Table 5: Location and climate of the subset of representative farms.

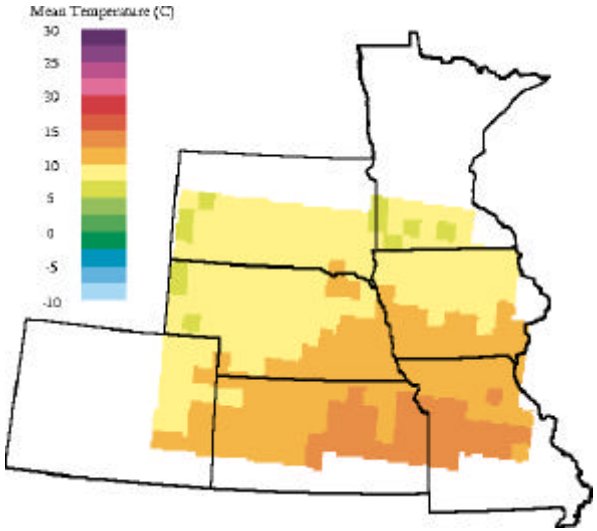
Farm #	State	Climate Station	North Latitude	West Longitude	Annual Precip.	Annual Max. Temp.	Annual Min. Temp.
			--------degrees-------		mm (total)	---------- C ----------	
1	Iowa	Fayette	42.8	92.2	883	13.8	2.5
2	Iowa	Ames	42.1	93.6	922	15.0	2.9
3	Iowa	Chariton	41.1	93.2	914	16.5	4.1
4	Iowa	Castana	42.3	95.5	811	15.5	3.6
5	Missouri	Hannibal	39.9	91.6	944	17.8	6.2
6	Missouri	Conception	40.3	94.6	882	17.2	4.7
7	Missouri	Columbia	38.6	92.5	1064	19.2	7.1
8	Kansas	Oskaloosa.	40.0	95.5	935	18.8	6.8
9	Kansas	Pratt	37.9	98.6	681	20.7	6.8
10	Kansas	Quinter	38.9	100.3	569	18.6	4.3
11	Nebraska	Clarkston	41.5	96.9	765	16.3	3.7
12	Nebraska	Curtis	40.8	100.7	501	17.4	1.7
13	Nebraska	Merriman	42.7	101.8	465	16.4	0.9

Figure 4(a-d): Seasonal mean temperatures for baseline climate

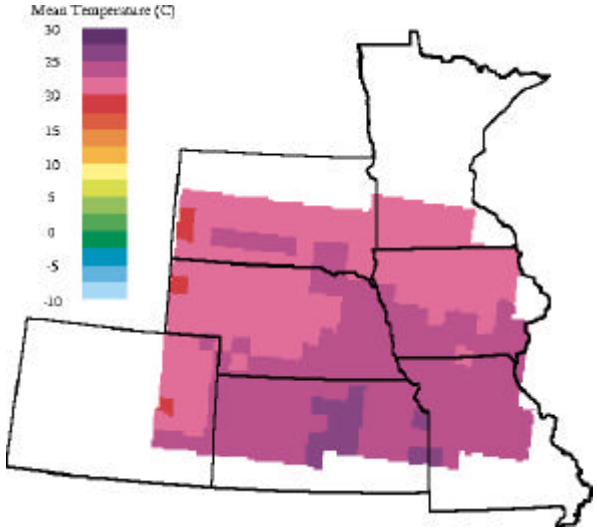
a. Winter (DJF)



b. Spring (MAM)



c. Summer (JJA)



d. Fall (SON)

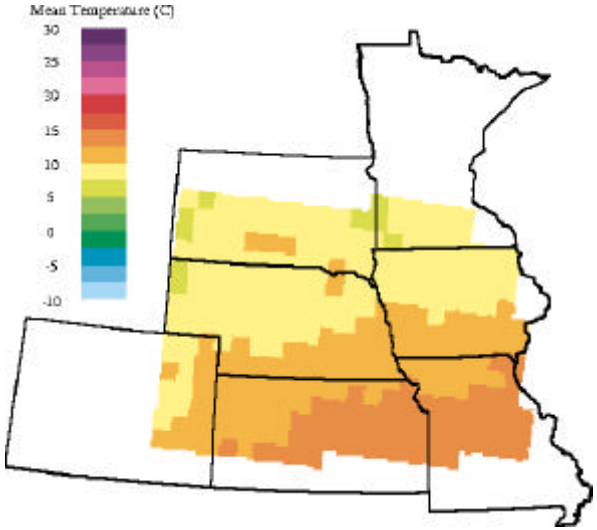
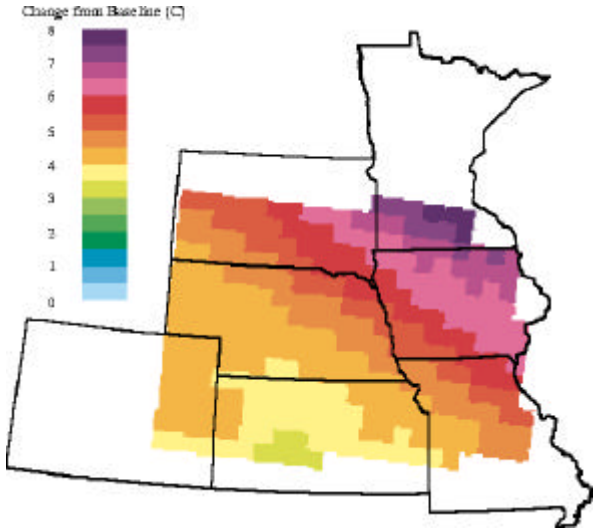
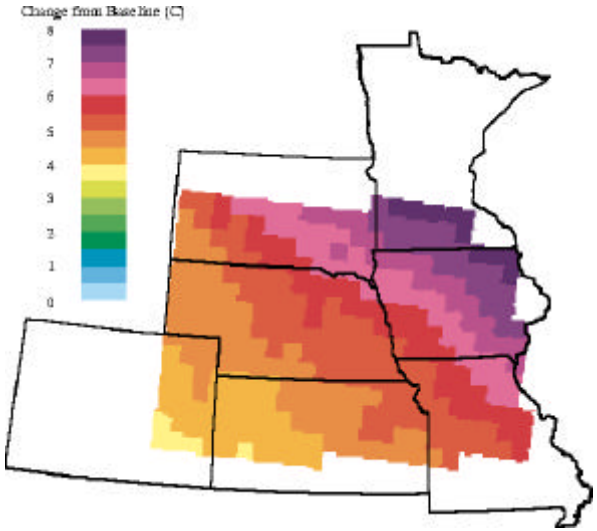


Figure 5(a-d): Seasonal mean temperature deviations from baseline for CSIRO climate change scenario

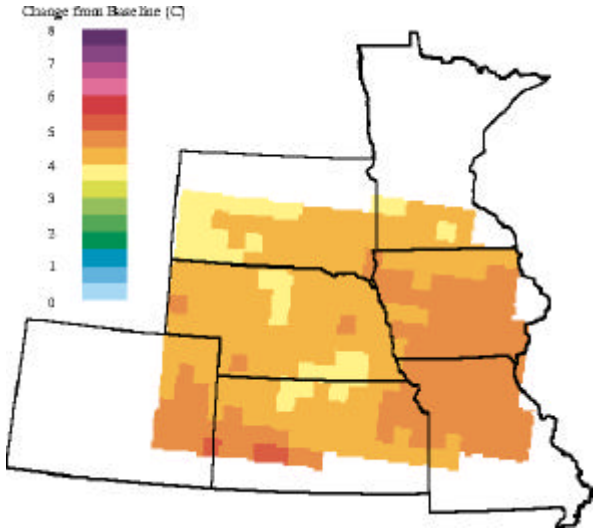
a. Winter (DJF)



b. Spring (MAM)



c. Summer (JJA)



d. Fall (SON)

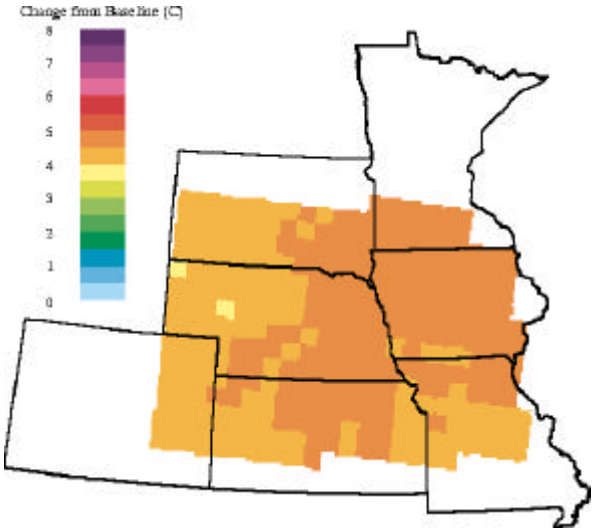
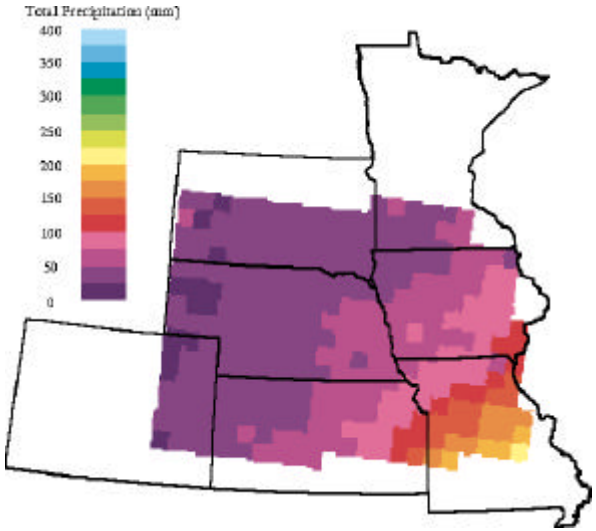
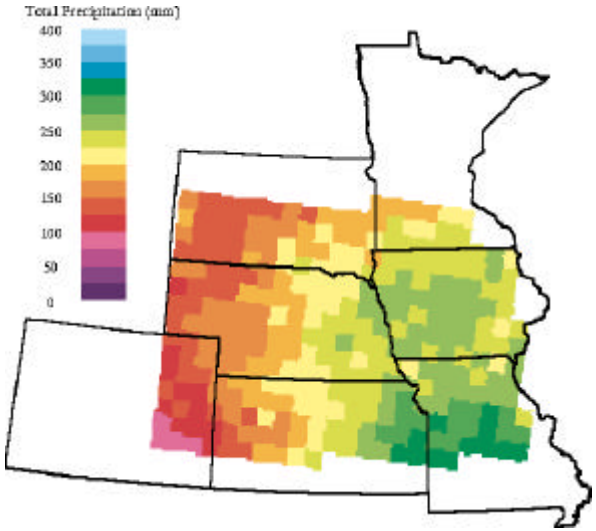


Figure 6(a-d): Seasonal precipitation totals for baseline climate

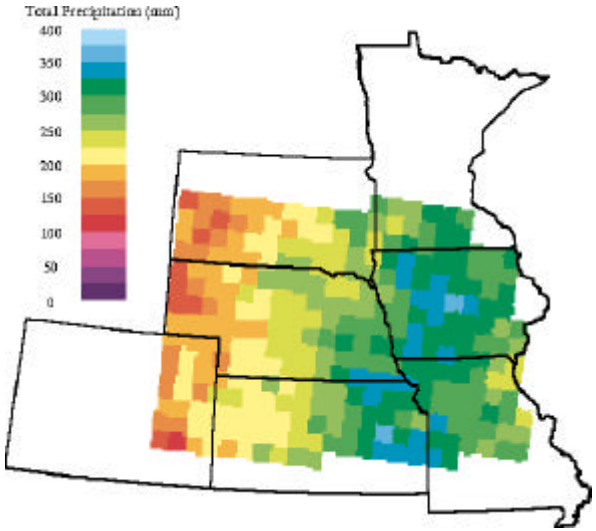
a. Winter (DJF)



b. Spring (MAM)



c. Summer (JJA)



d. Fall (SON)

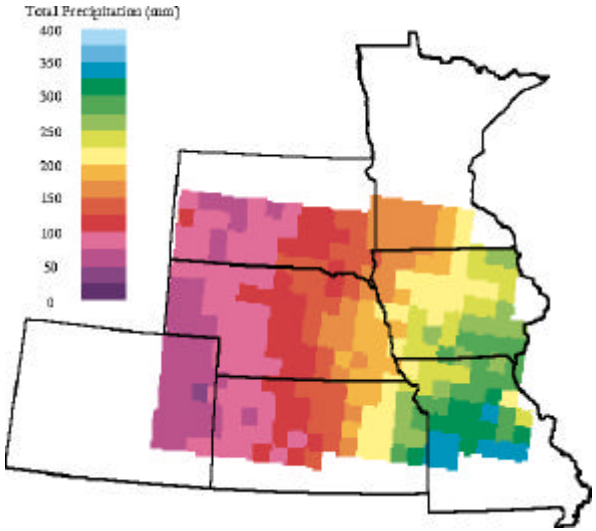
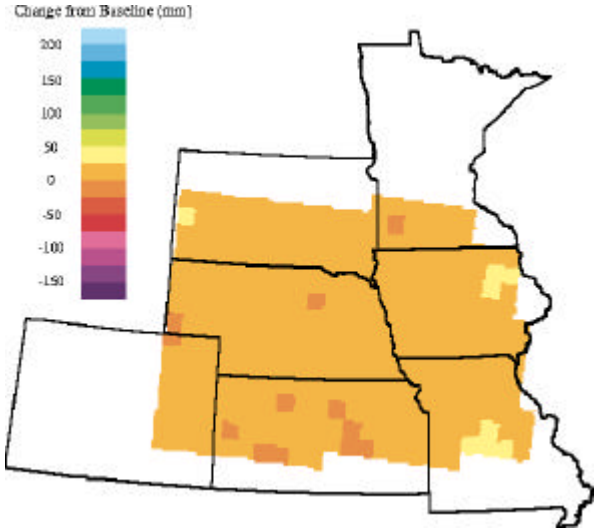
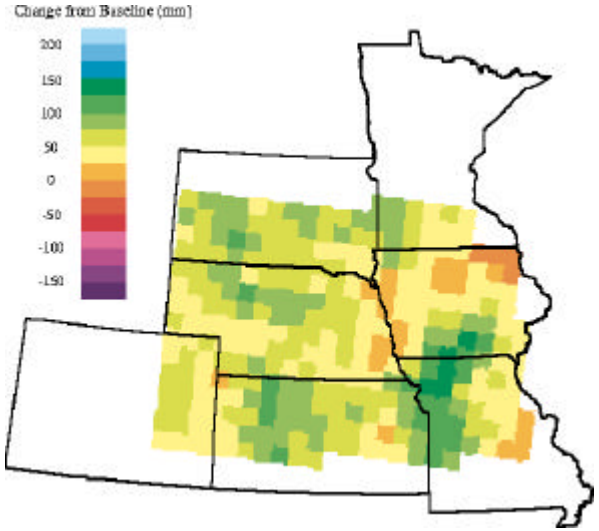


Figure 7a-d): Seasonal precipitation deviations from baseline for CSIRO climate change scenario

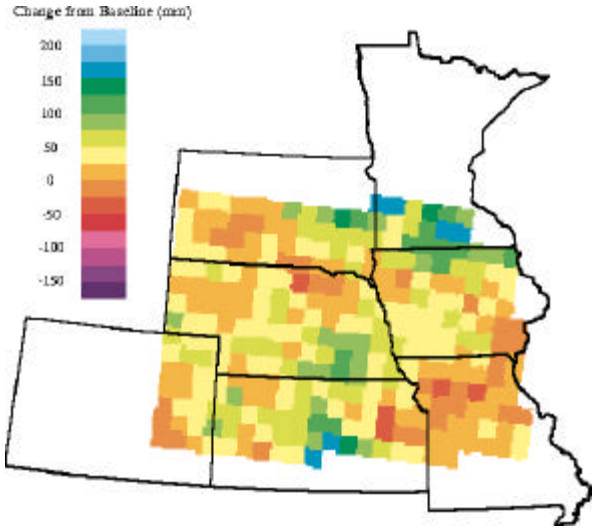
a. Winter (DJF)



b. Spring (MAM)



c. Summer (JJA)



d. Fall (SON)

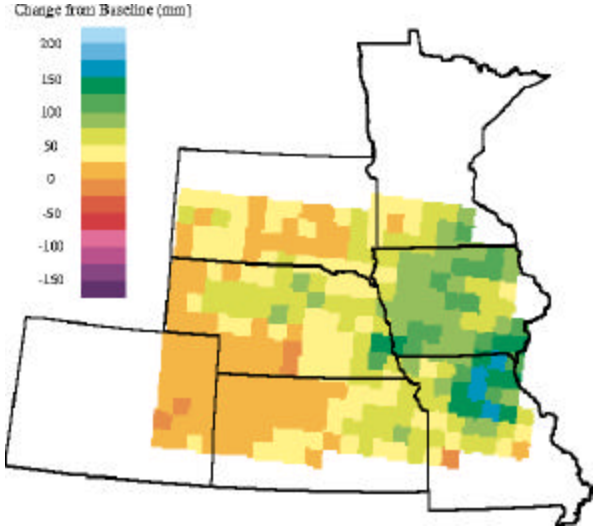


Table 6: Mean seasonal baseline temperatures and deviations from baseline under the CSIRO climate change scenario

Farm #	Winter (D,J,F)			Spring (M,A,M)			Summer (J,J,A)			Fall (S,O,N)		
	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change
	---------- (C) ----------											
1	-6.7	0.1	6.8	8.7	16.2	7.5	21.5	26.2	4.6	9.0	13.8	4.8
2	-5.3	1.1	6.4	9.4	16.1	6.7	22.0	26.9	4.9	9.7	14.4	4.8
3	-3.3	2.7	5.9	10.5	16.9	6.4	22.9	27.6	4.7	11.1	15.8	4.7
4	-4.5	1.5	6.0	10.0	16.3	6.3	22.6	27.2	4.7	10.1	14.9	4.8
5	-1.3	4.5	5.7	12.1	18.6	6.5	24.2	29.1	4.9	12.9	17.6	4.7
6	-2.4	2.7	5.1	11.2	16.8	5.6	23.5	28.4	4.9	11.6	16.2	4.6
7	1.0	5.7	4.7	13.3	18.8	5.5	24.4	29.1	4.7	13.9	18.4	4.5
8	0.0	4.2	4.3	12.9	18.0	5.1	24.8	29.4	4.6	13.5	18.1	4.6
9	1.6	5.2	3.6	13.6	17.9	4.3	25.7	30.4	4.7	14.2	18.9	4.7
10	-0.9	2.9	3.7	11.0	15.3	4.3	23.8	28.1	4.3	11.8	16.2	4.4
11	-3.5	1.5	5.0	10.2	15.8	5.6	23.2	27.6	4.5	10.3	15.1	4.8
12	-2.9	1.3	4.2	9.4	14.3	4.9	22.2	26.5	4.3	9.5	14.2	4.7
13	-3.7	0.9	4.6	8.1	13.2	5.1	21.4	25.7	4.2	8.8	13.0	4.2

Table 7: Mean seasonal baseline precipitation and deviations under the CSIRO climate change scenario

Farm #	Winter (D,J,F)			Spring (M,A,M)			Summer (J,J,A)			Fall (S,O,N)		
	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change	Baseline	$2XCO_2$	Change
	---------- mm ----------											
1	84	113	29	254	266	12	298	343	44	247	361	115
2	72	92	21	271	316	46	354	391	37	225	344	119
3	73	88	15	255	387	132	303	357	55	284	363	79
4	56	67	11	271	311	40	299	316	18	186	273	87
5	128	140	12	269	313	44	250	257	7	297	426	129
6	80	91	11	254	360	107	321	322	1	227	275	48
7	168	196	28	305	359	54	286	314	28	304	400	96
8	93	106	13	296	376	81	289	302	13	258	321	63
9	64	66	1	226	300	74	253	403	151	139	157	19
10	48	49	2	208	330	122	217	269	52	96	115	19
11	56	63	7	245	291	47	278	325	47	186	231	45
12	37	49	12	170	214	44	209	275	66	85	95	10
13	31	38	7	139	218	79	215	246	30	80	93	13

C. Crop yields under Baseline Climate

Corn

Dryland corn yields (Table 8, Figure 8a) ranged from 0.6 to 8.0 t/ha across the study region. The highest yields, ranging from 7.0 to 8.0 t/ha, occur in Iowa and Missouri (farms 1-7). Water stress was minimal in this region as were N and P stress. Temperature stress from 8 to 21 days occurred on farms 1-7 making it the most frequent of the stresses on all but farm 5. Cold at the beginning of the growing season accounts for many of the stress days. The high yields in northern Iowa show, however, that corn is well within its growing range. Corn yields were slightly lower in the central zone (farms 8,9,11) ranging from 5.7 to 6.0 t/ha -- high enough to justify dryland corn production in the eastern portion of Kansas and Nebraska. Corn yields for the western zone (farms 10, 12, 13) ranged from 3.5 to 4.6 t/ha. Due to low annual precipitation, water stress is frequent and limits yields in this region. Temperature stress is also frequent here due both to low temperatures at the beginning of the growing season and high temperatures during the summer months.

Sorghum

The highest sorghum yields (Table 9, Figure 9a) of 5.0 to 6.0 t/ha occur in eastern Nebraska and Kansas (farms 8 and 11). Sorghum yields were lower, ranging from 3.0 to 5.0 t/ha in Iowa and Missouri (farms 1-7). These lower yields are associated with temperature stress days occurring on 14 to 29 days. Cold stress at the beginning of the growing season is a contributing factor. Yields in northern Iowa (farm 1) were quite low (3.6 t/ha) even with ample precipitation. These low yields signal the northern boundary of the effective growing range for sorghum. Sorghum is less sensitive than corn to low precipitation. Yields remain reasonable (4.1 to 4.2 t/ha) in central Nebraska and Kansas (farms 10, 12), but are very low (0.0 to 1.0 t/ha) in the westernmost farms because of frequent water and temperature stress.

Soybeans

Soybeans, generally grown in dryland rotation with corn, yield best (2.3 to 2.9 t/ha) in Missouri and central Iowa (farms 2,3,4,5,6,7). Yields (Table 10, Figure 10a) show a slight decrease in northern Iowa (farm 1) due to early season low temperatures and a short growing season. Soybean yields in central Kansas and Nebraska range from 2.0 to 2.5 t/ha (farms 8 and 11) with the lower yields related to water stress. Yields in the western zone, generally less than 1.5 t/ha, are associated with frequent water and temperature stress. N stress is negligible on all farms and P stress on 12 days is a factor only on farm 3 in southern Iowa.

Winter Wheat

The spatial pattern of winter wheat yields (Table 11, Figure 11a) differs from that of the summer grown crops whose yields are lowest in the western zone (farms 8,9, 10, 12, 13). Yields on these farms of 1.0 to 3.0 t/ha are commercially viable. Low annual precipitation limits yields of summer crops in this region. Winter wheat appears less sensitive to water

shortages than to the stress of low temperature. Only farms 10, 12 and 13 record 10 or more water stress days for the entire growing season. Winter wheat yields range from 2.5 to 3.5 t/ha in the eastern part of the study region. Here as well, temperature stress dominates, undoubtedly due to cold conditions before, during and after the crop's winter dormancy period.

Switchgrass

Switchgrass yields (Table 12, Figure 12a) range from 2.2 to 12.0 t/ha across the study region with the highest yields (9.0 to 12.0 t/ha) in southern Kansas and Missouri (farms 7,8,9) and the lowest (< 4.0 t/ha) in western Nebraska. All of the aboveground biomass of switchgrass is harvested. A direct comparison of switchgrass with the other crops, in which only the grain is harvested can, therefore, be misleading. In addition, stress day and growing season statistics must be interpreted differently since switchgrass is a perennial crop. Stress days are generally larger in number since they are accumulated during the entire year. Growing season, the period when temperatures are high enough to allow photosynthetic activity, is also much longer than for the grain crops. Temperature stress was the most frequent of stresses on all of the farms due to low temperatures at the beginning and end of the growing season and during the winter months when no growth occurs. Nitrogen stress averaged 37 days for all farms in the study area signaling, perhaps, that optimal switchgrass production may require N fertilizer applications greater than 120 kg/ha currently used in the simulations. The patterns of phosphorus stress were similar. Water stress was evident only on farms 10-13 located in the western zone. Yields at these sites ranged from 4.0 to 6.0 t/ha. Yields ranging from 4.0 to 7.0 t/ha occur in northern portions of the study region (farms 1,2,3, 11). These relatively low yields are due to a short growing season and cold induced temperature stress.

D. Crop Yields under the CSIRO Climate Change Scenario with no CO_2-fertilization ([CO_2] = 365 ppm)

Corn

Under the CSIRO climate change scenario and no CO_2-fertilization, corn yields (Table 8, Figure 8b) decreased on farms 1-8 in Missouri, Iowa and eastern Kansas and Nebraska and increased on farms 10, 12, and 13 in western Kansas and Nebraska. Yields increased in the western zone because of increased in precipitation which reduced the frequency of water stress. Higher temperatures, while not severe enough to offset the benefits of extra precipitation, did increase the number of temperature stress days. In Missouri and Iowa, yield decreases are attributable to the higher temperatures which shorten the growing season and increase the number of heat stress days. Central Kansas and Nebraska represent a transition zone with both positive and negative yield effects in response to the changed climate. Yield increases result from increased precipitation; the decreases are due to increased temperature stress and a shortened growing season.

Sorghum

The CSIRO climate change scenario decreased sorghum yields (Table 9, Figure 9b) throughout the study region except for western Nebraska and northwestern Kansas (farm

12). The yield increases result from reductions in both water stress and cold-induced temperature stress due to the increased precipitation and higher temperatures under the climate change scenario. The largest decreases in sorghum yield occur in Missouri and eastern Kansas (farms 6, 7, 8). These decreases, never more than 1.0 t/ha, are due, primarily, to a shortened growing season on all the farms. Cold induced temperature stress on farms 1, 2, 4, 6 under the baseline climate is relieved by the climate change. Nonetheless, yields on these farms were lower than under the baseline climate.

Soybeans

The spatial pattern of soybean yield change (Table 10, Figure 10b) is similar to that of sorghum. Yields decreased on farms in Missouri, Iowa and eastern Kansas and increased in western and central Nebraska. Soybean yield increases in the western zone (farm 12) result from decreased water stress due to increased precipitation under the CSIRO climate change. The higher temperatures also benefit yields by decreasing the frequency of cold-temperature stress. Soybean yield losses were greatest on farms in central and southern Missouri (farms 5, 7). These losses are due to the higher temperatures which both shortened the growing season and increased the incidence of heat stress. The decrease in soybean yields in Iowa and eastern Nebraska is not as severe as in the zone to the south. Here the yield decreases are due to higher temperatures which shorten the growing season. However, the decreases are offset by the reduction in cold-temperature stress due to the higher temperatures of the climate change scenario.

Winter Wheat

Changes in winter wheat yields (Table 11, Figure 11b) under the CSIRO climate change are more uniform than is the case for summer crops. Most changes are within ± 0.5 t/ha. Winter wheat yields throughout the central and western portions of the study region (farms 9, 13) generally benefit from the climate change, with the yield increases explained by a decrease in both water and temperature stress. Wheat yields also increase for a scattering of sites in the eastern zone (farm 6), again explained by the combined benefits of decreased water and temperature stress. Wheat yields decrease from baseline on most of the farms in Missouri and Iowa (farms 2, 3, 5, 7). Farms in northeastern Iowa (typified by farm 1) experience the most severe yield losses of any in the study region. These losses are associated with increases in winter and spring temperature (figs 7a, 7b) that, while decreasing cold related temperature stress, also increase crop water demand leading to increased water stress.

Switchgrass

Notably, switchgrass yields (Table 12, Figure 12b) increase from baseline under the CSIRO climate change scenario. Increases in excess of 8.0 t/ha occur in Iowa and eastern Nebraska (farms 1, 2, 3, 4). Temperature increases of up to 8.0 C in this region benefit switchgrass yields by reducing cold temperature stress and by lengthening the growing season for this perennial crop. Yield increases of 2.0 to 5.0 t/ha are common in the western and central portions of the region (farms 8-13). The lesser yield increases are due to more moderate increases in spring and winter temperature. Unlike the grain crops

which end their growth when physiological maturity is achieved, switchgrass, a perennial, continues to grow for as long as lethally low temperatures do not occur. Thus, higher temperature lengthens the switchgrass growing season. The longer growing season does, however, lead to increased water stress on all farms despite increased precipitation. Nitrogen stress is virtually eliminated on all farms. Warmer temperatures affect the soil nitrogen cycle with the net effect of increasing plant available N. While N stress is reduced to zero, P stress is increased proportionally in some cases (farms 1, 3). The higher growth rate of switchgrass may exhaust crop available P which results in higher stress levels.

E. Climate Change with the CO_2-fertilization effect

The effects of the CSIRO climate change scenario on EPIC-simulated yields are modified when the CO_2-fertilization effect is involved. The prior simulations with [CO_2] = 365 ppm were repeated with [CO_2] = 560 ppm. Results are presented for farms 1-13 for corn, sorghum, soybean, winter wheat and switchgrass in Tables 8-12, respectively.

While yield response to increased [CO_2] is unique for each crop and location, consistent trends worth noting emerge. Increasing [CO_2] decreases water stress. This trend is more noticeable in the central and western zones (farms 9-13) in which water is short even under the climate change scenario. Corn and sorghum yields are most responsive to decreases in water stress, while winter wheat is least affected. In the eastern zone (farms 1-7), water stress days for the traditional crops are virtually non-existent under the climate change scenario so that despite improved water use efficiency, the impact on yield is minimal. Elevated [CO_2] does not affect temperature stress. N stress, on the other hand, increases in all crops but soybeans by elevated [CO_2]. Reduced crop water use may impact the N supply by increasing runoff or percolation through the soil root zone. The increases in N stress are most likely due to increased production of biomass and withdrawal of N from the soil.

Relative yield increases under CO_2-fertilization are greatest for soybean and winter wheat. For soybeans, the increased [CO_2] pushed yields to or above baseline levels, overcoming the negative effects of climate change throughout the region (farms 1-3, 10-13). Yield increases from baseline range from 0.1 t/ha (farm 1,2) to 0.9 t/ha (farm 12). Yield gains for winter wheat are greatest in Iowa and Missouri with maximum increases from baseline of 0.5 t/ha (farm 4, 6). Yields increased only slightly at [CO_2] = 560 ppm on wheat farms in central and western Kansas and Nebraska (farms 9 – 13). However, these increases were large enough to raise the yields to or above baseline in all cases. Since soybean and winter wheat are C3 crops, the effect of increased water use efficiency and greater photosynthetic efficiency combine to benefit yields.

Corn and sorghum respond similarly but less dramatically to the higher [CO_2]. Relative yield increases are smaller than in soybean and winter wheat. Yield increases correlate with decreased water stress. Corn and sorghum are C4 plants and their photosynthetic efficiency is only slightly improved by higher [CO_2]. Corn yields in the central and western zones (farms 9-13) increase to or above baseline levels under the climate change scenario without CO_2-fertilization. On farm 13 CO_2-fertilization raises this yield by a further 0.4 t/ha. The greatest percent yield increase occurs on farm 13, where a corn yield

increase of 17% is correlated with decreased water stress (21 fewer days than baseline). Yield increases due to CO_2-fertilization range from 0.1 to 0.6 t/ha for corn farms in the eastern zone (farms 1-8) and by 0.1 to 0.4 t/ha for sorghum. In neither case are these increases sufficient to push yields above baseline levels and only sorghum yields for farms 1,2 are restored to baseline levels.

Of all the crops studied, switchgrass shows the greatest response to CO_2-fertilization of all crops studied with increases up to 2.6 t/ha (farm 7) above that under climate change alone. As with the other C4 crops – corn and sorghum – the yield increases at higher [CO_2] are due to increases in water use efficiency and, in fact, water stress days decrease under elevated [CO_2] for all farms except farms 6 and 12. As with the other crops, N stress increases for some sites under elevated [CO_2], although on fewer farms (1, 2, 3, 12 and 13) than in the case of the other crops. Switchgrass, however, is the only crop in which P stress increased higher [CO_2], as many as 65 days more than under the baseline climate (farm 9). The increased P stress is explained by two factors: first, switchgrass's higher growth rate may exhaust crop available P which results in higher stress levels and second, diminished temperature, water and N stress will result in more stress days even if P stress does not change appreciably. This point is an artifact of EPIC assigning a stress day for the highest recorded stress regardless of the severity of the stress and is underscored by the fact that despite the high P stress, yields, which are the true measure of how well a plant adapts and grows in a specific environment, increase.

Table 8: EPIC-simulated yields of dryland corn under baseline and the CSIRO climate change with [CO2] of 365 and 560 ppm

Farm #		Yield	Yield std. dev.	Stress Days Water	Temp.	Nit.	Phos.	Growing Season
		----------t/ha----------		----------d----------				
1	Baseline	7.2	1.1	3	21	3	0	137
	CSIRO (365)	6.3	1.0	3	19	2	1	118
	CSIRO (560)	6.7	1.1	2	18	4	2	118
2	Baseline	7.2	1.2	8	13	0	1	168
	CSIRO (365)	6.2	1.0	5	16	0	1	126
	CSIRO (560)	6.8	1.1	3	15	0	3	126
3	Baseline	7.2	1.2	3	14	6	1	155
	CSIRO (365)	6.4	1.0	2	19	3	2	130
	CSIRO (560)	6.7	1.1	1	18	6	4	130
4	Baseline	7.7	1.2	6	12	0	3	139
	CSIRO (365)	6.6	1.2	1	20	0	2	121
	CSIRO (560)	7.0	1.2	1	20	0	3	121
5	Baseline	7.4	1.1	2	11	12	3	136
	CSIRO (365)	6.6	1.1	3	17	4	2	120
	CSIRO (560)	6.9	1.1	1	15	8	5	120
6	Baseline	7.9	1.4	5	13	2	1	155
	CSIRO (365)	6.9	1.2	2	18	0	0	126
	CSIRO (560)	7.4	1.2	1	18	1	1	126
7	Baseline	7.8	1.2	1	8	7	7	155
	CSIRO (365)	7.2	1.1	1	13	2	4	128
	CSIRO (560)	7.5	1.2	1	11	4	8	128
8	Baseline	5.8	1.0	3	6	14	1	158
	CSIRO (365)	5.2	0.9	1	8	12	1	126
	CSIRO (560)	5.3	0.9	1	7	15	1	126
9	Baseline	5.7	1.4	9	7	8	0	161
	CSIRO (365)	5.8	1.0	2	8	8	1	126
	CSIRO (560)	5.9	1.0	1	7	12	3	126
10	Baseline	4.6	2.0	17	13	7	0	169
	CSIRO (365)	4.7	0.9	3	10	11	14	132
	CSIRO (560)	4.8	0.9	1	9	15	17	132
11	Baseline	6.0	1.0	3	10	19	0	162
	CSIRO (365)	5.8	1.0	1	16	6	0	128
	CSIRO (560)	6.0	1.0	1	16	10	0	128
12	Baseline	4.7	1.6	25	13	2	0	170
	CSIRO (365)	5.5	0.9	3	17	11	0	127
	CSIRO (560)	5.5	0.8	1	17	17	0	127
13	Baseline	3.5	1.8	36	30	4	0	138
	CSIRO (365)	3.7	1.9	22	31	6	0	127
	CSIRO (560)	4.1	1.6	15	31	15	1	127

Table 9: EPIC-simulated yields for dryland sorghum under baseline and the CSIRO climate change with [CO2] of 365 and 560 ppm.

Farm #		Yield	Yield std. dev.	Stress Days Water	Temp.	Nit.	Phos.	Growing Season
		----------t/ha----------		----------d----------				
1	Baseline	3.6	0.7	2	23	0	0	99
	CSIRO (365)	3.4	0.6	2	14	0	1	84
	CSIRO (560)	3.6	0.6	1	14	0	1	84
2	Baseline	5.1	1.0	6	29	0	1	121
	CSIRO (365)	4.7	0.8	4	11	1	1	91
	CSIRO (560)	5.1	0.9	2	10	2	3	91
3	Baseline	5.1	0.9	3	22	2	1	109
	CSIRO (365)	4.7	0.8	2	13	4	1	91
	CSIRO (560)	4.9	0.8	1	12	6	1	91
4	Baseline	4.4	0.7	3	16	0	1	98
	CSIRO (365)	4.0	0.7	1	14	0	1	86
	CSIRO (560)	4.3	0.7	1	14	0	1	86
5	Baseline	4.9	0.8	1	16	13	1	117
	CSIRO (365)	4.4	0.7	1	16	6	1	103
	CSIRO (560)	4.6	0.7	1	16	9	1	103
6	Baseline	5.6	0.9	4	27	1	1	134
	CSIRO (365)	5.0	0.8	2	17	1	1	110
	CSIRO (560)	5.3	0.9	2	17	1	1	110
7	Baseline	5.6	0.9	1	14	6	3	133
	CSIRO (365)	5.1	0.8	1	12	2	3	111
	CSIRO (560)	5.3	0.8	1	11	4	5	111
8	Baseline	5.0	0.9	5	6	10	7	127
	CSIRO (365)	4.4	0.7	2	4	5	5	94
	CSIRO (560)	4.5	0.8	1	3	7	6	94
9	Baseline	4.8	1.3	12	4	7	1	130
	CSIRO (365)	4.4	1.0	5	5	3	1	95
	CSIRO (560)	4.7	0.9	3	5	6	2	95
10	Baseline	4.2	1.5	22	16	9	1	133
	CSIRO (365)	4.0	0.9	7	6	7	1	96
	CSIRO (560)	4.2	0.8	3	6	12	3	96
11	Baseline	5.8	1.0	9	25	4	1	137
	CSIRO (365)	5.4	0.9	2	13	3	1	105
	CSIRO (560)	5.6	0.9	1	13	6	1	105
12	Baseline	4.1	1.1	31	32	0	0	140
	CSIRO (365)	5.1	0.8	5	17	1	0	106
	CSIRO (560)	5.4	0.8	2	17	6	0	106
13	Baseline	2.2	0.7	25	24	0	0	108
	CSIRO (365)	2.1	0.7	17	26	0	0	101
	CSIRO (560)	2.5	0.7	14	27	1	0	101

Table 10: EPIC-simulated yields for dryland soybeans under baseline and the CSIRO climate change with [CO2] of 365 and 560 ppm.

Farm #		Yield	Yield std. dev.	Stress Days Water	Temp.	Nit.	Phos.	Growing Season
		----------t/ha----------		----------d----------				
1	Baseline	2.1	0.5	3	21	0	1	111
	CSIRO (365)	2.0	0.3	2	12	0	1	91
	CSIRO (560)	2.2	0.4	1	12	0	2	91
2	Baseline	2.5	0.5	9	26	0	1	145
	CSIRO (365)	2.2	0.4	4	10	0	1	99
	CSIRO (560)	2.6	0.4	3	10	0	2	99
3	Baseline	2.3	0.4	4	15	0	12	129
	CSIRO (365)	2.1	0.4	2	12	0	6	101
	CSIRO (560)	2.3	0.4	1	10	0	12	101
4	Baseline	2.5	0.4	6	12	0	1	102
	CSIRO (365)	2.2	0.4	2	14	0	1	88
	CSIRO (560)	2.5	0.5	1	13	0	2	88
5	Baseline	2.7	0.5	4	10	0	0	106
	CSIRO (365)	2.1	0.4	3	12	0	0	89
	CSIRO (560)	2.5	0.4	1	12	0	0	89
6	Baseline	2.7	0.5	9	19	0	0	128
	CSIRO (365)	2.3	0.5	2	11	0	0	95
	CSIRO (560)	2.7	0.5	2	12	0	0	95
7	Baseline	2.9	0.5	3	9	0	0	129
	CSIRO (365)	2.3	0.4	1	11	0	0	99
	CSIRO (560)	2.7	0.5	1	11	0	0	99
8	Baseline	2.4	0.6	11	12	0	3	123
	CSIRO (365)	1.8	0.4	5	10	0	0	91
	CSIRO (560)	2.2	0.4	3	10	0	1	91
9	Baseline	2.1	0.7	20	5	0	0	127
	CSIRO (365)	1.5	0.5	11	11	0	0	91
	CSIRO (560)	1.9	0.5	7	13	0	0	91
10	Baseline	1.7	0.7	35	16	0	0	131
	CSIRO (365)	1.6	0.5	12	10	0	0	92
	CSIRO (560)	2.1	0.5	8	10	0	0	92
11	Baseline	2.4	0.6	15	24	0	6	135
	CSIRO (365)	2.3	0.5	5	12	0	2	101
	CSIRO (560)	2.6	0.5	3	10	0	12	101
12	Baseline	1.4	0.4	38	30	0	0	145
	CSIRO (365)	1.9	0.5	9	13	0	0	101
	CSIRO (560)	2.4	0.5	6	14	0	0	101
13	Baseline	0.9	0.3	25	19	0	0	107
	CSIRO (365)	0.9	0.3	15	23	0	0	100
	CSIRO (560)	1.1	0.3	13	23	0	0	100

Table 11 EPIC-simulated yields for dryland winter wheat under baseline and the CSIRO climate change with [CO2] of 365 and 560 ppm.

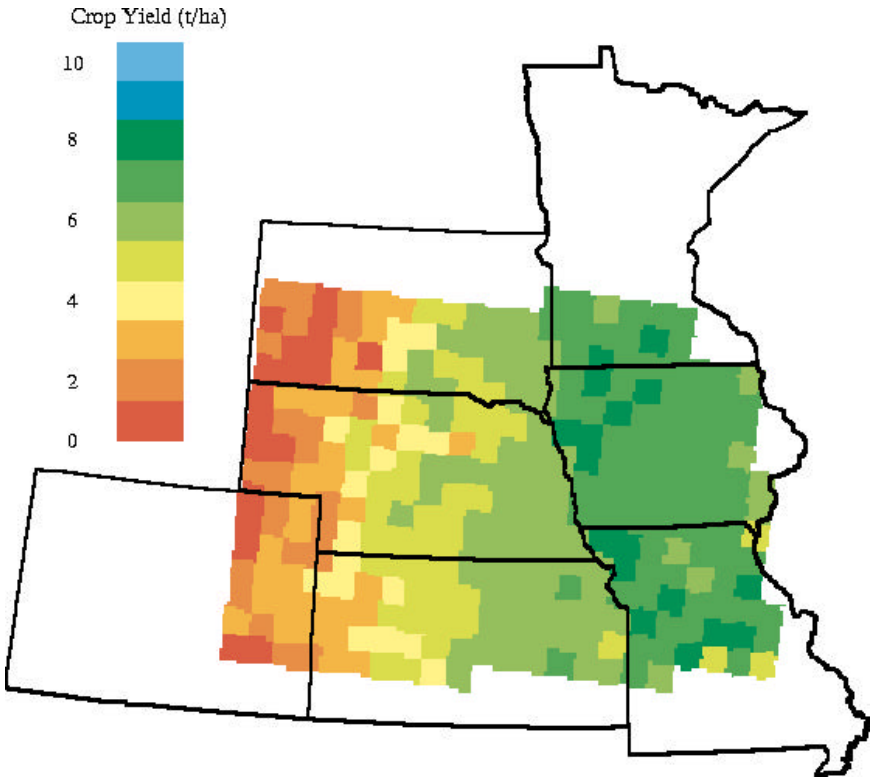
Farm #		Yield	Yield std. dev.	Stress Days Water	Temp.	Nit.	Phos.	Growing Season
		----------t/ha----------		----------d----------				
1	Baseline	3.0	0.6	26	144	0	0	268
	CSIRO (365)	2.5	0.5	33	76	0	0	230
	CSIRO (560)	2.9	0.6	33	84	1	1	230
2	Baseline	3.0	0.6	24	138	0	0	263
	CSIRO (365)	2.8	0.7	23	65	1	0	229
	CSIRO (560)	3.2	0.8	23	85	2	1	229
3	Baseline	3.3	0.6	23	125	0	2	262
	CSIRO (365)	3.0	0.7	15	78	4	11	228
	CSIRO (560)	3.3	0.8	14	75	9	16	228
4	Baseline	2.9	0.6	28	131	0	2	262
	CSIRO (365)	2.9	0.8	25	74	0	2	230
	CSIRO (560)	3.4	0.9	24	82	0	4	230
5	Baseline	2.7	0.5	22	103	4	3	241
	CSIRO (365)	2.6	0.6	9	58	27	7	207
	CSIRO (560)	2.8	0.7	8	56	36	9	207
6	Baseline	3.0	0.6	26	112	0	0	245
	CSIRO (365)	3.2	0.7	15	71	1	3	216
	CSIRO (560)	3.5	0.8	15	73	3	7	216
7	Baseline	3.2	0.6	14	84	5	15	233
	CSIRO (365)	2.9	0.7	7	54	11	26	204
	CSIRO (560)	3.1	0.7	6	52	22	26	204
8	Baseline	2.7	0.6	13	96	20	1	251
	CSIRO (365)	2.7	0.7	6	65	39	3	224
	CSIRO (560)	2.8	0.7	5	63	51	2	224
9	Baseline	2.5	0.5	13	80	50	0	245
	CSIRO (365)	2.7	0.6	11	62	53	2	223
	CSIRO (560)	2.8	0.7	6	61	65	1	223
10	Baseline	2.4	0.5	26	110	15	0	259
	CSIRO (365)	2.4	0.6	14	79	43	3	235
	CSIRO (560)	2.5	0.6	11	77	59	1	235
11	Baseline	2.8	0.5	24	129	6	2	277
	CSIRO (365)	2.8	0.7	22	67	16	7	249
	CSIRO (560)	2.9	0.7	17	86	28	9	249
12	Baseline	2.4	0.4	27	122	25	0	282
	CSIRO (365)	2.4	0.6	23	64	28	0	254
	CSIRO (560)	2.5	0.6	17	92	40	0	254
13	Baseline	1.6	0.3	35	129	42	0	287
	CSIRO (365)	1.7	0.3	39	68	40	4	258
	CSIRO (560)	1.7	0.3	35	89	50	4	258

Table 12: EPIC-simulated yields for dryland switchgrass under baseline and the CSIRO climate change with [CO2] of 365 and 560 ppm.

Farm #		Yield	Yield std. dev.	Stress Days Water	Temp.	Nit.	Phos.	Growing Season
		----------t/ha----------		----------d----------				
1	Baseline	6.2	2.5	4	203	51	38	142
	CSIRO (365)	15.9	6.1	21	159	1	78	218
	CSIRO (560)	17.7	6.8	13	158	5	86	218
2	Baseline	7.1	2.8	10	197	50	37	201
	CSIRO (365)	15.7	6.5	37	158	1	64	212
	CSIRO (560)	17.4	7.0	27	157	2	76	212
3	Baseline	7.0	2.9	12	188	56	42	198
	CSIRO (365)	16.4	6.4	30	133	4	81	213
	CSIRO (560)	17.2	6.8	24	139	8	85	213
4	Baseline	9.0	3.7	10	191	44	45	184
	CSIRO (365)	16.2	6.2	43	153	0	66	194
	CSIRO (560)	18.8	7.1	28	152	0	81	194
5	Baseline	9.5	3.8	16	172	51	53	198
	CSIRO (365)	14.5	5.7	51	125	0	76	226
	CSIRO (560)	16.8	6.7	39	125	1	87	226
6	Baseline	8.8	3.4	17	183	47	44	199
	CSIRO (365)	15.8	6.4	48	139	0	65	211
	CSIRO (560)	18.0	7.2	37	138	0	76	211
7	Baseline	10.8	4.0	19	160	45	53	204
	CSIRO (365)	15.4	6.2	49	114	0	89	232
	CSIRO (560)	18.0	7.0	36	114	0	101	232
8	Baseline	9.4	3.6	31	166	24	62	192
	CSIRO (365)	13.0	5.1	59	123	0	79	228
	CSIRO (560)	15.2	5.9	45	123	0	92	228
9	Baseline	10.9	4.0	6	181	24	0	195
	CSIRO (365)	10.9	4.5	90	129	0	54	229
	CSIRO (560)	12.3	5.1	79	128	0	65	229
10	Baseline	6.3	2.4	51	181	32	39	186
	CSIRO (365)	10.3	4.2	89	137	0	50	217
	CSIRO (560)	11.2	4.6	70	137	0	72	217
11	Baseline	6.8	2.7	24	191	46	37	189
	CSIRO (365)	13.0	5.1	52	146	0	65	220
	CSIRO (560)	15.1	5.9	40	145	0	77	220
12	Baseline	5.6	2.1	28	208	60	2	132
	CSIRO (365)	11.9	4.6	84	167	1	21	158
	CSIRO (560)	13.1	5.0	74	166	5	30	158
13	Baseline	4.3	1.8	37	212	41	14	118
	CSIRO (365)	8.7	3.6	69	170	0	52	158
	CSIRO (560)	9.6	3.9	59	168	11	57	158

Figure 8a-b: Baseline yields of dryland corn and deviations from baseline under the CSIRO 2xCO_2 climate scenario (no CO_2 fertilization effect).

a. Baseline yield



b: Deviations from baseline for climate change scenario (no CO_2 fertilization)

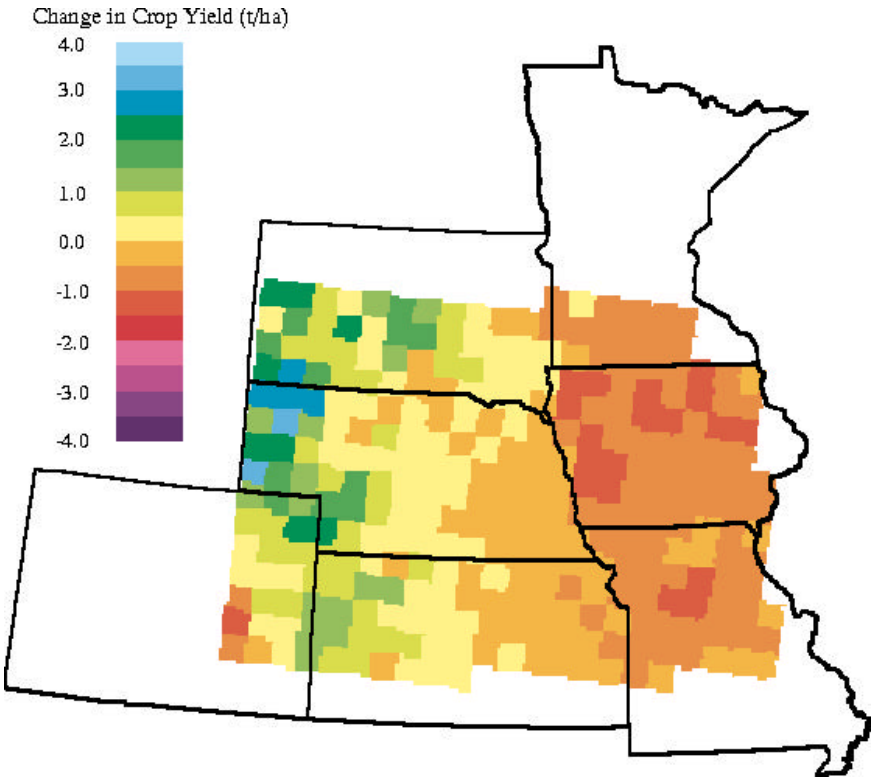
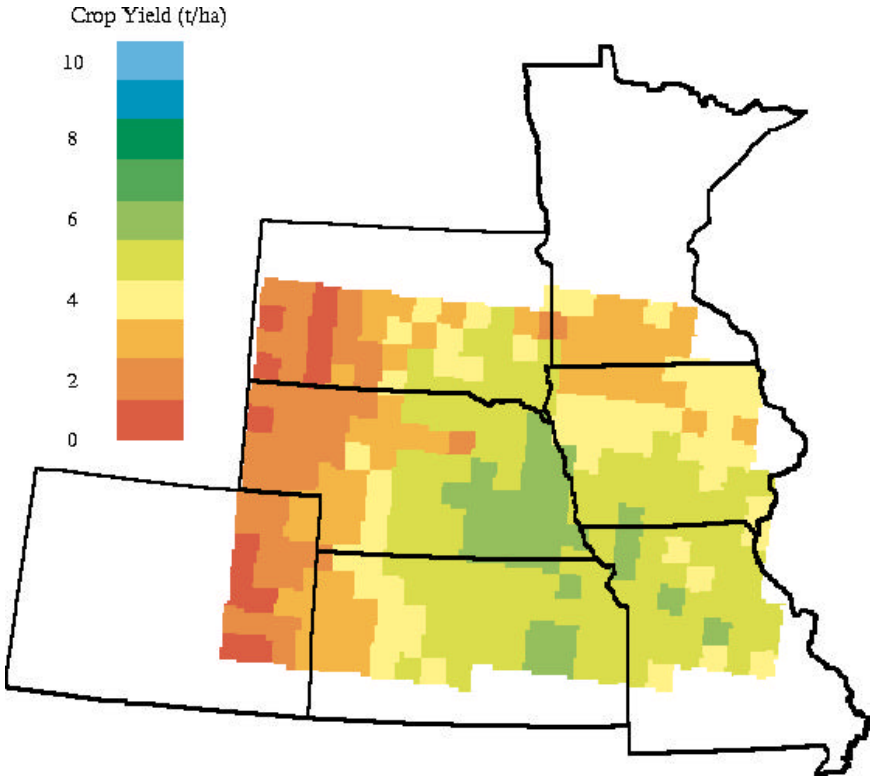


Figure 9a-b: Baseline yields of sorghum and deviations from baseline for the CSIRO 2xCO_2 climate change scenario (no CO_2 fertilization)

a. Baseline yield



b. Deviations from baseline for climate change scenario (no CO_2 fertilization)

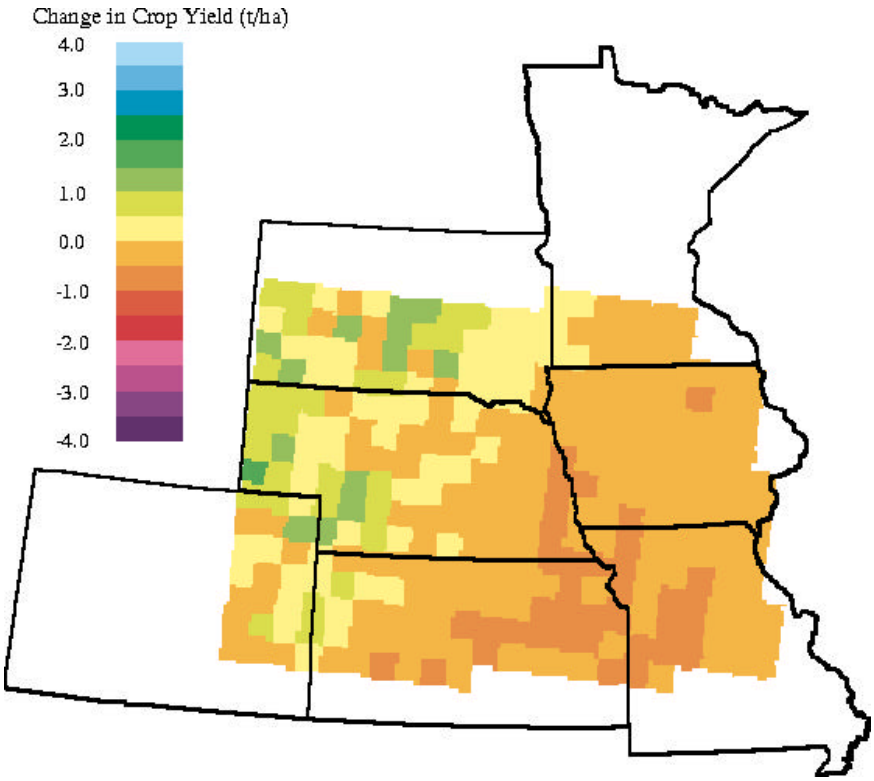
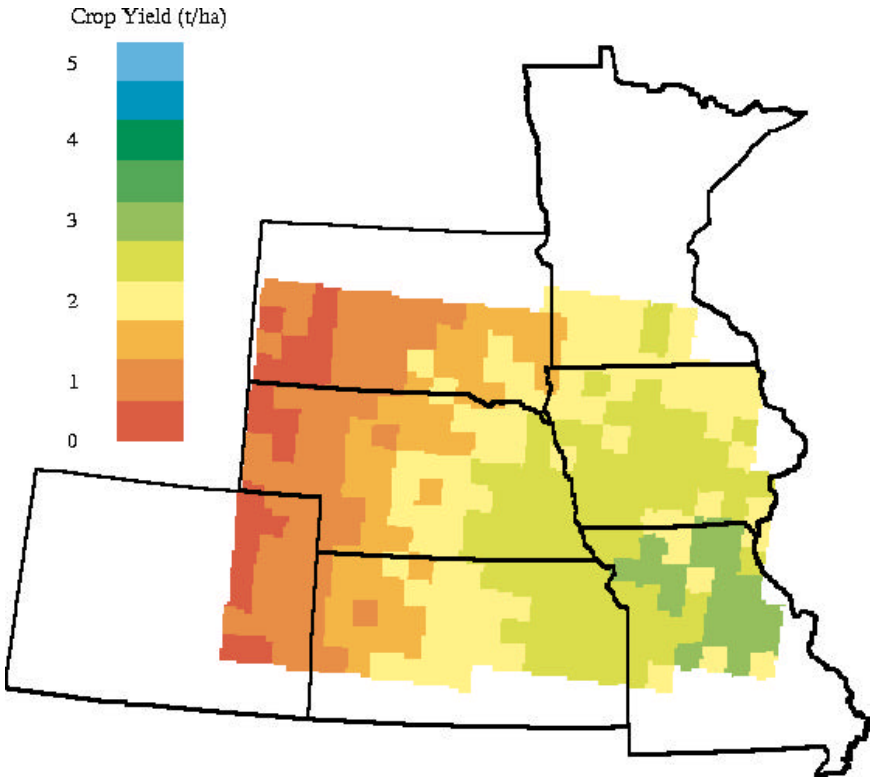


Figure 10a-b: Baseline yields of soybeans and deviations from baseline for the CSIRO 2xCO_2 climate change scenario (no CO_2 fertilization)

a. Baseline yields



b. Deviations from baseline for climate change scenario (no CO_2 fertilization)

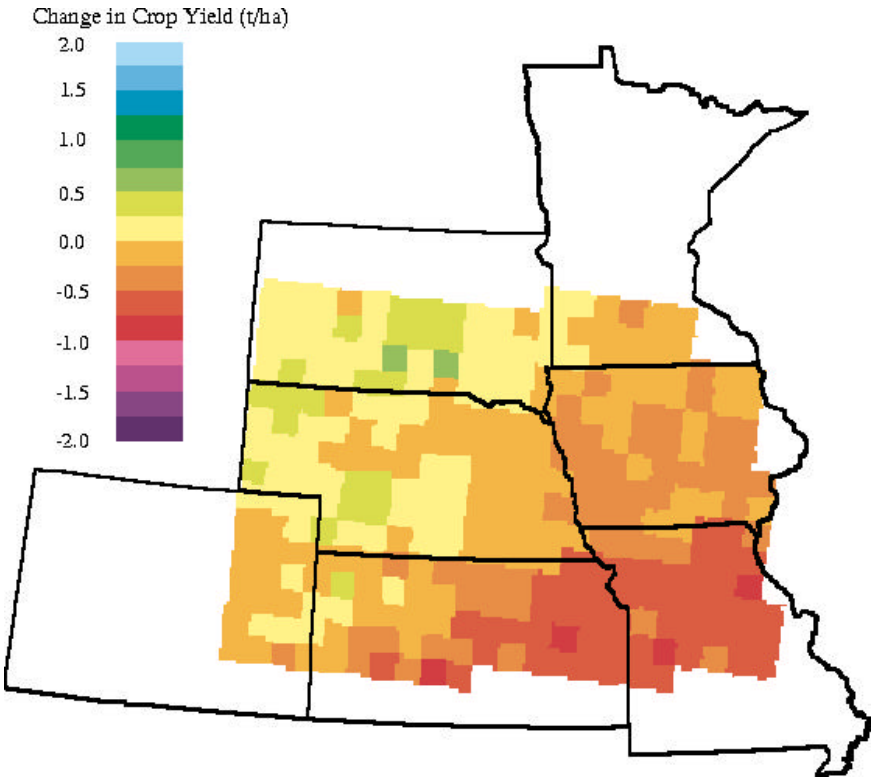
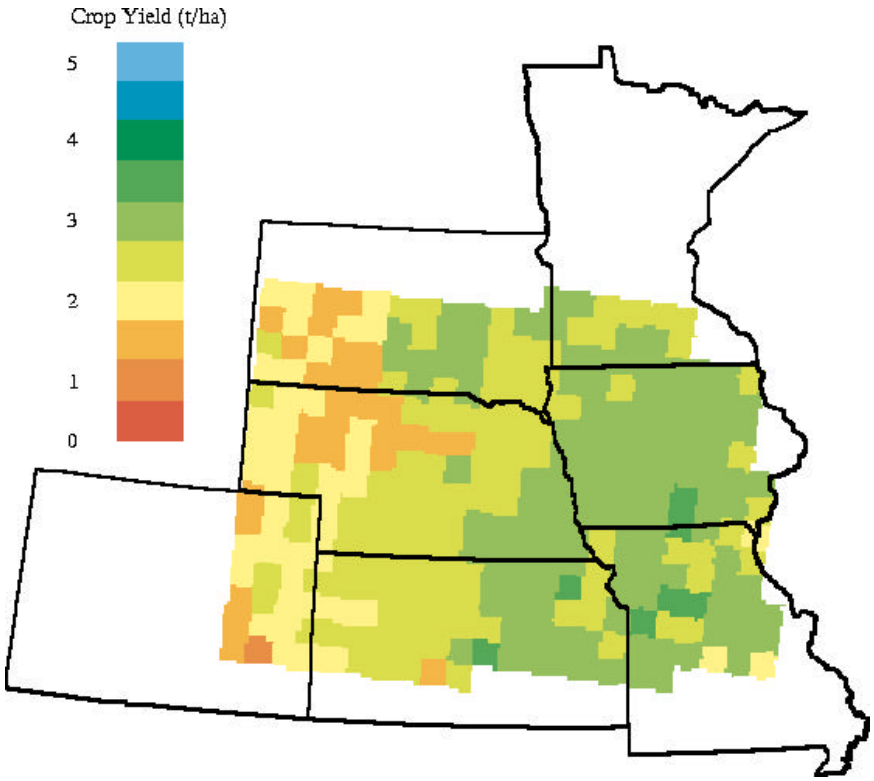


Figure 11a-b: Baseline yields of winter wheat and deviations from baseline for the CSIRO 2xCO_2 climate change scenario (no CO_2 fertilization)

a. Baseline yields



b. Deviations from baseline for climate change scenario (no CO_2 fertilization)

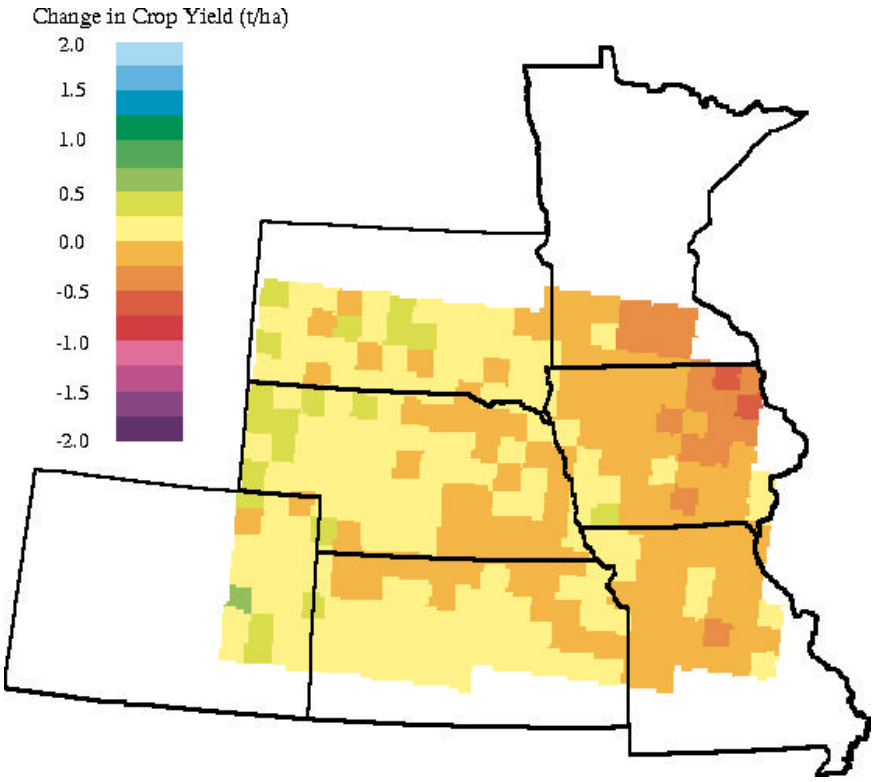
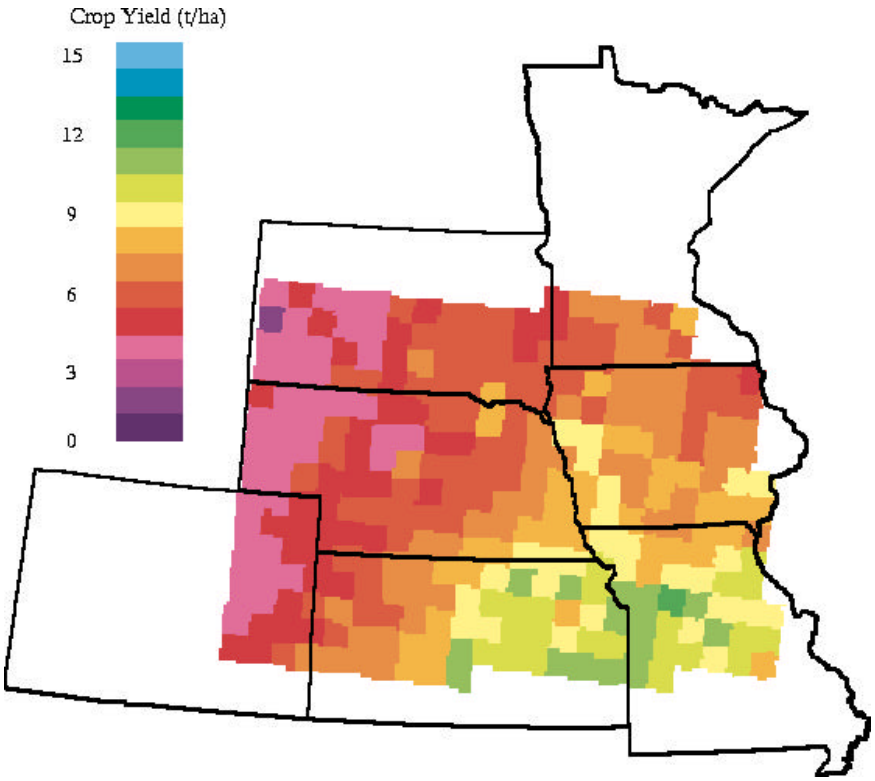
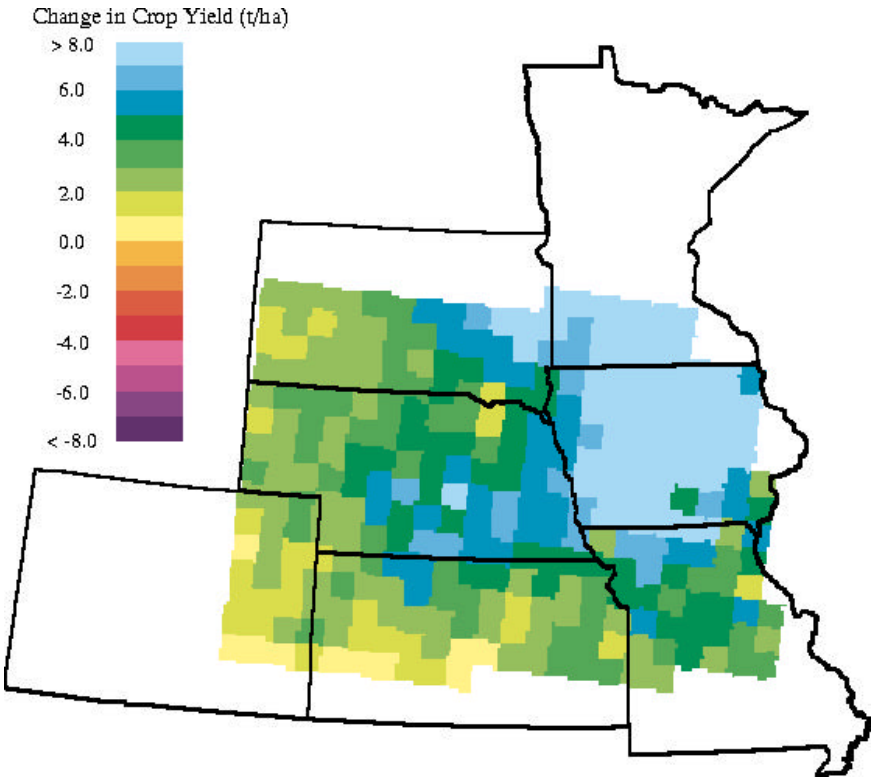


Figure 12a-b: Baseline yields of switchgrass and deviations from baseline for the CSIRO 2xCO_2 climate change scenario (no CO_2 fertilization)

a. Baseline Yields



b. Deviations from baseline for climate change scenario (no CO_2 fertilization)



F. Regional crop production under the baseline and CSIRO 2x CO_2 climate scenarios

The EPIC-simulated yields can be scaled up to provide a first order view of how agricultural production in the study region might be affected by climate change and the introduction of a biomass energy crop. Figure 13 (a-e) presents a series of Potential Supply Functions (PSF) for each crop under baseline climate and the CSIRO 2xCO_2 climate, with and without CO_2-fertilization. These functions were developed by plotting the EPIC yields in each model grid in ascending order against total cropland for that grid. Cropland is defined in the 1992 Agricultural Census as land from which crops were harvested, hay was cut, fallow land, cropland in rotation, and pasture and meadow which can be used by crops without any additional improvement (US Department of Census, 1992). *Total cropland* was used in this analysis rather than cropland under current production for a specific crop since it is unclear how cropping patterns and land use will be affected by climate change. The total cropland metric allows an estimate of potential supply of a particular a crop, were it grown on all available land in the region.

Shifts in the PSFs of the individual crops in response to changing climate or increasing [CO_2] reflect the results obtained for the individual farms presented and discussed in the preceding section. The PSF for corn (Figure 13a) under the CSIRO climate change shows an increase above baseline for the less productive farms (western zone) and a decrease from baseline for the more productive farms in the eastern zone. Under the climate change this trend tends to 'flatten out' the supply function and diminish regional yield differences for corn. Increasing [CO_2] to 560 ppm further promotes this trend. Sorghum (Figure 13b) behaves much like corn with potential production increasing in the less productive areas. However, sorghum differs from corn in that potential production does not significantly decrease in the more productive regions under the climate change. All crops exhibit a net benefit in potential production with elevated [CO_2] under climate change. Soybean production (figure 13c) responds most strongly with potential production surpassing baseline under this scenario. The PSFs for winter wheat (figure 13d) show no discernable change from baseline under the CSIRO 2xCO_2 climate. As with soybean, higher [CO_2] increases the PSF above baseline throughout the full range of productivity. The switchgrass PSF shows an approximate doubling of biomass production from baseline in response to the climate change scenario. The increasing slope indicates an increasing difference between low and high productivity regions. As with the other crops, higher [CO_2] benefits switchgrass production, but not as much as the climate change alone.

Figure 13 (a-e): Expected yield for corn, sorghum, soybean, winter wheat and switchgrass for the MINK region under baseline climate, CSIRO climate ([CO_2] = 365 ppm) and CSIRO climate ([CO_2] = 560 ppm).

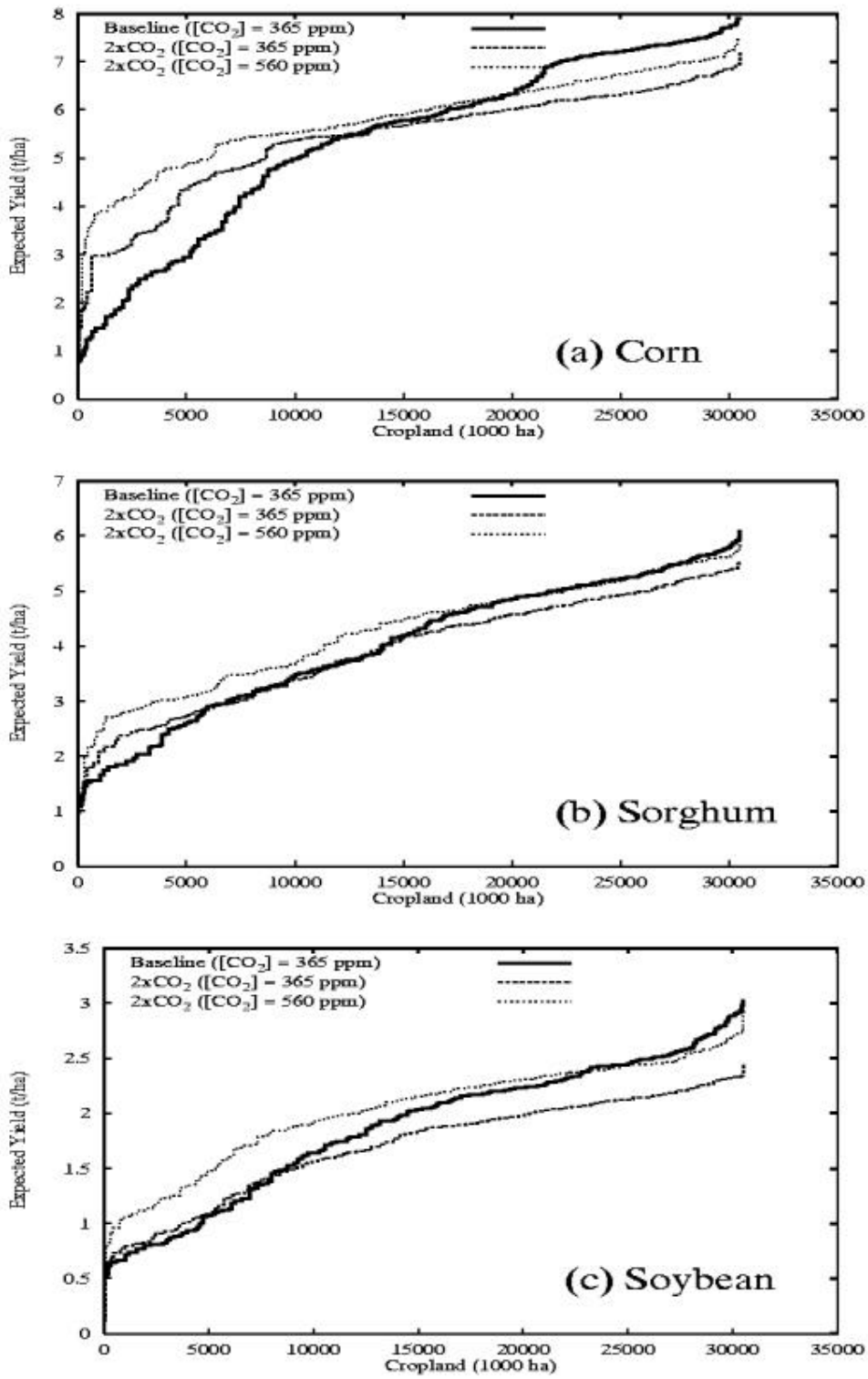
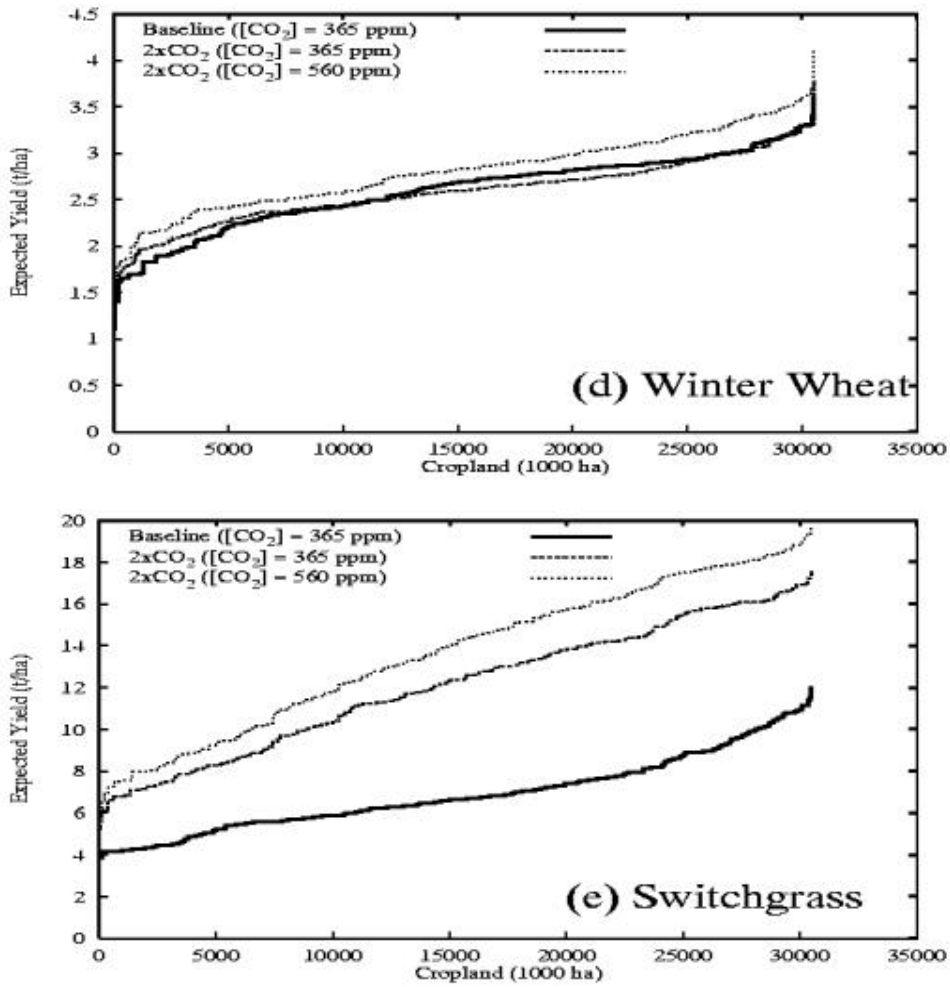


Figure 13
(cont.)



G. Evapotranspiration, Runoff and Soil Erosion under the baseline and CSIRO 2x CO_2 climate scenarios

In this section, we summarize simulated actual evapotranspiration (ET), potential evapotranspiration (PET), runoff and soil erosion data for corn (Table 13), winter wheat (Table 14) and switchgrass (Table 15) under both baseline climate and the CSIRO climate change scenario at [CO_2] levels of 365 and 560 ppm.

Evapotranspiration

Under baseline climate, switchgrass consumes more water than either corn or winter wheat for all locations. PET values differ only slightly between corn and wheat with that of corn ranging from 1117 (farm 1) to 1905 mm (farm 9) and of wheat ranging from 1131 (farm 1) to 1912 mm (farm 9). PET for switchgrass is slightly higher with a range of 1193 (farm 1) to 1947 mm (farm 10). The geographic distribution of PET values is similar for all crops with the higher values in the southern zone of the study region (farms 8, 9, 10, 12). Actual ET differs more among crops. The wheat crop consumes the least water with ET values ranging from 372 (farm 13) to 644 mm (farm 7). Corn ET is slightly higher than wheat ET for all farms, while switchgrass ET exceeds both corn and wheat ranging from 414 mm (farm 10) to 901 mm (farm 7). The perennial switchgrass has a longer growing season than do corn and winter wheat; hence its water use requirement is greater.

Water use increases for all crops under the CSIRO climate change scenario. Switchgrass water use increases most, with increases in ET over baseline ranging from 95 mm (farm 13) to 247 mm (farm 1). Corn and wheat ET also rise, but more moderately -- corn from 11 mm (farm 8) to 86 mm (farm 12); wheat from 40 mm (farm 1) to 107 mm (farm 9). Increased ET under the climate change scenario follows from the higher temperatures, which increase the plant's evaporative demand and from greater precipitation, which increases the soil water supply. In switchgrass, the lengthened growing season under the CSIRO climate and increased plant biomass and leaf area index also push water use higher. For corn and wheat, on the other hand, the CSIRO climate change scenario shortens the growing season –- a factor that decreases ET.

Because the CO_2-fertilization effect increases water use efficiency, crop water use is decreased under the CSIRO climate with [CO_2] set at 560 ppm. In all cases, ET values decreased below the climate change scenario with [CO_2] = 365 ppm. In some cases corn ET decreased below its baseline climate levels (farms 4, 6 – 9 , 11) The sensitivity of ET to increasing [CO_2] varies by crop and location. For switchgrass, the largest decreases in ET occur in the northeastern zone in Iowa (farms 1, 2, 3) while corn and wheat farms show a more consistent spatial pattern of ET decreases across the entire study region.

Runoff

Simulated annual runoff (Q) was lower at most locations under switchgrass cultivation than under corn or wheat cultivation. Due to the low annual baseline precipitation, runoff in the western zone (farms 10-13) was minimal with Q virtually zero (< 10 mm) for all crops. Runoff was greater on the eastern farms. Farm 8 in Kansas had the largest Q values – 79 mm for wheat, 73 mm for corn and 66 mm for switchgrass. Runoff on farms 1 and 5 in the eastern zone was minimal.

Runoff increased under the CSIRO climate change scenario with farms growing corn and wheat displaying greater sensitivity to the changed climate than farms growing switchgrass. Increases from baseline runoff ranged from 2 mm (farm 12) to 82 mm (farm 8) with corn as cover; from 2 mm (farm 12)

to 80 mm (farm 8) with wheat and from 2 mm (farm 12) to 57 mm (farm 2) with switchgrass. While the greatest absolute increases in runoff occurred on farms in the eastern and central zone of the study region (farms 2, 8), the relative changes on farms 10-13 in the western zone are also notable. Elevated [CO_2] increased runoff on most farms; however the increases were small with little discernable difference among crops.

Erosion

The soil erosion data presented in Tables 13 – 15 represent the combined effects of water and wind erosion. With some exceptions, rates of erosion are higher on farms growing corn. The corn crop budgets employed in this study included more frequent tillage operations which disturbed a greater portion of the soil than the winter wheat and switchgrass budgets. The high erosion rates for corn farms 10 (6.0 mm/year) and 13 (11.6 mm/year) are due to the severe slope at these two sites. These values are outliers from the rest of the data and indicate that, as simulated here, dryland corn is unsustainable on farms 10 and 13. Erosion rates for these farms under switchgrass and wheat cultivation decrease to more sustainable levels. Erosion values at farms 1 (1.0 mm/year) and 2 (0.8 mm/year) are slightly higher under switchgrass cultivation than corn or wheat cultivation. These higher erosion values are explained by the incidence of strong wind erosion during the establishment phase (year 1 out of 10) of switchgrass management which accounts for > 95% of the total erosion. Ranney and Marks (1994) present experimental data with similar results. They conclude that the majority of erosion for short rotation woody crops grown for biomass energy occurs during the establishment period and suggest that proper management of crop residues and mulches could mitigate much of this erosion.

The sensitivity of erosion to the CSIRO climate change scenario differed among crops. Winter wheat erosion, already low under baseline conditions, was the least sensitive with 5 farms decreasing from baseline (1, 6, 9, 10, and 13) and two farms (8 and 11) increasing. Corn erosion increased on farms 1-11 with farm 8 experiencing the maximum increase of 2.1 mm/year. The higher erosion rates are due to the increased precipitation and subsequent runoff under the CSIRO climate. Erosion under switchgrass culture decreases on farms 1, 2, 3, 5, 9, 10 and 12 under the CSIRO climate. The decreases are small with the maximum decrease of 0.4 mm/year occurring on farms 1 and 2.

Table 13: Potential Evapotranspiration (PET), actual evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under corn cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm. (all in mm/yr)

Farm	Baseline				CSIRO Climate – [CO_2] 365 ppm				CSIRO Climate – [CO_2] 560 ppm			
#	PET	ET	Q	Erosion	PET	ET	Q	Erosion	PET	ET	Q	Erosion
	----------mm ----------				----------mm ----------				----------mm ----------			
1	1117	533	1	0.7	1307	578	12	1.8	1307	545	14	1.7
2	1321	618	31	0.3	1554	669	97	1.0	1553	636	100	0.9
3	1368	626	45	1.1	1479	670	78	2.0	1478	632	79	1.9
4	1229	618	32	0.7	1409	655	82	1.3	1409	617	90	1.3
5	1358	654	5	1.2	1592	722	50	2.3	1590	682	55	2.2
6	1317	627	12	0.4	1522	658	35	0.8	1520	617	36	0.7
7	1396	736	19	0.3	1581	767	64	0.5	1579	726	66	0.5
8	1424	682	73	1.9	1602	693	155	4.0	1601	659	160	4.0
9	1905	623	6	3.7	2096	642	16	3.8	2094	599	18	3.8
10	1722	558	5	6.0	1936	659	18	6.4	1933	621	20	6.3
11	1348	599	7	0.9	1531	630	25	1.3	1530	589	26	1.2
12	1483	499	0	2.5	1645	585	2	2.3	1642	555	2	2.3
13	1336	394	2	11.6	1441	437	15	8.4	1439	428	16	8.4

Table 14: Potential Evapotranspiration (PET), evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under winter wheat cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm.

Farm	Baseline				CSIRO Climate – [CO_2] 365 ppm				CSIRO Climate – [CO_2] 560 ppm			
#	PET	ET	Q	Erosion	PET	ET	Q	Erosion	PET	ET	Q	Erosion
	----------mm ----------				----------mm ----------				----------mm ----------			
1	1131	494	1	0.3	1320	535	15	0.2	1314	508	15	0.2
2	1345	558	35	0.1	1567	615	104	0.1	1558	582	106	0.1
3	1379	566	47	0.2	1489	646	84	0.2	1477	606	85	0.2
4	1248	542	39	0.1	1420	597	93	0.1	1412	568	96	0.1
5	1375	587	7	0.2	1604	649	56	0.2	1593	608	57	0.2
6	1334	538	14	0.1	1534	598	35	0.0	1525	561	36	0.0
7	1407	644	24	0.0	1606	712	64	0.0	1587	671	65	0.0
8	1435	636	79	0.3	1618	728	159	0.5	1604	677	167	0.5
9	1912	576	4	0.5	2100	634	13	0.4	2093	585	15	0.3
10	1727	514	9	1.1	1935	624	21	0.7	1930	578	22	0.6
11	1363	531	10	0.1	1549	632	27	0.2	1534	583	28	0.2
12	1489	485	0	0.1	1652	569	2	0.1	1645	523	2	0.1
13	1348	372	4	0.9	1445	414	18	0.8	1442	386	18	0.8

Table 15: Potential Evapotranspiration (PET), evapotranspiration (ET), runoff (Q) and eroded soil loss (Erosion) for selected farms under switchgrass cultivation at baseline climate and CSIRO climate at [CO_2] = 365 and 560 ppm.

Farm	Baseline				CSIRO Climate – [CO_2] 365 ppm				CSIRO Climate – [CO_2] 560 ppm			
#	PET	ET	Q	Erosion	PET	ET	Q	Erosion	PET	ET	Q	Erosion
	----------mm ----------				----------mm ----------				----------mm ----------			
1	1193	627	1	1.0	1486	874	12	0.6	1373	825	13	0.6
2	1438	718	30	0.8	1800	938	87	0.4	1659	899	92	0.4
3	1517	769	38	0.7	1751	1006	69	0.5	1610	967	73	0.5
4	1362	719	27	0.4	1664	865	68	0.4	1539	851	72	0.4
5	1490	791	5	0.7	1907	954	42	0.4	1754	941	47	0.4
6	1490	758	12	0.0	1839	927	34	0.0	1698	908	35	0.0
7	1576	901	20	0.0	1916	1034	57	0.0	1757	1018	59	0.0
8	1651	802	66	0.1	1968	935	122	0.1	1802	925	129	0.1
9	1913	608	1	0.2	2494	753	15	0.1	2295	751	15	0.1
10	1947	561	4	1.1	2355	694	14	0.2	2158	693	15	0.2
11	1521	666	7	0.4	1818	817	19	0.4	1679	804	21	0.4
12	1674	500	0	0.2	2025	629	2	0.1	1887	629	2	0.1
13	1458	414	2	1.2	1684	509	13	1.3	1565	503	14	1.3

Summary & Discussion

Crop Yields under Baseline Climate

The EPIC simulations correctly reproduce the actual geographic distribution of crop yields in the MINK region. Corn, soybean and winter wheat yields are best on representative farms in Iowa and Missouri – a very productive region. Simulated crop yields in this region are high because water, N and P stresses are low, rarely occurring on more than 10 days for any crop or location. Simulated sorghum yields in excess of 6.0 t/ha occur in eastern Nebraska and Kansas. More frequent cold temperature stress reduces sorghum yields in Iowa and Missouri. Cold temperature stress also affects corn, soybean and winter wheat in the eastern zone, but has less of an impact on these crops. Sorghum yields average 3.0 t/ha for farms in northern and central Iowa, indicating the northern boundary of the crop's effective growing region.

Lower precipitation and higher summer temperatures reduce corn and soybean yields in the central zone of the MINK region. Sorghum and winter wheat yields are commercially viable in this region, demonstrating the ability of these crops to yield a satisfactory crop under less humid conditions. Corn, sorghum and soybean yields decline precipitously in the western portion of the MINK region, approaching zero in some cases. Low annual precipitation, extreme temperature and poor soil fertility all contribute to the low yields. Winter wheat yields also decline in this zone but in most cases remain at or above 1.0 t/ha.

The highest simulated switchgrass yields (12.0 t/ha) occur in southern Kansas and Missouri. As with sorghum, low temperatures constrain switchgrass yields decreasing them to 6.0 t/ha in northeast Iowa. Low temperatures reduce that crop's photosynthetic potential and shorten its growing season. Switchgrass yields tend to decrease in the western zone part of the MINK region. Increasing water stress contributes to the yield reduction but low temperatures are the more important factor.

The CSIRO 2xCO2 climate change scenario

The CSIRO climate change scenario increases both temperature and precipitation in the MINK region. Temperature increases ranging from 3.5 to 5.0 C in summer and fall are uniformly distributed throughout the region. The greatest temperature increases, as much as 8.0 C, occur in winter and spring. Temperatures increase from the SW to the NE. Precipitation increases range from 0 to 200 mm in the spring, summer and fall. The pattern of change in summer precipitation is complex. Small decreases are noted on a handful of grids scattered throughout the study region. In spring and fall, the largest increases occur in southern Iowa and northern Missouri. Precipitation increases in winter are modest, ranging from 0 to 50 mm.

Crop yields under the CSIRO 2xCO2 climate change scenario

Yield responses to the CSIRO climate change scenario vary by crop and region. Nevertheless, careful analysis reveals certain patterns that are consistent throughout the EPIC simulations. First, switchgrass yields increase at all locations. Yield increases range from 2.0 to 8.0 t/ha with the greatest changes occurring in central and northern Iowa. Second, yields of corn, sorghum, soybean and winter wheat generally increase in the western and decrease in the eastern portions of the study region with a clear zone of transition in the central portion. Third, a north to south pattern emerges with changes in the northern portion more moderate than in the southern portion of the study region. In the case of soybeans, for example, the latter two geographic change patterns result in yield increases of 1.0 t/ha in northwest Nebraska and yield decreases of 1.0 t/ha in southeast Missouri. While the CSIRO climate change scenario alters the yield distribution of all crops throughout the MINK region, these changes are not large enough for us to conclude that the preferred growing region of certain crops will shift either westward or northward.

Temperature increases under the CSIRO climate are important in determining yield response. In general, temperature increases lowered yields of the traditional crops, while switchgrass yields were benefited. In the traditional agricultural crops, higher temperatures speed up time to maturity which, all else equal, decreases yields. This finding is consistent with results in Easterling et al (1992) and Rosenzweig et al (1994) which also show the negative impact of rising temperatures and subsequent shortened growing season on grain yields. In contrast, higher temperatures lengthen the switchgrass growing season. Temperature increases also impact yields by reducing cold stress and/or increasing heat stress. Yields in the northern zone of the study region were improved by warming through a decrease in the number of cold stressn days. However, for farms located in the southern zone, warming increased the frequency of heat stress, impacting crop yields negatively.

Increases in precipitation benefited crop yields by reducing water stress. Benefits due to increased precipitation were most obvious on farms in western Kansas and Nebraska, a region which is water short under the baseline climate. Corn, soybean and sorghum are the most responsive to water stress reduction. Switchgrass differs from the other crops in that it generally experiences increased water stress under the $2xCO_2$ climate because higher temperatures increase its water use and the length of the season during which it consumes water.

The 'CO2 Fertilization Effect'

In all cases, the higher CO_2 concentration increased yields under the CSIRO climate change scenario. However, the yield sensitivity differed among crops and locations. The C3 plants – soybean and winter wheat – show greater relative increases in yield than do the C4 plants – corn, sorghum and switchgrass. This is expected since increased [CO_2] improves both the photosynthetic and water use efficiency of C3 species but only the latter in C4 species. The incidence of water stress decreases for both C3 and C4 plants under increased [CO_2]. Water stress days decrease most in the drier western and central

portions of the study region. While water stress decreases, N stress increases at higher [CO_2]. Two factors explain this phenomena: first, increased plant growth increases crop demand for N; second, and most importantly, decreases in water stress make it more likely that N shortage will create the most severe stress on any given day of the growing season. Under this circumstance N stress will be registered even though yields may not change appreciably. We note that the impact of more N stress days is small, since yields generally increase at higher levels of [CO_2].

Impacts on Water Use, Runoff and Soil Erosion

Our analysis of EPIC simulated plant water use, runoff and soil erosion shows that a land use conversion from traditional crops to switchgrass could have environmental implications at the farm level and for the region as a whole. Under baseline climate, switchgrass consumes more water than do the traditional agricultural crops. The longer switchgrass growing season and higher growth rate are responsible for the greater water use. Increased temperature and precipitation under the CSIRO climate change scenario increases ET in all crops. The increase is greater in switchgrass than in the traditional crops.

Because of greater the ET, runoff from switchgrass is less than it is under corn and wheat cultivation at the same sites. Runoff differences in the western portion of the study region are not extreme because of the low precipitation under baseline climate. The increases in precipitation that occur under the CSIRO climate result in substantially more runoff throughout the study region. Runoff from switchgrass is less affected, primarily because of the crop's greater water demand under that scenario.

Under corn, the most intensively tilled crop modeled, erosion was generally greater than under wheat or switchgrass cultivation. Soil erosion under corn management was particularly severe at a few sites in the western region because of steeply sloping topography in this region. Soil erosion was considerably less under wheat and switchgrass management. Interestingly, at a few sites in Iowa erosion was greater under switchgrass than under corn cultivation. This was due, primarily, to strong wind erosion during switchgrass establishment – a problem that can be minimized with proper soil management techniques.

Our results with regard to changes in water use, runoff and soil erosion apply to the individual sites modeled and depend on the specific soil, climate and management regime chosen. To fully address the potential implications of climate change and biomass energy crops for regional water resources will require integration of our farm level results with a regional hydrologic assessment of impacts on water quality and quantity.

Implications for adaptation to climate change

Past analyses have addressed or commented on the tradeoffs among biomass energy production, traditional energy sources and agriculture (Lowenberg-DeBoer and Cherney, 1989; Reese, et al, 1989; Vogel, 1996b), but have not considered the implications of greenhouse forced climate change on biomass production. Other analyses have examined the impact of climate change on agriculture in the U.S. Midwest using crop growth simulation models (Rosenzweig, 1989; Rosenberg, 1993; Rosenzweig, et al 1994; Brown and Rosenberg, 1997). Certain of these assessments consider farm level adaptations to climate change, but until now biomass cropping has not been among the adaptations considered. We compared the yield response of switchgrass to changes in temperature and precipitation to those of corn, soybeans, sorghum and wheat and concluded that switchgrass not only competes, in agronomic terms, with traditional crops under baseline climate, but may also hold a comparative advantage over these crops in a warmer and dryer climate. Our findings here are consistent with those of an earlier study (Brown and Rosenberg, 1996) and taken together lead us to conclude that switchgrass can very likely sustain a biomass energy industry in the MINK region. Our findings also demonstrate the possible usefulness of switchgrass, a species native to the Great Plains, as an option for agricultural adaptation to climate change. Further, it wil be easier for farmers to adopt switchgrass than some woody species for biomass production since the same farm machinery and equipment as is used for grain production in the region can be employed. Our analysis addresses only the potential production of switchgrass at the farm level. A full economic analysis of the crop's potential, which considers, production costs, transportation costs and market demand is needed before the practicality of a switchgrass agriculture for the MINK region can be assessed.

Conclusions

Our analysis points to the following conclusions:

1. Switchgrass yields are comparable, in agronomic terms, with yields of traditional annual grain crops under baseline climate of the MINK region.
2. Under a climate change scenario characterized by increases in both temperature and precipitation, switchgrass yields increase over baseline levels for the entire MINK region. Yields of the traditional agricultural crops generally decrease for the eastern and southern portions of the MINK region due to higher temperatures. Increases in precipitation in the western and central Great Plains improve yields of both switchgrass and traditional crops over baseline and may increase this region's ability to sustain dryland agriculture.
3. Increases in atmospheric CO_2 increase yields for all crops with soybean and winter wheat exhibiting the greatest response due to improvements in photosynthetic and water use efficiency. The C4 crops, corn, switchgrass and sorghum, are more responsive to increased atmospheric CO_2 in the water scarce regions because of their improved water use efficiency.
4. Switchgrass generally consumes more water than do the traditional crops under all climate conditions and also reduces runoff. Soil erosion rates under switchgrass cultivation are comparable to those under winter wheat and are generally lower than those under corn cultivation.
5. Switchgrass yields were sufficient under both baseline and the CSIRO climate change scenario to show promise as a biomass energy feedstock for the MINK region. Because switchgrass thrives in warmer temperatures, the crop may serve as an agricultural adaptation to climate change as well.

Works Cited

Abrol, Y.P. and K.T Ingram. 1996. Effects of higher day and night temperatures on growth and yields of some crop plants. In Global Climate Change and Agricultural Production. F. Bazzaz and W. Sombroek, eds. John Wiley & Sons. New York. pp 123-140.

Anderson, B. 1989. Establishing Dryland Forage Grasses. NebGuide G81-543. Cooperative Extension, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln.

Anderson, B. and C.A. Shapiro. 1990. Fertilizing grass pastures and haylands. NebGuide G78-406. Cooperative Extension, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln.

Brown, R.A. and N.J. Rosenberg. 1997. Sensitivity of crop yield and water use to change in a range of climatic factors and CO_2 concentrations: A simulation study applying EPIC to the central United States. Agricultural and Forest Meteorology 83: 171-203.

Brown, R.A. and N.J. Rosenberg. 1996. The potential for biomass energy production in the Missouri-Iowa-Nebraska-Kansas (MINK) region. In Proc. 1995 Society of American Foresters Convention Oct. 28 – Nov 1. 1995. Portland Me. pp 204-209.

Easterling, W. E., A. Weiss, C.J. Hays, L.O. Mearns. 1998. Optimum spatial scales of climate information for simulating the effects of climate change on agrosystem productivity: the case of the U.S. Great Plains. Agricultural and Forest Meteorology (in press).

Easterling, W.E., N.J. Rosenberg, M.S. McKenney, C.A. Jones, P.T. Dyke, and J.R. Williams. 1992. Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO_2. Agricultural and Forest Meteorology 59:17-34.

Fajer, E.D., M.D. Bowers, and F.A. Bazzaz. 1989. The effects of enriched carbon dioxide atmospheres on plant-insect-herbivore interactions. Science. 243: 1198-1200.

Giorgi, F., L.O. Mearns, C. Shields and L. McDaniel. 1998. Regional nested model simulations of present day and $2xCO_2$ climate over the central plains of the U.S. Climatic Change (in press).

Giorgi, F., M.R. Marinucci and G.T. Bates. 1993a. Development of a second generation regional climate model (RegCM2): boundary layer and radiative transfer processes. Monthly Weather Review. 121: 2794 – 2813.

Giorgi, F., M.R. Marinucci, G. De Canio and G.T. Bates. 1993b. Development of a second generation regional climate model (RegCM2): convective processes and assimilation of lateral boundary conditions. Monthly Weather Review. 121: 2814 – 2832.

Graham, R.L. 1994. An analysis of the potential land base for energy crops in the conterminous United States. Biomass and Bioenergy. 6: 175:189.

Graham, R.L., L.L. Wright, and A.F. Turhollow. 1992. The potential for short-rotation woody crops to reduce U.S. CO_2 emissions. Climatic Change. 22: 223-238.

Hall, D.O., H.E. Mynick and R.H. Williams. 1993. Cooling the greenhouse with bioenergy. Nature 353: 11-12.

Hall, D.O., H.E. Mynick and R.H. Williams. 1990. Carbon sequestration versus fossil fuel substitution: alternative roles for biomass in coping with greenhouse warming. PU/CEES Report No. 255. Center for Energy and Environmental Studies, Princeton University.

Idso, K.E. and S.B. Idso. 1994. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past 10 years research. Agricultural and Forest Meteorology. 69: 153-203.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 770 prior observations. Agron. J. 75:779-788.

Kimball, B.A., N.J. Rosenberg, and L.H. Allen Jr., eds. 1990. Impacts of carbon dioxide, trace gases and climate change on global agriculture. American Society of Agronomy Special Publication 53:1-133.

Kiniry, J.R., M.A. Sanderson, J.R. Williams, C.R. Tischler, M.A. Hussey, W.R. Ocumpaugh, J.C. Read, G. Van Esbroeck, and R.L. Read. 1996. Simulating Alamo switchgrass with the ALMANAC model. Agronomy Journal. 88:602-606.

Kiniry, J.R., D.A. Spanel, J.R. Williams, C.A. Jones. 1990. Demonstration and validation of crop grain yield simulation by EPIC. EPIC – Erosion Productivity Impact Calculator, Model Documentation. USDA-ARS Tech. Bull. No. 1768, pp 220-234.

Lowenberg-DeBoer J. and J.H. Cherney. 1989. Biophysical simulation for evaluating new crops: the case of switchgrass for biomass energy feedstock. Agricultural Systems. 29: 233-246.

Mearns, L.O., F. Giorgi, W. Easterling, and A. Weiss, 1996: Development of a nested regional model for the conterminous U.S. and formation of high resolution climate

change scenarios with an application to crop-climate models. In Toward an integrated regional research program on global change and the nation's major grasslands, Great Plains Regional Center for Global Env. Change, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln, U.S. Dept. of Energy, Report No. GPRC 96-01, pp 47-50.

McCarl, B. A., Chang, C., J.D. Atwood, W.I. Nayda. 1998. Documentation of ASM: The U.S. Agricultural Sector Model. Texas A & M University, Dept. of Agricultural Economics Technical Paper.

McCarl, B.A. 1982. Cropping Activities in Agricultural Sector Models: A Methodological Proposal. Amer. J. Agric. Econ. 64:768-772.

McKenney, M.S., and N.J. Rosenberg, 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. Agricultural and Forest Meteorology 64: 81-110.

McLaughlin, S.B. 1993. New switchgrass biofuels research program for the southeast. In Proc. 1992 Annual Automotive Technol. Dev. Contractors Coordinating Meeting. Nov. 2-5. 1992. Dearborn, MI. pp 111-115.

Mitchell, R., L. Moser, B. Anderson, S. Waller. 1994. Switchgrass and big bluestem for grazing and hay. NebGuide G94-1198-A. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Mooney, H.A. and G.W. Koch. 1994. The impact of rising CO2 concentrations on the terrestrial biosphere. Ambio. 23: 74-76.

Reese, R.A., S.V. Aradhyula, J.F. Shogren, K.S. Tyson. 1993. Herbaceous biomass feedstock production: the economic potential and impacts on US agriculture. Energy Policy. 21: 726-734.

Rosenberg, N.J., 1982. The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity. II. Effects through CO_2 induced climatic change. Climatic Change 4: 239-254.

Rosenberg, N.J., B.A. Kimball, Ph. Martin, and C.F. Cooper. 1990. Climate change, CO_2 enrichment and evapotranspiration. in P.E Waggoner, ed. Climate Change and US Water Resources. John Wiley and Sons, New York. pp 151-175.

Rosenberg, N.J., M.S. McKenney, W.E. Easterling, and K.M. Lemon. 1992. Validation of EPIC model simulations of crop responses to current climate and CO_2 conditions: comparisons with census, expert judgement and experimental plot data. Agricultural and Forest Meteorology 59: 35-51.

Rosenberg, N.J., ed. 1993. A methodology for assessing regional agricultural consequences of climate change: Application to the Missouri-Iowa-Nebraska-Kansas (MINK) region. Special issue of Agricultural and Forest Meteorology 59: 1-127.

Rosenzweig, C., B. Curry, J.T. Ritchie, J.W. Jones, T.-Y. Chou, R. Goldberg and A. Iglesias. 1994. The effects of potential climate change on simulated grain crops in the United States. a chapter in Rosenzweig, C. and A. Iglesias, eds. Implications of Climatic Change for International Agriculture: Crop Modeling Study. U.S. Environmental Protection Agency Report EPA 230-B-94-003.

Rosenzweig, C. 1989, 'Potential effects of climate change on agricultural production in the Great Plains: A simulation study', in Smith, J.B. and Tripak, D. (eds.), The Potential Effects of Global Climate Change on the United States, Appendix C, vol. 1. United States Environmental Protection Agency, Office of Policy, Planning, and Evaluation, Washington, D.C.

Sanderson, M.A., R.L. Reed, S.B. McLaughlin, S.D. Wullschleger, B.V. Conger, D.J. Parrish, D.D. Wolf, C. Taliaferro, A.A. Hopkins, W.R. Ocumpaugh, M.A. Hussey, J.C. Read, and C.R. Tischler. 1996. Switchgrass as a sustainable bioenergy crop. Bioresource Technology. 56:83-93.

Schneider, S.H. and N.J. Rosenberg. 1989. The greenhouse effect: its causes, possible impacts and associated uncertainties. In Greenhouse Warming: Abatement and Adaptation. N.J. Rosenberg, W.E. Easterling, P.R. Crosson, and J. Darmstadter. eds. Resources for the Future. Washington D.C. pp 7-34.

Steiner, J.L., J.R. Williams and O.R. Jones. Evaluation of EPIC using a dryland wheat-sorghum-fallow crop rotation. EPIC-Erosion Productivity Impact Calculator. 1. Model Documentation. USDA-ARS Technical Bulletin No. 1768, pp: 191-205.

Stockle, C.O., J.R. Williams, N.J. Rosenberg, and C.A. Jones. 1992a. A method for estimating direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I -- Modification of the EPIC model for climate change analysis. Agricultural Systems 38: 225-238.

Stockle, C.O., P.T. Dyke, J.R. Williams, C.A. Jones, and N.J. Rosenberg. 1992b. A method for estimating direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part II -- Sensitivity analysis at three sites in the Midwestern USA. Agricultural Systems 38: 239-256.

United States Department of Agriculture –National Agricultural Statistics Service: 1982-1994, Crops County Data Database. Washington DC.

United States Department of Agriculture – Soil Conservation Service. 1992. STATSGO – State soils geographic data base. Soil Conservation Service. Publication number 1492, Washington, DC.

United States Department of Census – Economics and Statistics Administration. 1992 Census of Agriculture, Volume 1: geographic area series, part 51: United States, summary and state data.

Vogel, K.P. 1996a. Genetic variation among switchgrasses for agronomic traits, forage quality and biomass fuel production – Annual Report for 1995. Biofuels Feedstock Development Program, Oak Ridge National Laboratory.

Vogel, K.P. 1996b. Energy production from forages (or American agriculture – back to the future). Jour. of Soil and Water Conservation. 51: 137-139.

Watterson I.G., M.R. Dix, H.B. Gordon and J.L. McGregor. 1995. The CSIRO nine-level atmospheric general circulation model and its equilibrium present and doubled CO_2 climates. Aust. Met. Mag. 44: 111-125.

Wright, L.L. 1994. Production technology status of woody and herbaceous crops. Biomass and Bioenergy. 6: 191-209.

Williams, J.R. 1995. The EPIC model. In V.P. Singh (ed.) Computer models of watershed hydrology. Water Resources Pubs. Highlands Ranch, Colorado. pp 909-1000.

Appendix : Example Representative Farms

RegCM Grid 2859 (farm 8)
State: Iowa
Crop: Corn
Cooperative Climate Station: C139132, Winterset IA
Major Soil Type: Canisteo (Aquoll, clay loam)
Soil Depth: 1.52 m
Slope Length: 100 m
Slope: 1%

Crop Budget for Corn
Crop Heat Units: 1500

Year	Month	Day	Agricultural Operation
1	5	1	Field cultivator
1	5	9	Pesticide sprayer (Lasso, 2 kg/ha)
1	5	14	Planter, row (5 pl/m^2) with fertilizer (Min. N 88 kg/ha, Min P 15 kg/ha)
1	6	15	Anhydrous ammonia application (Anhydrous NH_3 54 kg/ha N)
1	6	18	Cultipacker
1	10	29	Harvest with Grain Wagon

Crop Budget for Switchgrass
Crop Heat Units: 2300

Year	Month	Day	Agricultural Operation
1	4	1	Moldboard plow
1	4	2	Tandem disk
1	4	3	Pesticide sprayer (Amitrol, 1 kg/ha)
1	4	3	Fertilizer spreader (Min. N 40 kg/ha, Min P 20 kg/ha)
1	4	10	Planter, drill (4 pl/m^2)
2-10	5	15	Fertilizer spreader (Min. N 120 kg/ha, Min P 20 kg/ha)
2-10	8	15	Harvest with Baler

RegCM Grid 2654 (farm 5)
State: Nebraska
Crop: Sorghum
Cooperative Climate Station: C251660, Clarkson, NE
Major Soil Type: Moody (Ustoll, silty clay loam)
Soil Depth: 1.57 m
Slope Length: 72 m
Slope: 4%

Crop Budget for Sorghum
Crop Heat Units: 1500

Year	Month	Day	Agricultural Operation
1	3	30	Anhydrous ammonia application (Anhydrous NH_3 100 kg/ha N)
1	4	5	Fertilizer spreader (Min. N 25 kg/ha, Min. P 15 kg/ha)
1	4	15	Tandem disk
1	5	15	Field cultivator
1	5	24	Planter, row (6 pl/m^2)
1	5	29	Pesticide sprayer (Brom-O-S, 5 kg/ha)
1	10	20	Harvest
1	11	10	Offset disk
1	11	15	Moldboard plow

Crop Budget for Switchgrass
Crop Heat Units: 2300

Year	Month	Day	Agricultural Operation
1	4	1	Moldboard plow
1	4	2	Tandem disk
1	4	3	Pesticide sprayer (Amitrol, 1 kg/ha)
1	4	3	Fertilizer spreader (Min. N 40 kg/ha, Min P 20 kg/ha)
1	4	10	Planter, drill (4 pl/m^2)
2-10	5	15	Fertilizer spreader (Min. N 120 kg/ha, Min P 20 kg/ha)
2-10	8	15	Harvest with Baler