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Sensitivity of winter wheat yields in the Midwestern United States to future changes in climate, climate variability, and CO_2 fertilization

J. Southworth[1,*], R. A. Pfeifer[2], M. Habeck[3], J. C. Randolph[1], O. C. Doering[3], D. Gangadhar Rao[4]

[1]School of Public and Environmental Affairs, 1315 E. Tenth Street, Indiana University, Bloomington, Indiana 47405, USA
[2]3839 S. Creekside Dr., New Palestine, Indiana 46163–9105, USA
[3]Department of Agricultural Economics, Purdue University, 1145 Krannert Bldg #565, West Lafayette, Indiana 47907–1145, USA
[4]Central Research Institute for Dryland Agriculture, Hyderabad, India

ABSTRACT: This research investigates the potential impacts of climate change on winter wheat *Triticum aestiuum* L. production, looking at changes both in the mean climate and in climate variability, under conditions of elevated atmospheric CO_2 concentrations. The study region is comprised of the 5 states of Indiana, Illinois, Ohio, Michigan, and Wisconsin in the US. This analysis was conducted for the period 2050–59 for 10 representative farm locations in the 5 states for 6 future climate scenarios using the crop growth model CERES-Wheat. Wheat is currently the most widely grown crop in the world, with approximately 250 million ha planted each year. This region, while not a critical area for winter wheat production under current climate, is in a marginal area that could become a more important production region under a warmer climate. As such, the impacts of climate change on wheat growth are of great significance both regionally and globally. With future atmospheric CO_2 concentrations of 555 ppmv, wheat yields increased 60 to 100% above current yields across the central and northern areas of the study region when modeled for 2050–59 climate change scenarios. In the southern areas of the study region, small increases (0.1 to 20%) and small decreases (–0.1 to –15%) were found. These decreases in yield were more frequent under climate conditions associated with the more extreme Hadley Center greenhouse gas run (HadCM2-GHG, representing a 1% increase in greenhouse gases per year) and for the doubled climate variability analyses. Across all sites, earlier planting dates (September 2 is optimal) performed best; yields decreased as planting was delayed. These results have implications for spring-planted crops. CO_2 fertilization effects also are found to be significant for wheat, representing an average yield increase greater than 20% under future climate scenarios, with greater benefits occurring under more moderate future climate scenarios. Without the effects of CO_2 fertilization in the model, many of the southern locations had greater decreases in yields. The overall climate change impact across the study area resulted in large increases in yields with only a few locations exhibiting decreases, and those decreases occurring only under the more extreme climate scenarios.

KEY WORDS: Midwestern United States · Winter wheat · Carbon dioxide · HadCM2 model · CERES-Wheat · Climate variability

1. INTRODUCTION

Global climate change, specifically the impacts of potential climate change on many sensitive sectors (e.g. agriculture, forestry), is becoming an increasingly important issue. Within the climate change research community, general consensus has been reached recognizing the serious implications of potential changes in climate, especially the combined effects of elevated temperatures, increased atmospheric CO_2 concentrations, increased probability of extreme events (droughts, floods), and the possibility of reduced crop-water availability on the agricultural sector (Chiotti &

*Present address: University of Florida, Land Use and Environmental Change Institute (LUECI), & Department of Geography, 3141 TUR, PO Box 117315, Gainesville, Florida 32611-7315, USA. E-mail: jsouth@geog.ufl.edu

Johnston 1995, IPCC 1995). Climate influences crop growth and yields directly through impacts on phenology, photosynthesis, and other physiological processes. Indirect effects relate to nutrient availability, weeds, pests and diseases, and ability of farmers to work in the field (field days). These effects will be modified by moisture availability and temperature ranges (Olesen et al. 2000).

With respect to agriculture, changes in solar radiation, temperature, and precipitation will produce changes in crop yields, crop mix, cropping systems, scheduling of field operations, pest conditions, and grain moisture content at harvest. Climate change will also have effects on the economics of agriculture, including changes in process, farm profitability, trade, and regional or national comparative advantage. The impacts of climate change will depend on both the magnitude of the change in climate and how well agriculture can adapt to these changes (Rosenzweig 1993, Kaiser et al. 1995, Rosenzweig & Hillel 1998). Hence, global climate change, which will alter temperature and precipitation patterns, will have a major impact on crop growth and production systems in many locations.

Climate change, which results in increased temperatures, will vary spatially in its impacts on crop growth. Cereal crops, such as winter wheat *Triticum aestiuum* L., respond to warmer temperatures, in general, with a reduction of the crop and grain growth duration and, hence, lower yields in locations where winter wheat is currently at an optimum with the climate (Saarikko & Carter 1996). In areas where current growth of wheat is limited in some way (e.g. by temperatures or moisture availability), then climate change may provide an ideal opportunity for increased growth and higher yields. In contrast to the direct impact of higher temperatures, an increase in atmospheric concentration of CO_2 increases yields of wheat, by increasing photosynthetic rates and decreasing transpiration. In addition, the effect of CO_2 fertilization is higher at increased temperatures (Wheeler et al. 1996).

While most studies of climate change impacts on agriculture have analyzed effects of mean changes of climatic variables on crop production, impacts of changes in climate variability have been studied much less (Mearns 1995, Mearns et al. 1997). Yet the consequences of changes in variability may be as important as those that arise due to variations in mean climatic variables (Mearns et al. 1984, Rind 1991, Liang et al. 1995, Gangadhar et al. 1996, Semenov & Barrow 1997, Carnell & Senior 1998, Hulme et al. 1999). Additional examination of climate variability, and its potential changes under future climates, is therefore essential to evaluate, specifically for its possible impacts on agriculture (Rind 1991, Barrow et al. 1996, Semenov et al. 1996, Semenov & Barrow 1997).

Wheat is currently the most widely grown crop in the world, with approximately 250 million ha planted each year. In addition, wheat exceeds all other grains combined as a world trade commodity (Wittwer 1995). Winter wheat is a highly adaptable fall-sown, long-duration crop extensively grown throughout the United States and Europe. Within the US the key wheat production areas are found in Kansas and Oklahoma. Wheat is moderately frost and drought resistant and is grown under temperature ranges from –40 to +40°C. Winter wheat is planted in the fall, germinates, and can survive snow cover and temperatures to at least –30°C. The following spring the seedlings grow and mature rapidly, prior to summer heat (Wittwer 1995). While this study region is on the margins of current wheat production areas in the US, this is a prime location for expansion under future climate change, should those changes in climate result in an improved wheat growth compared to the currently dominant corn and soybean crops.

Currently this study region produces about 1% of the world's winter wheat (with the US comprising 12%) (USDA NASS 2000). Under conditions of changing climate, e.g. a longer growing season, it may become more important for winter wheat production. Winter wheat is important in crop rotations in portions of the 5-state study region. Previous research has found decreased maize yields within the southern reaches of the study region under many of the climate scenarios considered (Southworth et al. 2000), while soybean yields generally increased for the same areas (Southworth et al. 2000, 2002). This may allow the soybean/wheat double cropping system to be used more extensively in this region.

Another factor within the climate change debate is the fertilizing effect of increased atmospheric concentrations of CO_2. This effect was reported over 100 yr ago and may have been observed much earlier. In 1888 the benefits of elevated CO_2 for increasing growth in greenhouse crop cultivation were recognized and reported in Germany. Similar studies were conducted throughout western and northern Europe, and all reported significant increases in plant growth and productivity (Wittwer 1995). Different types of plants (usually referred to as C_3 and C_4 according to their dominant photosynthetic pathway) exhibit different responses to CO_2 fertilization, with C_3 plants, such as wheat, benefiting more than C_4 plants from increased atmospheric concentrations of CO_2. Wheat is widely recognized as one of the most responsive to CO_2 fertilization of all cereal crops as a result of enhanced photosynthesis and improved water use efficiency. Much of the positive effect of CO_2 fertilization on wheat yields is due to the improved resistance to drought conditions (Wittwer 1995).

This study addresses the impacts of possible future climates on current agricultural practices across the midwestern United States. Specifically: (1) the impacts of mean climate change on wheat yields in the midwestern United States; (2) the impacts of changing climate variability and changes in the mean climate on wheat yields; (3) the impact of CO_2 fertilization and changing future climate on wheat yields; (4) the spatial variability of yield changes and implications of such changes on midwestern agriculture; and (5) the possible adaptation strategies for farmers in the Midwest to these potential changes.

2. METHODOLOGY

2.1. Study region

The midwestern Great Lakes region (Indiana, Illinois, Ohio, Michigan, and Wisconsin) was divided into 10 areas based on climate, soils, land use, and current agricultural practices. Representative farms were created in each area based upon local characteristics and farm endowments (Fig. 1). For the climate change analysis 7 climate scenarios were created, 1 current climate, 2 future climates, and 4 variability analyses as part of a sensitivity study. Wheat growth was modeled for these 7 climate scenarios across the 10 locations for the wheat variety Arthur. Each model run also modeled 9 potential planting dates, in order to allow us to address the issue of shifts in planting schedules as a potential farm-level adaptation to climate change. These data were then used to determine potential future changes in wheat growth across our study area and to identify areas of likely change.

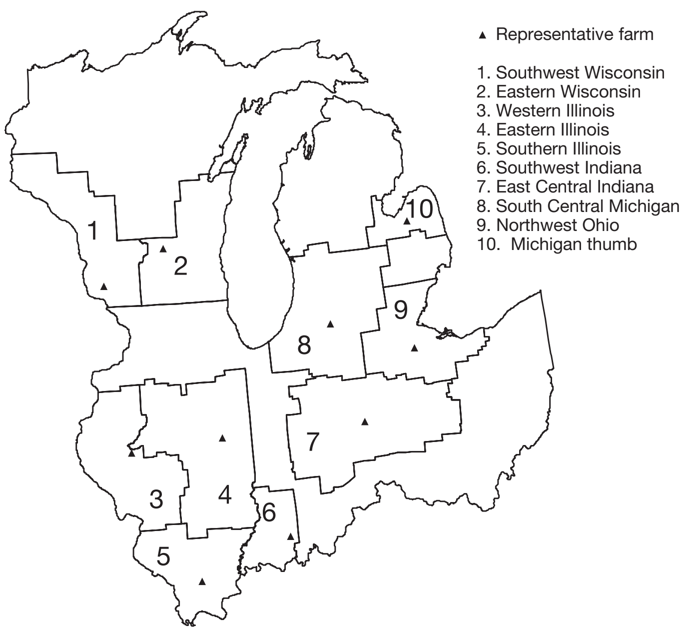

Fig. 1. Representative farm locations within the Midwestern study region

2.2. Wheat crop model (CERES-Wheat)

The Decision Support System for Agrotechnology Transfer (DSSAT) software is a suite of crop models that share a common input-output data format. The DSSAT itself is a shell that allows the user to organize and manipulate data and to run crop models in various ways and analyze their outputs (Hoogenboom et al. 1995, Thornton et al. 1997). DSSAT version 3.5 was used in this analysis. Such use of crop simulation models in climate change assessments has occasionally been criticized due to the poor results obtained from inadequate validation (Olesen et al. 2000), so this research independently validated the model across the study region.

We selected the CERES-Wheat model for this research because: (1) the model simulates crop response to major climate variables, includes the effects of soil characteristics on water availability, and is physiologically based; (2) the model has a plant growth dependence on both mean daily temperatures and diurnal temperature range (not just a daily mean temperature growth dependence); (3) the daily time step of the model allows analysis from different planting dates to meet adaptations and farm management requirements; (4) the model can simulate CO_2 fertilization adequately; (5) the model is developed with compatible data structures so that the same soil and climate datasets can be used for all varieties of crops which helps in comparison (Adams et al. 1990); and (6) comprehensive validation has been done across a wide range of different climate and soil conditions, and for different crop hybrids (Hoogenboom et al. 1995, Semenov et al. 1996, Wolf et al. 1996).

Crop growth using the DSSAT CERES-Wheat model was simulated, with a daily time step during the period from sowing to maturity, based on physiological processes that describe the crop's response to soil and other physical environmental conditions. Phasic development is quantified according to the plant's physiological age. The input data required to run the model include daily weather information (maximum and minimum temperatures, rainfall, and solar radiation); soil characterization data (data by soil layer for extractable phosphorus and nitrogen and soil water content); a set of genetic coefficients characterizing the wheat variety being grown; and crop management information, such as emerged plant population, row spacing, seeding depth, and fertilizer and irrigation schedules (Thornton et al. 1997). The soil data were obtained from the US Soil Conservation Service (SCS; now known as the Natural Resources Conservation Service) and were selected to represent the dominant local soils of each of the 10 representative areas. The model apportions the rain received on any day into runoff and infiltration into the soil, using the runoff curve number technique. We assigned a runoff curve number to each soil, based on the soil type, depth and texture as obtained from the STATSGO databases. We chose not to make nitrogen and phosphorus limiting to crop growth, so these modules were turned off within our model runs.

The CERES-Wheat model includes the capability to simulate the direct physiological effects of increased atmospheric CO_2 concentrations on plant photosynthesis and water use, based on experimental results. Higher levels of atmospheric CO_2 concentrations have been found to increase photosynthesis and stomatal resistance, resulting in increases in yield and water use efficiency. Because climate change scenarios are associated with concomitant higher levels of atmospheric CO_2 concentrations and other trace gases, we included these physiological effects of CO_2 concentrations within the crop simulations. The atmospheric CO_2 concentration for the future climate scenarios used in this research, based on the years 2050–59, is 555 ppmv. The photosynthetic enhancement of 555 ppmv CO_2 results in a photosynthesis multiplier of 1.15 and a transpiration ratio of 0.96 for wheat (Siqueira et al. 1994, Hoogenboom et al. 1995).

2.3. Crop model validation

CERES-Wheat model has been extensively validated by others (Otter & Ritchie 1985, Ritchie & Otter 1985, Godwin et al. 1989, Ritchie 1991). Wheat modeling efforts were initiated in 1977, when the United States Department of Agriculture—Agricultural Research Service (USDA-ARS) was asked to improve the US Government capability to predict domestic and foreign wheat yields. Earlier models were mostly empirical and statistical using monthly weather data. The CERES-Wheat model was 1 of 3 models initially developed by USDA-ARS (Willis 1985). In the present study experiments conducted by University of Wisconsin were used for model validation. Dahlke et al. (1993) conducted a planting-date experiment at the University of Wisconsin, Arlington, research station for 4 yr during the 1988–91 growing seasons. We selected this experiment for wheat model validation as it dealt with planting dates over a 4 yr period in our study region. Soil data were obtained from Arlington Research Station, and the nearest NOAA climate station was used for the weather data. The management information was taken from Dahlke et al. (1993), but the information on genotypes differed as they used the genotypes Merrimac and Cardinal in their study and information of their genetic coefficients was unavailable. For our modeling we used a similar cultivar which was representative of this study region. The long-season winter wheat DSSAT cultivar (genotype 990003in DSSAT 3.5 was used to represent wheat variety Arthur) was used for our simulations for the entire study region and for the model validation. (The main genetic coefficients are P1V = 6.0, P1D = 0.5, P5 = –5.0, G1 = 5.0, G2 = 1.2, G3 = 1.4, and PHINT = 80.0.) Within the DSSAT model runs soil water was re-initialized at the beginning of each crop cycle. Simulation results were compared with observed yields.

Observed and simulated results for yields versus planting dates were analyzed (Fig. 2a), but due to the differences in cultivar and weather data these results were averaged for the validation analysis and are presented as means for the planting date response to wheat (Fig. 2b). An R^2 of 0.75 indicates that the yield trends and patterns are represented well by the model. Growing conditions during the 4 yr period represented a range that growers in the Midwest typically encounter when growing a soft red winter wheat. Differences in the growing season resulted in significant variation in the performance of the wheat model. The model predicted slightly higher yields for late-sown wheat (starting from day of the year 276) compared to observed responses (Fig. 2b). Simulated and observed maturity dates matched well even as planting dates varied (Fig. 2c), especially given the differences in cultivar used in modeling.

The model was also validated at each representative farm location using historical yield and climate data from that area to ensure the model could replicate past yields of wheat. This provided assurance that the changes in yield under the new climate scenarios resulted from climate change as all other variables were held constant (Siqueira et al. 1994). In addition, experienced agronomists in each location were contacted and asked for their expert opinion of the impact of planting date on yield. The simulations from current climate (both VEMAP and NOAA data were used in the comparison) agreed well with the agronomists' predictions (Fig. 3).

2.4. Current climate analysis (VEMAP)

The VEMAP dataset includes daily, monthly, and annual climate data for the continental US including maximum, minimum, and mean temperature, precipitation, solar radiation, and humidity (Kittel et al. 1996).

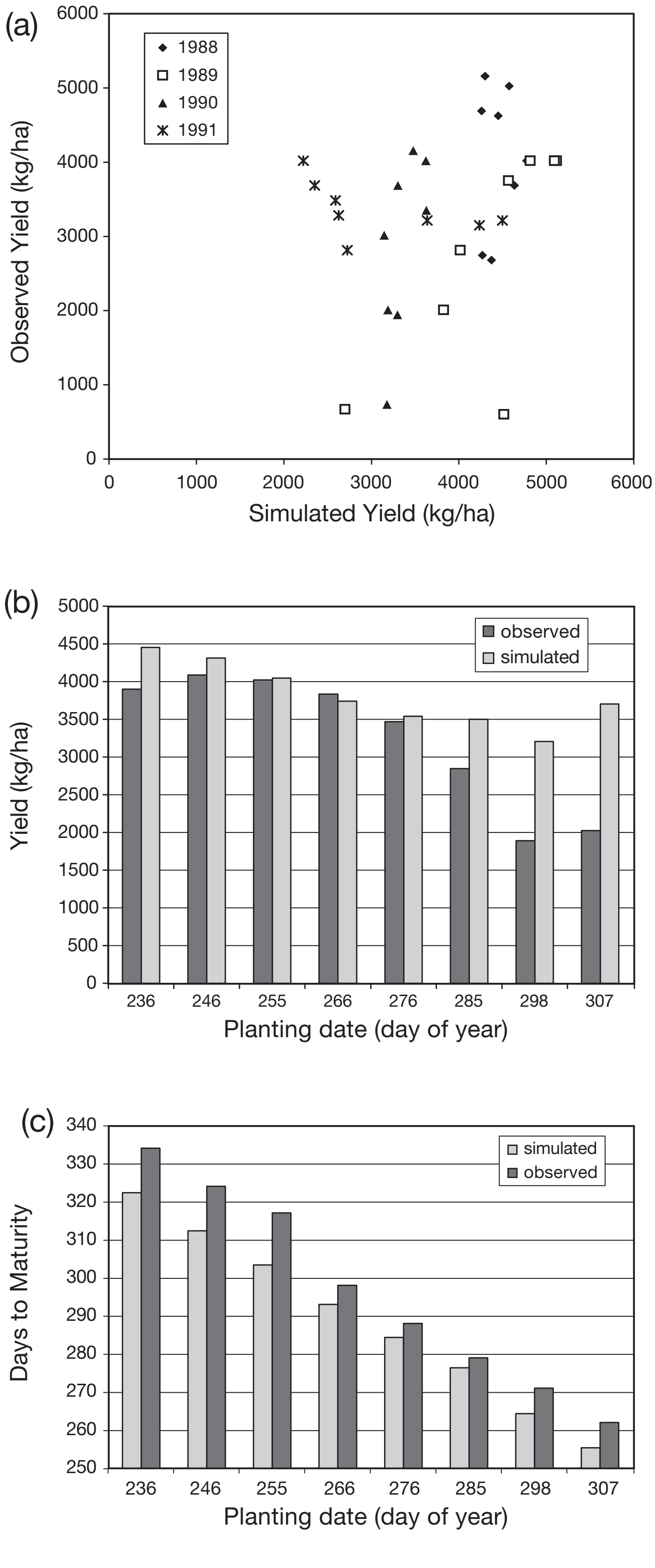

Fig. 2. Model validation of observed vs predicted values for Arlington, WI, experimental farm data for (a) individual planting dates vs yield values across 4 yr of analysis, (b) 4 yr averages of yield vs planting dates, and (c) 4 yr averages of days to maturity vs planting dates

The VEMAP baseline (30 yr historical mean) climate data was used for each of 10 representative agricultural areas in our study region (Fig. 1). VEMAP data was used in this analysis, as many of the representative farm locations did not have a NOAA weather station nearby and VEMAP allowed us to use standardized and corrected climate data. In addition we did not want to model a specific year for current climate data, but rather we wished to model a typical current climate versus future climate scenarios. This enabled us to avoid comparing current climate data under years of extreme moisture stress or late-season frosts, but rather we represented mean current climate and mean current crop yields. This VEMAP data was compared to the NOAA data in locations where it was available, and the data were very similar and resulted in similar yields (Fig. 3).

The weather generator SIMMETEO (as used in DSSAT version 3.5) used these climate data to stochastically generate daily weather data in model runs. The use of monthly data to generate daily data was the only option available for the future climate scenarios, due to the HadCM2 data only being available at a monthly time step, and to enable comparison the monthly data were also used for the current climate from which the daily data was generated. Hence, the datasets for the current and future climates were created in similar ways, and as such differences in resultant crop yields should not be due to differences in data-generation techniques, but rather due to differences in climate.

2.5. Future climate scenarios

Future climate experiments performed at the Hadley Center in England used the Unified Model. The Unified Model was modified slightly to produce a new, coupled ocean-atmosphere GCM, referred to as

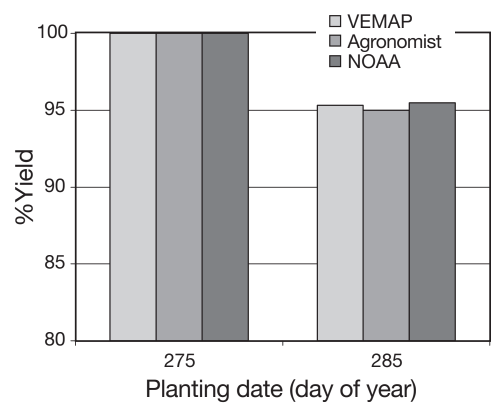

Fig. 3. Expert agronomists' prediction vs model values for yields vs planting dates for winter wheat in eastern Illinois

HadCM2, which has been used in a series of transient climate change experiments using historic and future greenhouse gas and sulfate aerosol forcing. Transient model experiments are considered more physically realistic and complex, and they allow atmospheric concentrations of CO_2 to rise gradually over time (Harrison & Butterfield 1996).

HadCM2 has a spatial resolution of 2.5° × 3.75° (latitude by longitude), and the representation produces a grid box resolution of 96 × 73 grid cells, which produces a surface spatial resolution of about 417 × 278 km, reducing to 295 × 278 km at 45° north and south. The atmospheric component of HadCM2 has 19 levels, and the ocean component 20 levels. The equilibrium sensitivity of HadCM2, that is, the global-mean temperature response to a doubling of effective CO_2 concentration, is 2.5°C, somewhat lower than most other GCMs (IPCC 1995).

Two future climate model runs were used in this research. The greenhouse-gas-only version, HadCM2-GHG, used the combined forcing of all greenhouse gases as an equivalent CO_2 concentration. HadCM2-SUL used the combined equivalent CO_2 concentration plus a negative forcing from sulfate aerosols. The addition of the negative forcing effects of sulfate aerosols represents the direct radiative forcing due to anthropogenic sulfate aerosols by means of an increase in clear-sky surface albedo proportional to the local sulfate loading (Carnell & Senior 1998). The indirect effects of aerosols were not simulated. Our research used the period 2050–59 for climate scenarios. The results from HadCM2-GHG and HadCM2-SUL represent 2 possible realizations of how the climate system may respond to a given forcing (i.e. they are not predictions or forecasts).

The weather generator SIMMETEO used these future climate data to stochastically generate daily weather data in model runs. The climate variables' distribution patterns mimic the current climate variables' distributions. Sensitivity analysis determined the effects of climatic condition upon yield over a series of potential planting dates. A comparison of the main 3 climate datasets (Table 1) highlights the differences in projected mean climate data for the study region.

2.6. Climate variability analysis

A climate variability analysis was also conducted on these 2 scenarios, thus increasing the number of future climate scenarios to 6. To separate crop response to changes in climatic means from crop response to changes in climate variability, it is necessary first to model the impacts of mean temperature changes on crop growth. The approach of using monthly data to generate daily data allowed us to generate variability scenarios. Thus a time series of climate variables with changed variability can be constructed and added to the mean change scenarios. Hence, when the analysis is undertaken on future mean and variability changes, it is therefore possible to infer what type of climate change caused changes in yield (Mearns 1995). In addition, such sensitivity analyses allows for greater interpretation of crop responses to climate change.

Table 1. Comparison of HadCM2-GHG and HadCM2-SUL climate scenario mean monthly maximum and minimum temperature and precipitation values, compared to VEMAP current mean monthly climatic conditions, for March. VEMAP: VEMAP dataset for current climate data. HadCM2-GHG: Hadley Center data for 2050–59 from the greenhouse-gas-only run. HadCM2-SUL: Hadley Center data for 2050–59 from the greenhouse gas and sulfate run. S-IL: southern Illinois; SW-IN: southwest Indiana; W-IL: western Illinois; E-IL: eastern Illinois; EC-IN: east-central Indiana; NW-OH: northwest Ohio; SC-MI: south-central Michigan; SW-WI: southwest Wisconsin; E-WI: eastern Wisconsin; and Th-MI: the 'thumb' area of Michigan

Site	VEMAP			HadCM2-GHG			HadCM2-SUL		
	Max. temp. (°C)	Min. temp. (°C)	Total monthly precip. (mm)	Δ in max. temp. (°C)	Δ in min. temp. (°C)	Δ in total monthly precip. (mm)	Δ in max. temp. (°C)	Δ in min. temp. (°C)	Δ in total monthly precip. (mm)
S-IL	13.9	1.5	118	−0.29	+3.46	−23.77	−1.47	+2.32	−27.80
SW-IN	13.3	1.5	113	−0.58	+3.05	+2.15	−1.70	+2.10	−3.12
W-IL	10.9	−1.2	71	+2.71	+6.16	+23.23	+1.53	+5.02	+19.20
E-IL	12.6	−1.6	76	+1.01	+5.96	+18.23	−0.17	+4.82	+14.20
EC-IN	13.8	−2.1	81	−1.08	+6.65	+30.13	−2.20	+5.70	+28.88
NW-OH	11.1	−2.9	68	+0.95	+6.90	+32.22	+0.07	+5.88	+26.36
SC-MI	9.3	−2.8	60	+1.79	+6.09	+22.54	+0.31	+4.96	+31.43
SW-WI	9.4	−3.7	49	+2.21	+6.40	+27.37	+0.57	+5.02	+28.71
E-WI	9.0	−4.5	51	+2.61	+7.20	+25.37	+0.97	+5.82	+26.71
Th-MI	8.4	−4.3	47	+2.96	+7.59	+35.54	+1.21	+6.46	+44.43

The variance of maximum and minimum temperature and precipitation values for each month were altered separately, according to the following algorithm from Mearns (1995):

$$X'_t = \mu + \delta^{1/2}(X_t - \mu) \quad (1)$$

and

$$\delta = \sigma'^2/\sigma^2 \quad (2)$$

where X'_t = new value of climate variable X_t (e.g. monthly mean maximum February temperature for year t); μ = mean of the time series (e.g. the mean of the monthly mean maximum February temperatures for a series of years); δ = ratio of the new to the old variance of the new and old time series; X_t = old value of climate variable (e.g. the original monthly mean February temperature for year t); σ'^2 = new variance; and σ^2 = old variance.

To change the time series to have a new variance σ'^2, the variance and mean of the original time series was calculated and then a new ratio (δ) was chosen (e.g. halving the variance). From the parameters μ, δ, and the original time series, a new time series with variance was calculated using Eq. (1). This algorithm was used to change both maximum and minimum temperatures and the precipitation time series. This simple method, developed by Mearns (1995), was used even though more complex methodologies are being developed to allow comparisons of variability techniques. Mearns et al. (1996, 1997) found the results obtained from more computationally advanced statistical techniques were similar to results from more statistically simple methodologies. The approach we used permits the incorporation of changes in both mean and variability of future climate in a computationally simple, consistent, and reproducible manner. Consequently, we have examined a range of probable climate changes and a range of their impacts on wheat growth.

2.7. Model limitations

The CERES-Wheat model, as with all models, contains a number of assumptions. Our simulation results do not take into account possible changes in plant diseases, pest damage or weed competition (Hoogenboom et al. 1995), which will undoubtedly occur under conditions of climate change. Competitive crop-weed interactions could change, particularly if the crop and weed have different photosynthetic pathways (C_3 vs C_4), which may be differentially affected by elevated CO_2 or climate changes. We did not consider potential changes in nutrients, such as an increase in C:N ratio, which has been observed in some plants grown in elevated CO_2 concentrations (Phillips et al. 1996). In addition, the model does not simulate extreme soil conditions such as salinity, acidity, compaction or extreme weather events such as floods, tornadoes, hail, droughts and hurricanes (Hoogenboom et al. 1995).

Other limitations relate to the simplified reality of our representative farms and the use of a single dominant soil type at each location. The climatic tolerance of the cultivar was assumed to be unchanged from the base runs through the simulation. As with other climate change studies, in the present simulation study we are using the currently available wheat genotypes for the study beginning from 2050. However, contemporary experience is that during a period of 50 yr, new genotypes with varied response to climatic factors will become available. We are not modeling this aspect. Additionally, this study assumes cultivars with resistance to Hessian fly will be used in the future scenarios. This would preclude the need to delay planting until the 'fly-free date'.

A limitation of using GCMs is that, although they may accurately represent current global climate and so we can assume a good representation of future climate, their estimates of current, and hence we can also assume future, regional climate are often inaccurate. Such regional scaling problems often relate to areas with significant topography or large water bodies, which may not be well represented in the model. In addition, the spatial scale of GCMs may be too large, in that they may also not represent the range of potential climate change across a region. GCMs can be used with regional downscaling models to create more regionally appropriate climates, which better address differences due to regional topography and water bodies. However, this study region is a fairly flat and quite homogeneous land area, and so it was considered that the selected GCM, which models current climate accurately, would also represent future climates well. Currently, downscaling methods are still being evaluated, and no single method is yet being put forward as the most appropriate for climate change studies; as this is so, the current methodology was deemed appropriate for this region.

Finally, the experimental conditions used to examine increased CO_2 effects on photosynthesis may overestimate yields (Rosenzweig et al. 1994). While the assumptions discussed may tend to either overestimate or underestimate simulated yields, our validation and analysis at the farm level attempts to ensure validity in spite of model limitations.

3. RESULTS AND DISCUSSION

3.1. Changes in wheat yields

Currently, winter wheat yields are greatest across the southern states in the study region and decrease in

Table 2. Mean decadal winter wheat yields (kg ha^{-1} with standard deviations in parentheses) vs planting dates for all 7 climate scenarios for (a) southern Illinois and (b) eastern Wisconsin. Shaded cells indicate a decrease in yields compared to current (VEMAP) yields. $^1/_2$/2× var.: halved and doubled variability, respectively

	VEMAP	HadCM2-SUL	HadCM2-GHG	HadCM2 $^1/_2$ var. SUL	HadCM2 2× var. SUL	HadCM2 $^1/_2$ var. GHG	HadCM2 2× var. GHG
(a) Southern Illinois							
Sep 2	5922 (1155)	6232 (1639)	5929 (632)	6584 (355)	6236 (567)	5740 (367)	5313 (448)
Sep 12	5361 (934)	5773 (1209)	5668 (793)	6188 (506)	5664 (703)	5464 (404)	4913 (671)
Sep 22	4624 (849)	5034 (984)	5091 (929)	5627 (551)	4915 (705)	4993 (477)	4439 (747)
Oct 2	3871 (769)	4415 (942)	4399 (890)	5090 (629)	4097 (770)	4369 (457)	3861 (819)
Oct 12	3350 (699)	3565 (1144)	3619 (940)	4615 (1003)	3475 (963)	3888 (628)	3220 (1020)
Oct 22	2635 (731)	3192 (1225)	3102 (1056)	4303 (990)	2958 (839)	3559 (746)	2557 (1119)
Nov 1	2275 (506)	2610 (1254)	2376 (1014)	3879 (1084)	2726 (1029)	3095 (699)	1934 (1030)
Nov 11	1980 (657)	2488 (1253)	2089 (684)	3563 (934)	2643 (1009)	2743 (801)	1603 (1017)
Nov 21	2226 (897)	2709 (1301)	1817 (558)	3396 (840)	2780 (931)	2617 (568)	1758 (959)
(b) Eastern Wisconsin							
Sep 2	4766 (647)	5663 (633)	5630 (599)	5858 (428)	5350 (1016)	5416 (529)	5047 (892)
Sep 12	4139 (483)	4993 (722)	5129 (815)	5267 (480)	4679 (1002)	4910 (591)	4571 (837)
Sep 22	3346 (502)	4089 (905)	4372 (1062)	4571 (491)	4041 (1049)	4332 (505)	3993 (909)
Oct 2	2762 (655)	3357 (949)	3527 (1210)	4102 (504)	3291 (1172)	3879 (421)	3238 (1177)
Oct 12	2058 (538)	2677 (1182)	2714 (1609)	3656 (709)	29.5 (988)	3432 (828)	2796 (1494)
Oct 22	1543 (412)	2522 (1220)	1996 (1329)	2940 (739)	2276 (1187)	2775 (838)	1983 (1589)
Nov 1	1648 (876)	2524 (1154)	1708 (799)	2849 (845)	2317 (1210)	2369 (903)	1706 (1524)
Nov 11	1880 (925)	3129 (824)	1712 (659)	2898 (810)	2260 (1256)	2171 (948)	1355 (1314)
Nov 21	2520 (618)	3082 (860)	2380 (913)	3590 (169)	2793 (597)	2718 (789)	2113 (1045)

the northern states (Table 2). Under conditions of climate change, across all planting dates, the halved-variability HadCM2-SUL climate scenario generally produced the highest yields (Table 2). The decreased climate variability and this less-extreme climate scenario resulted in the greatest yield increases under potential future climate change.

3.2. Future changes in wheat yields compared to current yield values

Fig. 4 shows values for projected mean maximum decadal yields compared to current mean maximum decadal yields. The mean maximum decadal yield averages are given regardless of planting date, i.e. the highest mean maximum decadal yield was used, and so the results potentially represent any of the 9 planting dates used. However the earliest planting date always did the best. The patterns illustrated by this analysis reveal that the central and northern areas had much greater yield increases compared to current values. Even though southern areas in the study region had the highest absolute yields, the northern areas had double the yields compared to current values.

The major changes in yield can be correlated with the climate change, although complexities abound. In the southern regions climate scenarios that increase winter temperatures may decrease the period of vernalization and reduce yields. Moisture stress was not a significant factor under any of the scenarios. Maturity dates under the changed climate do not significantly change.

Southern Illinois showed yield decreases under the most extreme future climate scenario, when compared to current yields (Fig. 4). Yield decreases of –0.1 to –5% occur under the doubled-variability HadCM2-GHG scenarios. However, under the remaining climate scenarios yields increase from 0.1 to 80%, with the greatest yield increases occurring under the halved-variability HadCM2-SUL model runs.

Southwestern Indiana has the greatest yield decreases of –0.1 to –15% for all runs except the halved variability scenarios, where yields increased 0.1 to 20% (Fig. 4). The greatest yield decreases were for the doubled-variability HadCM2-GHG scenario.

In the central and northern reaches of the study region, the warmer temperatures, particularly warmer minimum temperatures, under the HadCM2-SUL and HadCM2-GHG scenarios encourage vegetative growth. The duration of the growth stage from emergence to the terminal spikelet did not significantly change. This larger plant yielded an increased number of grains, resulting in higher overall yields. The maturity date of the crop in the northern region was approximately 10 d earlier under the future climate scenarios. Increasing the variability of the climate causes average yields to drop. The extremes in temperature are likely responsi-

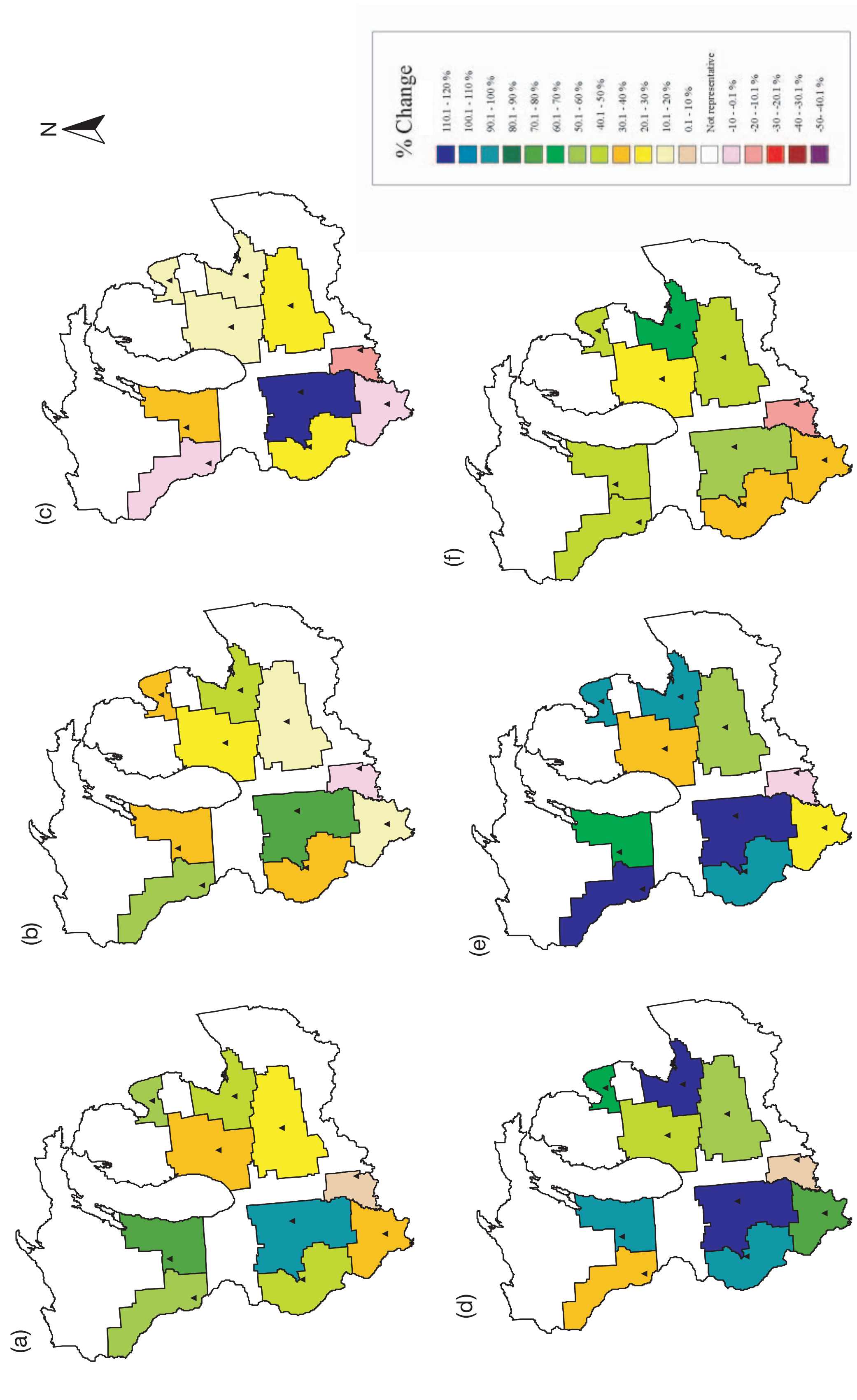

Fig. 4. Percent change in mean maximum decadal yield for winter wheat, compared to VEMAP yields, for (a) halved variability HadCM2-GHG, (b) HadCM2-GHG, (c) doubled variability HadCM2-GHG, (d) halved variability HadCM2-SUL, (e) HadCM2-SUL, and (f) doubled variability HadCM2-SUL

ble for this decrease, as periods of higher temperatures will force the plant through the stages of development more quickly, thus limiting potential yield.

Southwestern Wisconsin is the only northern location with yield decreases under the most extreme future climate scenario, when compared to current yields (Fig. 4). Yield decreases of –0.1 to –5% occur under the doubled-variability HadCM2-GHG scenarios. However, under the remaining climate scenarios, yields increase from 0.1 to 80%, with the greatest yield increases occurring under the halved-variability HadCM2-SUL model runs.

Western Illinois and eastern Wisconsin have increasing yields across all scenarios, of +20 to +100%, with the greatest yield increases under HadCM2-SUL and the halved-variability HadCM2-SUL model scenarios (Fig. 4).

Eastern Illinois has yield increases from +40 to +120% over current values, with the greatest increases under the doubled-variability HadCM2-GHG scenario. This is the only location for which the doubled-variability HadCM2-GHG scenario produces the highest yield increases.

East-central Indiana and south-central Michigan have yields increasing from 0.1 to +60% when compared to current yields (Fig. 4). Yield increases are greatest for the HadCM2-SUL model scenarios.

Northwest Ohio and the Michigan thumb wheat yields increase from 0.1 to +20% under doubled-variability HadCM2-GHG scenarios and increases over +80% under the halved-variability HadCM2-SUL climate scenario (Fig. 4). The increases for northwest Ohio are the largest of all those modeled.

Overall patterns show an increase in the yields of winter wheat compared to current values across most central and northern areas in the study region. In southern areas there are small yield decreases under the HadCM2-GHG and doubled-variability climate scenarios. The greatest yield increases occur under the halved-variability HadCM2-SUL runs, which represent a less-extreme climate scenario with CO_2 fertilization.

3.3. Implications of climate variability on future yields

It is important to model climate variability in analyses of climate change impacts. In general, we found the greatest increases in yields were associated with the halved-variability runs and the greatest decreases in yield were associated with the doubled-variability runs (Table 2, Fig. 5). Under climate scenarios with increased variability, temperatures spike above those conducive to wheat growth, especially during the period of grain fill, reducing yields. Conversely, the

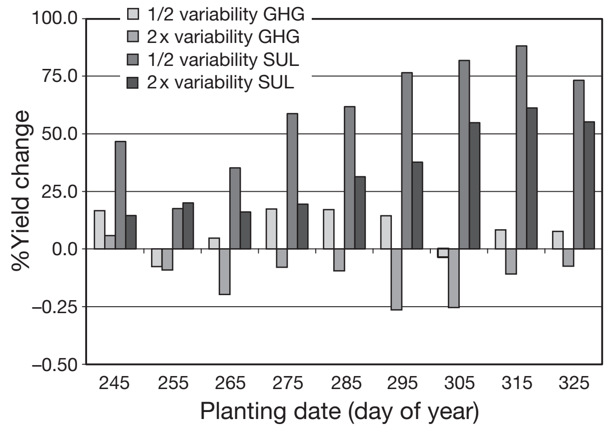

Fig. 5. Analysis of the impact of climate variability in the changed climate scenarios, for northwest Ohio, for winter wheat. Mean decadal yield per variability scenario minus the mean VEMAP yield, for each planting date

reduced-variability scenarios provide, by definition, a more steady state, and when the mean conditions are near those optimal for plant growth, reducing the variability around those means will aid in growth. These results emphasize the need to include some form of sensitivity analysis of climate variability within climate change studies. Sensitivity analyses within model runs also helps in defining critical temperature or precipitation thresholds within the climate data and enhances understanding of the crop outputs in terms of explicit climate conditions.

Semenov et al. (1996) incorporated a climate variability analysis into their modeling of climate change impacts on agriculture in Spain. Initial climate change runs with unchanged variability showed changes in wheat yield to be positive and in some locations large. However, when increased climate variability was incorporated there was a decrease in mean yield and the year-to-year yield variability increased dramatically. This change was related mainly to differences in the precipitation distribution. These results highlight the importance of including both changes in climate variability and mean climate in climate change studies. Similar results were also found by these researchers for Rothamsted, England (Semenov et al. 1996).

Wolf et al. (1996) found that an increase in temperature, with no other variables altered, generally resulted in decreased wheat yields across the UK and Spain. When precipitation and atmospheric CO_2 concentration were increased, higher wheat yields were predicted. Increasing the variability of the climate parameters usually resulted in decreased yields and, not surprisingly, much greater variability in yields.

3.4. Changes in future planting dates

Under all climate scenarios and across all locations, the most optimal planting date for winter wheat is September 2. Yields decrease beyond this planting date, although any date until October 2 results in relatively high winter wheat yields (Table 2). Southworth et al. (2000, 2002) and Jones et al. (1999) found the more favorable planting dates for both maize and soybeans shift to later dates under climate change. Thus, in future climates conflicts may arise between spring planted crops and fall planted crops. Shifts in spring planting dates to later in the season may also shift harvest dates of these crops to later in the season. Therefore planting dates for winter wheat would also shift later and yields would be much lower. Such shifts in planting dates would require adaptations in management strategies.

3.5. Impacts of CO_2 fertilization on wheat yields

Current research on the interactions of climate change and CO_2 fertilization, due to increased atmospheric CO_2 concentrations, is still underway. We found that CO_2 fertilization accounts for a significant proportion of the increased yields and prevents greater decreases in yield in southern areas. CO_2 fertilization for modeled CO_2 concentrations of 555 ppmv caused approximately 20% increases in yield. The primary reason is that the increased atmospheric CO_2 will reduce photorespiratory loss of carbon in the C_3 plant, enhancing plant growth and productivity (Allen et al. 1987). Many southern areas would have yield decreases had CO_2 fertilization not been included in the model. Our results clearly highlight how essential it is to use both future climate scenarios and increased CO_2 concentrations in crop modeling studies. Without the inclusion of CO_2 fertilization effects, more extreme crop losses may be predicted and incorrect adaptation or policy measures implemented.

Brown & Rosenberg (1999) also found winter wheat yields across the US increased with increasing atmospheric CO_2 concentrations under all climate change scenarios modeled (1, 2.5, and 5°C temperature increases). They reported that climate change alone reduced yields (compared to current values), and increasing CO_2 concentrations acts to restore yields to current levels and then to increase yields above current levels as CO_2 concentrations increase to 750 ppm. CO_2 fertilization was the most dramatic in semi-arid and arid regions, where water stress was high. Unfortunately, none of Brown & Rosenberg's sites for modeling winter wheat yields fell within our 5-state study region; thus, direct comparison of results was not possible.

European studies report similar findings. Results from Cuculeanu et al. (1999) wheat simulation modeling, using CERES-Wheat, run under conditions of future climate change in southern Romania, indicated that winter wheat yields increased in response to both increased temperatures and doubled CO_2 concentrations. Although maturity dates occurred earlier and the growing season became shorter, yields increased 15 to 21% across 5 sites. The negative effects of the shorter growing season, resulting from increased temperatures was counter balanced by increasing levels of atmospheric CO_2. Harrison & Butterfield (1996) also found increased yields of winter wheat across Europe under all the climate change scenarios they modeled. These increases in yield were attributed to the lower sensitivity of winter wheat to increased temperatures and a much higher sensitivity to elevated atmospheric CO_2 concentrations.

Bender et al. (1999) in modeling spring wheat yields under conditions of increased atmospheric concentrations of CO_2 for different sites across Europe found a mean increase in wheat yield of 35% with doubled CO_2 under current climate conditions. The spatial variability of results was high, with yield increases ranging from 11 to 121%, which the researchers were unable to explain. However, while increased atmospheric CO_2 concentration can increase crop yields, increased temperatures can decrease yields; thus, the interaction of these 2 effects is of great importance. The inclusion of CO_2 fertilization within crop growth models used in climate change model simulation studies is therefore essential (Tubiello et al. 1999).

3.6. Impacts of such yield changes at the farm level

Understanding responses of individual farms to changes in mean climate and changes in climate variability is essential to understanding the impacts of climate change on agriculture at a regional scale (Wassenaar et al. 1999). The research discussed here is part of a larger project examining possible farm-level adaptations to the potential changes predicted from the crop modeling. Previous research has modeled soybeans (DSSAT SOYGRO) and maize (DSSAT CERES-Maize), both in terms of the potential mean changes in future climate and the potential changes in climate variability for the study region. These results were used as inputs into the Purdue Crop Linear Program (PC/LP) model for farm-level decision analysis. The results from the DSSAT models (CERES-Maize, CERES-Wheat, and SOYGRO) flow into PC/LP, then as management/economic decisions change the type of production, results feed back into the crop model for further adjustment to crop production modeling. This process allows farm-level strategies to be created and then tested by running back through the model scenarios with the adaptations incorporated. Other research has examined agricultural response to climate change primarily on a regional or national basis. Both are important.

Preliminary results from the economic analyses further illustrate the north-south gradient and suggest that the impacts of climate change reach much further than simply influencing yields. Under the VEMAP current climate scenario at our southernmost site (southern Illinois), the farm will plant 4 % of the total acreage into a 2 yr corn/bean rotation–half beans, half corn each year. The other 96 % of the acreage is in a corn-wheat/bean 2 yr rotation. This is spring-planted, fall-harvested corn followed by fall-planted wheat. The wheat is harvested in the early summer, and beans are planted immediately afterwards for a late-fall harvest. Thereby we get 3 crops in 2 yr. PC/LP runs under the future scenarios incorporate the changing corn and soybean yields under climate change (Southworth et al. 2000, 2002). Under the future climate scenarios HadCM2-GHG and HadCM2-SUL, only 3 % of the farm will continue to be planted to the corn-wheat/bean rotation; 97 % will shift to a corn-bean rotation. This result is relatively insensitive to wheat revenue. If, for some reason, the revenue from wheat relative to corn and soybeans should increase even 30 %, then the highest return to resources on that farm would be seen with 26 % of the acreage in a corn-wheat/bean rotation.

In contrast, at the northernmost site (eastern Wisconsin), under the VEMAP current climate scenario, the whole acreage is in a corn-bean rotation. Under the HadCM2-SUL future climate scenario, 96 % of the acreage is planted in a corn-beans rotation, and 4 % of the acreage in continuous beans. Under the HadCM2-GHG future climate scenario, 57 % corn-beans rotation, 24 % continuous beans, and 11 % corn-wheat/beans rotation. If wheat returns were to go up 30 %, we would double the acreage in the corn-wheat/beans rotation.

4. CONCLUSIONS

Our primary conclusions are:

- The north-south temperature gradient in the midwestern Great Lakes states region is extremely important in influencing patterns of wheat yield under future climate conditions.
- Under future climate scenarios, central and northern locations in the study region will experience large increases in wheat yields compared to today's baseline, and southern locations will experience moderate increases or small decreases in yield.
- Optimal planting dates are the earliest available dates in the fall, but these may not be logistically possible as spring-planted crops may still be in the ground.
- Early planting of winter wheat may compete with harvesting of spring-sown crops under climate change.
- Climate variability is a significant factor influencing wheat yields because increased climate variability results in the largest decreases in future wheat yields, and reduced variability relates to increased yields.
- CO_2 fertilization produces a mean yield increase of 20 %, increasing to 30 % under moderate (HadCM2-SUL halved- and normal-variability runs) future climate scenarios.

Possible adaptation strategies to climate change and the effects of those strategies are critical issues. The most obvious adaptation we identified would be switching from maize (a C_4 crop) to wheat (a C_3 crop) in the more northern areas to take advantage of increased atmospheric CO_2 concentrations promoting increased growth and greater tolerances for higher temperatures. Under increased climate variability and increased frequency of extreme events, soil moisture management will become more critical and will require improved soil infiltration and water-holding capacity. Tillage and cropping systems that yield these benefits will increase in economic value to farmers. Also there will be increased concern about soil erosion with more extreme rain events, especially if agricultural program standards for conservation compliance that limits erosion are tightened.

At the local level, climate change research must include the full spectrum of climate, soils, biology, management, and economics if there is to be any link between analysis and usefulness for adaptation to climate change. This research hopes to provide the basis for strategic planning and risk management by farmers and the agricultural infrastructure to better adapt to such changing conditions.

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