Consequences of future climate change and changing climate variability on maize yields in the midwestern United States

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Abstract

Any change in climate will have implications for climate-sensitive systems such as agriculture, forestry, and some other natural resources. 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, grain moisture content at harvest, and hence, on the economics of agriculture including changes in farm profitability. Such issues are addressed for 10 representative agricultural areas across the midwestern Great Lakes region, a five-state area including Indiana, Illinois, Ohio, Michigan, and Wisconsin. This region is one of the most productive and important agricultural regions in the world, with over 61% of the land use devoted to agriculture.

Individual crop growth processes are affected differently by climate change. A seasonal rise in temperature will increase the developmental rate of the crop, resulting in an earlier harvest. Heat stress may result in negative effects on crop production. Conversely, increased rainfall in drier areas may allow the photosynthetic rate of the crop to increase, resulting in higher yields. Properly validated crop simulation models can be used to combine the environmental effects on crop physiological processes and to evaluate the consequences of such influences. With existing hybrids, an overall pattern of decreasing crop production under scenarios of climate change was found, due primarily to intense heat during the main growth period. However, the results changed with the hybrid of maize (*Zea mays* L.) being grown and the specific location in the study region. In general, crops grown in sites in northern states had increased yields under climate change, with those grown in sites in the southern states of the region having decreased yields under climate change. Yields from long-season maize increased significantly in the northern part of the study region under future climate change. Across the study region, long-season maize performed most successfully under future climate scenarios compared to current yields, followed by medium-season and then short-season varieties. This analysis highlights the spatial variability of crop responses to changed environmental conditions. In addition, scenarios of increased climate variability produced diverse yields on a year-to-year basis and had increased risk of a low yield. Results indicate that potential future adaptations to climate change for maize yields would require either increased tolerance of maximum summer temperatures in existing maize varieties or a change in the maize varieties grown. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Interest in the consequences of increasing atmospheric CO_2 concentration and its role in influencing climate change can be traced as far back as 1827, although more commonly attributed to the work of Arrhenius (1896) and Chamberlain (1897), as cited in Chiotti and Johnston (1995). A century later, concern over climatic change has reached global dimensions and concerted international efforts have been initiated in recent years to address this problem (Intergovernmental Panel on Climate Change (IPCC, 1995, 1990)). Future climate change could have significant impacts on agriculture, especially the combined effects of elevated temperatures, increased probability of droughts, and a reduced crop-water availability (Chiotti and Johnston, 1995).

Based on climate records, average global temperatures at the earth's surface are rising. Since global records began in the mid-19th century, the five warmest years have occurred during the 1990s and 10 of the 11 warmest years have occurred since 1980 (Pearce, 1997). Based on a range of several current climate models (IPCC, 1995, 1990), the mean annual global surface temperature is projected to increase by 1 to 3.5°C by the year 2100 and there will be changes in the spatial and temporal patterns of precipitation (IPCC, 1995).

The variability of the climate, under current and future climate scenarios, has been a topic of recent interest for a number of reasons. The consequences of changes in variability may be as important as those that arise due to variations in mean climatic variables (Hulme et al., 1999; Carnell and Senior, 1998; Semenov and Barrow, 1997; Liang et al., 1995; Rind, 1991; Mearns et al., 1984). 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 much less studied (Mearns et al., 1997; Mearns, 1995).

Within more recent historical records, there have been significant periods of climatic fluctuations such as the dustbowl conditions of the 1930s in the United States, when the dramatic and negative effects of climate variability on agriculture were realized. Katz and Brown (1992) showed that for a given climate variable a change in the variance has a larger effect on agricultural cropping systems than does a change in the mean. The effect of possible changes in climatic variability remains a significant uncertainty that deserves additional attention within integrated climate change assessments (Barrow et al., 1996; Mearns et al., 1996; Semenov et al., 1996). The study of economic effects of climate change on agriculture is particularly important because agriculture is among the more climate sensitive sectors (Kane et al., 1992).

Changes in climate will interact with adaptations to increase agricultural production affecting crop yields and productivity in different ways depending on the hybrids and cropping systems in a region. Important direct effects will be through changes in temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development (Saarikko and Carter, 1996). Also, an increased atmospheric CO_2 concentration could have a beneficial effect on the growth of some species.

Indirect effects will include potentially detrimental changes in diseases, pests, and weeds, the effects of which have not yet been quantified in most studies. Evidence continues to support the findings of the IPCC that "global agricultural production could be maintained relative to baseline production" for a growing population under $2 \times CO_2$ equilibrium climate conditions (Rosenzweig and Hillel, 1998, 1993). In middle and high latitudes, climate change will extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvesting, and the possibility of two or more cropping cycles during the same season. Climate change also will modify rainfall, evaporation, runoff, and soil moisture storage. Both changes in total seasonal precipitation or in its pattern of variability are important to agriculture. Moisture stress and/or extreme heat during flowering, pollination, and grain filling is harmful to most crops, such as maize, soybeans, and wheat (Rosenzweig and Hillel, 1993), the most important commodity crops in the midwestern United States.

In world markets, the United States accounts for more than 25% of the global trade in wheat, maize, soybeans, and cotton (USDA, 1997; Adams et al., 1999). An important question concerns the ability of North American agriculture to adapt to changing climatic conditions. Warmer climate scenarios (2–5°C increases in North America) have yielded estimates of negative impacts in eastern, southeastern, and Maize

Belt regions and positive effects in northern plains and western regions. More moderate warming produced estimates of predominately positive effects in some warm-season crops (IPCC, 1995).

Agricultural systems are managed and farmers always have a number of possible adaptations or options open to them. These adaptation strategies may potentially lessen future yield losses from climate change or may improve yields in regions where beneficial climate changes occur (Kaiser et al., 1995). Thus, agricultural production responds both to physiological changes in crops due to climate change and also to changes in agricultural management practices, crop prices, costs and availability of inputs, and government policies (Adams et al., 1999).

This research addresses the issues of changing mean climatic conditions and changes in the variability of climate around these means. The occurrence and frequency of extreme events will become increasingly important. This study addresses these issues for 10 representative agricultural areas in the midwestern United States for three hybrids of maize in terms of their current and future yields. Changes in climatic patterns may result in spatial shifts of agricultural practices, thereby impacting current land use patterns. Specifically, this research addresses (1) how the mean changes in future climate will affect maize yields across the study region for two future climate scenarios, (2) how the changes in climate variability, in addition to changes in the mean, affect potential future maize yields, (3) the implications of such changes spatially, examining potential future gains and losses, and (4) some possible future adaptation strategies.

2. Methods and materials

2.1. Study region

The midwestern Great Lakes region (Indiana, Illinois, Ohio, Michigan, and Wisconsin) was divided into 10 agricultural 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). This region is one of the most productive and important agricultural regions in the world (Smith and Tirpak, 1989).

2.2. Maize crop model

The decision support system for agrotechnology transfer (DSSAT) software is a set 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 crops, soils, and weather data and to run crop models in various ways and analyze their outputs (Thornton et al., 1997; Hoogenboom et al., 1995). The version of DSSAT used in this analysis was that supplied by ISBNAT, which is DSSAT 3.5.

Crop growth was simulated using the CERES-maize model, with a daily time step from sowing to maturity, based on physiological processes that describe the crop's response to soil and aerial environmental conditions. Phasic development is quantified according to the plant's physiological age. In CERES-maize, sub-models treat leaf area development, dry matter production, assimilate partitioning, and tiller growth and development. Potential growth is dependent on photosynthetically active radiation and its interception, whereas actual biomass production on any day is constrained by sub-optimal temperatures, soil water deficits, and nitrogen and phosphorus deficiencies. The input data required to run the CERES-maize model includes daily weather information (maximum and minimum temperatures, rainfall, and solar radiation); soil characterization data (data by soil layer on extractable nitrogen and phosphorous and soil water content); a set of genetic coefficients characterizing the hybrid being grown (Table 1); and crop management information, such as emerged plant population, row spacing, and seeding depth, and fertilizer and irrigation schedules (Thornton et al., 1997). The soil data were obtained from US Soil Conservation Service (SCS; now known as the Natural Resources Conservation Service) for the 10 farm sites. The model apportions the rain received on any day into runoff and infiltration into the soil, using the runoff curve number technique. A runoff curve number was assigned to each soil, based on the soil type, depth and texture as obtained from the STATSGO databases.

Concentrations of nitrogen and phosphorous in the soil were not limiting to crop growth and these modules are turned off within the CERES-maize model runs.

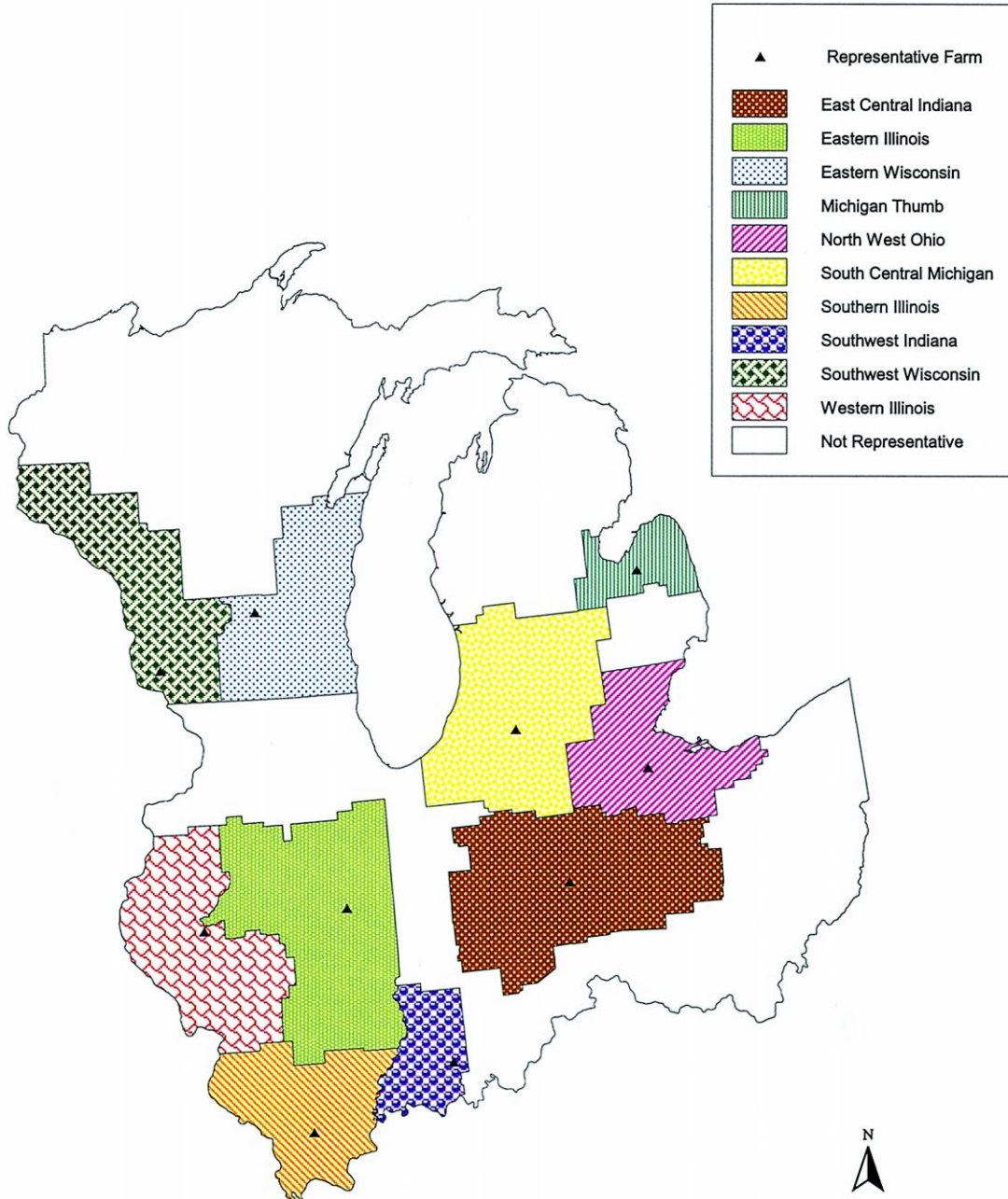The CERES-maize model includes the capability to simulate the effects of increased atmospheric CO_2

Fig. 1. Location of 10 representative agricultural regions in the midwestern Great Lakes states.

Table 1
Genetic coefficients for CERES-maize for (a) east-central Indiana, south-central Michigan, eastern Wisconsin, south-west Wisconsin, and the Michigan thumb, and for (b) eastern Illinois, southern Illinois, south-west Indiana, and western Illinois

Designation	P1[a]	P2[b]	P5[c]	G2[d]	G3[e]	PHINT[f]
(a)						
Long	320	0.52	940	620	6.0	38.9
Medium	200	0.30	800	700	6.3	38.9
Short	110	0.30	680	820	6.6	38.9
(b)						
Long	320	0.52	990	620	6.0	38.9
Medium	200	0.30	843	700	6.3	38.9
Short	110	0.30	716	820	6.6	38.9

[a] Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.

[b] Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h).

[c] Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C).

[d] Maximum possible number of kernels per plant.

[e] Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).

[f] Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

concentrations on photosynthesis and water use by the crop. Daily potential transpiration calculations are modified by the CO_2 concentrations (Lal et al., 1998; Dhakhwa et al., 1997; Phillips et al., 1996). Hence, under current conditions the model can run under the current atmospheric CO_2 concentration, approximately 360 ppmv. However, when evaluating crop growth under changed climate scenarios, which are based on the assumption of global warming due to increased concentration of CO_2 (and other greenhouse gases), the CO_2 concentration was increased accordingly. The atmospheric CO_2 concentration for the future climate scenarios used in this research, based on the years 2050–2059, is 555 ppmv.

CERES-maize does not have an algorithm that "kills" maize as a result of spring freezes. Hence, in this analysis, whenever a minimum air temperature of −2.0°C or less occurred during the spring (Julian Days 1–180) and after the emergence date, growth was terminated. This value of termination was based

on discussion with Dr. Joe Ritchie (personal communicatin, 1999) as being a realistic number for freeze loss of maize.

The selection of CERES-maize as the model for this research was based on (1) the daily time step of the model allows us to address the issue of changes in planting dates, (2) plant growth dependence on both mean daily temperatures and the amplitude of daily temperature values was desired (not just a daily mean temperature growth dependence as for EPIC), (3) the model simulates crop response to major climate variables, including the effects of soil characteristics on water availability, and is physiologically oriented, (4) the model is developed with compatible data structures so that the same soil and climate datasets can be used for all hybrids of crops which helps in comparison (Adams et al., 1990), and (5) comprehensive validation has been done across a wide range of different climate and soil conditions, and for different crop hybrids (Semenov et al., 1996; Wolf et al., 1996; Hoogenboom et al., 1995).

2.3. Crop model validation

CERES-maize has been extensively validated at sites both in the United States and abroad (Dhakhwa et al., 1997; Hoogenboom et al., 1995). Mavromatis and Jones (1998) found that using the CERES-wheat model coupled with a weather generator (WGEN or SIMMETEO) to simulate daily weather from monthly mean values is an efficient method for assessing the impacts of changing climate on agricultural production. Properly validated crop simulation models can be used to determine the influences of changes in environment, such as climate change, on crop growth (Peiris et al., 1996).

Intensive site-specific validation was also undertaken to ensure the model could mirror reality in the representative agricultural areas. Detailed experimental farm level data were used to ensure that yields produced by the model reflected the actual yields in each representative agricultural area. CERES-maize was initially validated using experimental data reported by Nafziger (1994) for maize planted at two locations in Illinois, USA (Fig. 2a). Experimental data were available for four planting dates over the period 1987–1990, and measured yields were compared against yields simulated using CERES-maize.
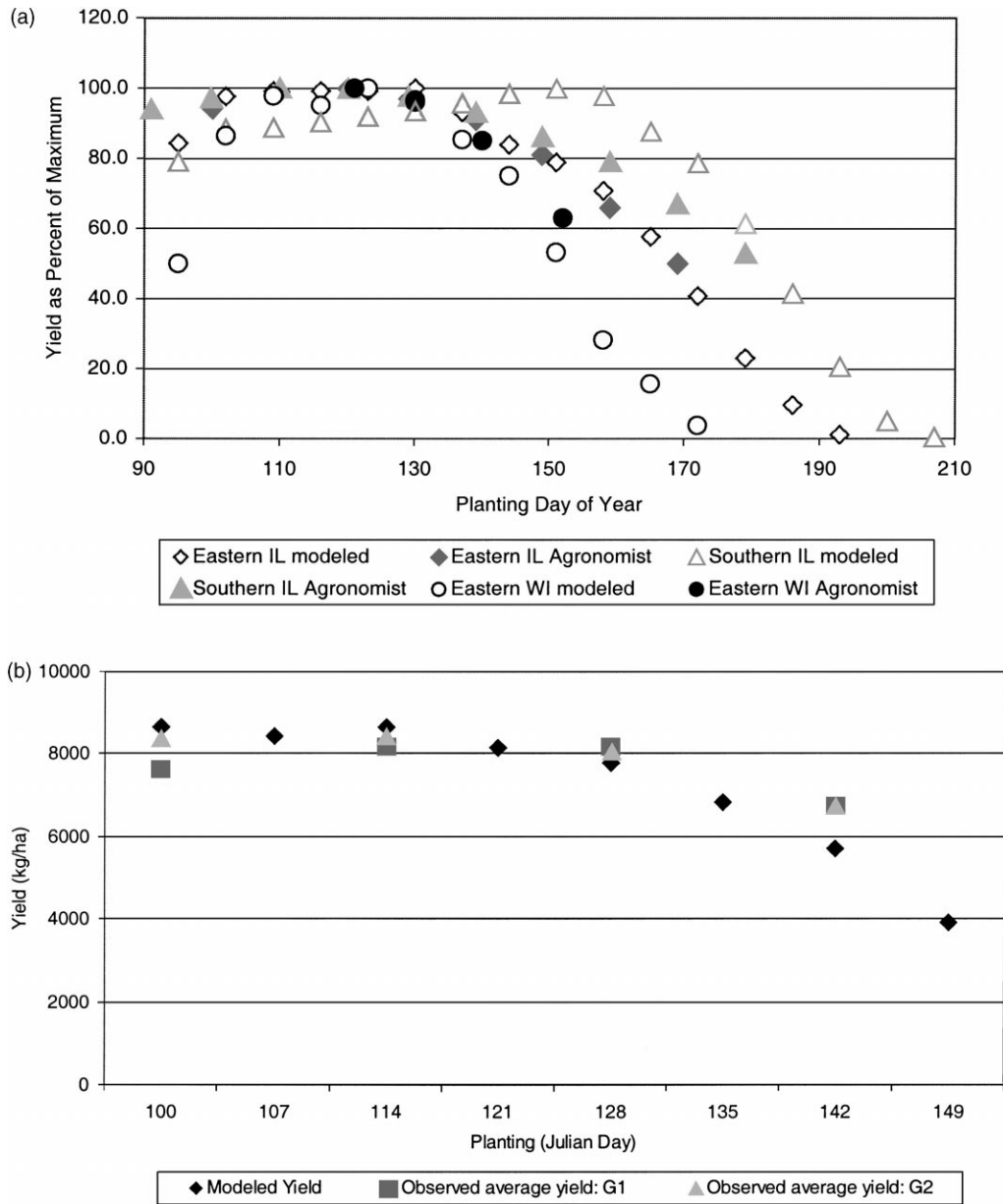
Fig. 2. Validation of CERES-maize results for (a) 15-year simulation of maize yield to planting dates at Dekalb, Illinois (1975–1990) and (b) long-season maize yields as a percent of maximum for eastern Illinois, southern Illinois, and eastern Wisconsin as modeled by CERES-maize compared to agronomist's predictions.

Simulated yields corresponded to within $+/-10\%$ of the observed maize yields. Overall response of simulated yields to planting date variation compared very favorably with observed yields.

In addition, each representative farm was validated using historical yield data and past daily climate information. This validation was used to ensure the model could replicate past yields, at each location being modeled, for longer-season (currently grown) maize varieties and that the medium and short-season maize varieties showed the correct trends based on expert opinions of agronomists (Fig. 2b).

In addition, CERES-maize was used to simulate the relationships between planting date and yield (expressed as a percentage of the highest yield observed for any combination of hybrid and planting date) for long, medium, and short-season maize varieties for 20 different planting dates. The relationship between planting date and yield suggest that long-season maize has higher yields than medium and short-season maize for earlier planting dates, medium-season maize has the highest yields for the middle planting dates, and short-season maize has the highest yields for late planting dates. These results are consistent with expectations about hybrid performance in this region. Further, the close match between the long-season hybrid performance and agronomist expectations gives us confidence that the model is able to describe the relationship between planting date and maize yield for these locations (Fig. 2b). Similar results have been obtained for all 10 representative agricultural areas in the study region.

2.4. Current climate analysis: VEMAP

The VEMAP dataset includes daily, monthly, and annual climate data for the conterminous United States including maximum, minimum, and mean temperature, precipitation, solar radiation, and humidity (Kittel et al., 1996). The VEMAP baseline (30-year historical mean) climate data was used for each of the 10 representative agricultural areas in the study region. The weather generator SIMMETEO (as used in DSSAT version 3.5) used these climate data to stochastically generate daily weather data in model runs. This approach of using monthly data to generate daily data allowed us to generate variability scenarios. The climate variables distribution patterns mimic the current climate variables distributions. As there is no way to know future distributions, they are based on current patterns. Sensitivity analysis determined the effects of differing climatic conditions upon differing combinations of planting and harvest dates.

2.5. Future climate scenarios

This research used the Hadley Center model 'HadCM2' from England for future climate scenario data. This model was created from the Unified Model, which was modified slightly to produce a new, coupled ocean-atmosphere GCM, referred to as HadCM2. This has been used in a series of transient climate change experiments using historic and future greenhouse gas and sulfate aerosol forcing. These models simulate time-dependent climate change (Barrow et al., 1996). Transient model experiments are considered more physically realistic and complex, and allow atmospheric concentrations of CO_2 to rise gradually over time (Harrison and Butterfield, 1996). The results from this model have been validated at a number of locations. HadCM2 is also one of the models used in the US National Assessment project.

HadCM2 has a spatial resolution of $2.5° \times 3.75°$ (latitude by longitude) and the representation produces a grid box resolution of 96×73 grid cells, which produces a surface spatial resolution of about $417\,km \times 278\,km$ reducing to $295\,km \times 278\,km$ 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, 1990).

The greenhouse-gas-only version, HadCM2-GHG, used the combined forcing of all the greenhouse gases as an equivalent CO_2 concentration. HadCM2-SUL used the combined equivalent CO_2 concentration plus a negative forcing from sulfate aerosols. HadCM2-GHG simulated the change in forcing of the climate system by greenhouse gases since the early industrial period. There is a small amount of forcing $(0.4\,W\,m^{-2})$ prior to this simulation period representing the small increase in greenhouse gases from 1765 to 1860. 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 and Senior, 1998). The indirect effects of aerosols were not simulated.

Our research used the period of 2050–2059 for climate scenarios. However, using a single scenario has limitations, as it is not possible to capture the range of uncertainties as described by the IPCC. This study used two model scenarios to represent the likely upper and lower boundaries of future (2050's) climate change. The results from HadCM2-GHG and HadCM2-SUL cannot be viewed as a forecast or prediction, but rather as two possible realizations of how the climate system may respond to a given forcing. A comparison of the main three climate datasets (Table 2) highlights the differences in projected mean climate data for the study region. Also, a climate variability analysis was conducted on these two scenarios, thus increasing the number of future climate scenarios to six. Hence, a range of probable climate change scenarios were examined to determine their impacts on maize growth.

2.6. Climate variability analysis

In order to separate crop response to changes in climatic means from its response to changes in climate variability, it is necessary first to model the impacts of mean temperature changes on crop growth. Then 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).

The mean conditions for the period 2050–2059 for each location, individual future years of climate data, and both GCM model runs were used in this analysis. The variance of the time series was changed for both temperature (maximum and minimum) and precipitation in time steps of one month. The variance of each month was altered separately, according to the following algorithm from Mearns (1995):

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

and

$$\delta = \frac{\sigma'^2}{\sigma^2} \tag{2}$$

where X'_t is the new value of climate variable X_t (e.g. monthly mean maximum February temperature for year t), μ the mean of the time series (e.g. the mean of the monthly mean maximum February temperatures for a series of years), δ the ratio of the new to the old variance of the new and old time series, X_t the old value of climate variable (e.g. the original monthly mean February temperature for year t), σ'^2 the new variance, and σ^2 the 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 equation one. This algorithm was used to change both maximum and minimum temperatures and the precipitation time series. This simple method, as developed by Mearns (1995) was used despite more complex methodologies being developed, due to the comparisons of variability techniques. Mearns et al., (1996, 1997) illustrated the results obtained from the more computationally advanced, upper-level statistical techniques were surprisingly similar to prior results from the more statistically simple methodologies. If anything, these researchers noted a likelihood of underestimating the negative impacts of climate variability on crop yields using the simpler techniques, but in these analyses the differences were quite minor. The approach used here permits the incorporation of changes in both the mean and the variability of future climate in a computationally inexpensive, highly consistent, and reproducible manner.

2.7. Model and data limitations

This study does not attempt to predict future climate, but rather, is an evaluation of possible future changes in agricultural production in the midwestern United States that might result from future changes in climate. Such potential changes provide insight into possible larger societal changes needed to control and reduce CO_2 in the atmosphere and to help select appropriate strategies to prepare for change (Adams et al., 1990).

The CERES-maize model, as with all models, contains several assumptions. Weeds, insects and crop diseases have no detrimental effect on yield. Also,

Table 2

Comparison of HadCM2GHG and HadCM2SUL climate scenario mean monthly maximum and minimum temperature and precipitation values, compared to VEMAP current mean monthly climatic conditions for July

Site[a]	VEMAP[b]			HadCM2GHG[c]			HadCM2SUL[d]		
	Maximum temperature (°C)	Minimum temperature (°C)	Total monthly precipitation (mm)	Δ in maximum temperature (°C)	Δ in minimum temperature (°C)	Δ in total monthly precipitation (mm)	Δ in maximum temperature (°C)	Δ in minimum temperature (°C)	Δ in total monthly precipitation (mm)
A	29.6	17.4	99.0	+9.3	+9.1	+17.4	+5.8	+6.6	+30.8
B	28.5	16.0	95.0	+6.9	+7.9	+32.1	+3.8	+5.8	+56.7
C	28.2	15.7	88.0	+4.3	+5.9	+16.5	+1.8	+4.2	+60.1
D	28.1	15.5	87.0	+4.5	+5.7	+11.3	+1.4	+3.9	+45.0
F	30.8	18.7	98.0	+8.1	+7.8	+18.4	+4.6	+5.3	+31.8
G	30.7	18.1	114.0	+4.7	+5.8	+15.5	+1.6	+3.7	+37.7
H	27.8	15.1	96.0	+7.8	+7.8	+10.0	+4.2	+5.6	+33.3
J	28.3	16.2	94.0	+7.3	+6.7	+12.0	+3.7	+4.5	+35.3
K	30.0	17.6	94.0	+8.9	+8.9	+22.4	+5.4	+6.4	+35.8
L	28.0	14.2	71.0	+4.6	+7.0	+27.3	+1.5	+5.2	+61.0

[a] A: eastern Illinois; B: east-central Indiana; C: north-west Ohio; D: south-central Michigan; F: southern Illinois; G: south-west Indiana; H: eastern Wisconsin; J: south-west Wisconsin; K: western Illinois; and L: Michigan thumb.

[b] VEMAP dataset for current climate data.

[c] HadCM2GHG is the Hadley Center data for 2050–2059 from the greenhouse gas only run.

[d] HadCM2SUL is the Hadley Center data for 2050–2059 from the greenhouse gas and sulphate run.

extreme climate-related events such as droughts or floods are not taken into account by the model in terms of extreme crop losses resulting from such events.

Other limitations relate to the simplified reality represented by the representative farms, the use of a single soil type at each location, and hence, the loss of the spatial variability of soils, although the selected soil type was that predominant at each location. However, the extensive validation and analysis at the farm level is in itself a more detailed analysis than previously undertaken.

Preparing agriculture for adaptation to climate change requires advance knowledge of how climate will change and when. The direct physical effects on plants and the indirect effects on soils, water, and other biophysical factors also must be understood. Currently, such knowledge is not available for either the direct or indirect effects of climate change. However, guidance can be obtained from an improved understanding of current climatic vulnerabilities of agriculture and its resource base. This knowledge can be obtained from the use of a realistic range of climate change scenarios and from the inclusion of the complexity of current agricultural systems and the range of adaptation techniques and policies now available and likely to be available in the future (Rosenburg, 1992).

3. Results

3.1. Consequences of changing mean climate and climate variability on maize yields

Changes in yield were evaluated by comparing the future maize yields to the current VEMAP yields, on the same hybrids, and then stating the change as percentage difference. Decreases in yield were greatest in doubled variability scenarios. Decreases in yield were greater for HadCM2-GHG scenarios than for HadCM2-SUL scenarios. Increasing the variability of the future climate scenarios increased the variability of the year-to-year crop yields obtained from the DSSAT model. The greater variance associated with the HadCM2-GHG climate scenario is due to the more extreme increases in mean temperatures associated with this climate scenario, compared to the lesser increases for the HadCM2-SUL climate scenario.

Long-season maize in all future climate scenarios (Fig. 3) clearly showed decreases in yields in the southern and central locations. The decreases range from 0 to −45% as compared to yields estimated using VEMAP data. The largest decreases in yield occurred in western Illinois for all future climate scenarios. In contrast, the northern locations showed increases in yields under these same future climate scenarios. In the four northernmost agricultural areas (east central Michigan, southwest Michigan, eastern Wisconsin, and western Wisconsin) increases in maize yield ranged from 0.1 to 45% as compared to yields using VEMAP data. An exception to this pattern was for the HadCM2-GHG scenario with doubled variance, where southwestern Michigan and western Wisconsin had −0.1 to −10% decreases in yield. The doubled variability runs of both scenarios resulted in extreme decreases in yield in the southern locations, and less significant increases in yield in the northern locations as compared to unchanged or halved variability runs. The greatest gains in yield occurred in the halved variability scenarios because the occurrence of very low or zero yields decreased substantially in the halved variability scenarios.

Medium-season maize yields (Fig. 4) showed dramatic decreases in yields as compared to VEMAP, even in the northern agricultural areas of the study region. Under the HadCM2-GHG and HadCM2-SUL scenarios all regions experienced decreases in yields of maize, ranging from −15.1 to −40%. In these scenarios, no locations experienced increases in yield. Under the doubled and halved variability scenarios, however, the northern most locations showed lesser decreases in yield and even some increases. Values ranged from −30 to 20% for the halved variability scenarios, and from −40 to 15% for the doubled variability scenarios. It must be noted that the actual (simulated) yields obtained for medium-season maize are usually higher than those obtained for longer-season maize for all climate scenarios (Table 3). However, when compared to the current VEMAP yields as a percentage change the yields frequently decrease.

Short-season maize showed a different pattern with all yields decreasing, as compared to yields using VEMAP data, except in western Illinois (Fig. 5). In this agricultural area, yields increased under all HadCM2-SUL scenarios and the halved variability HadCM2-GHG scenario, with increases ranging from
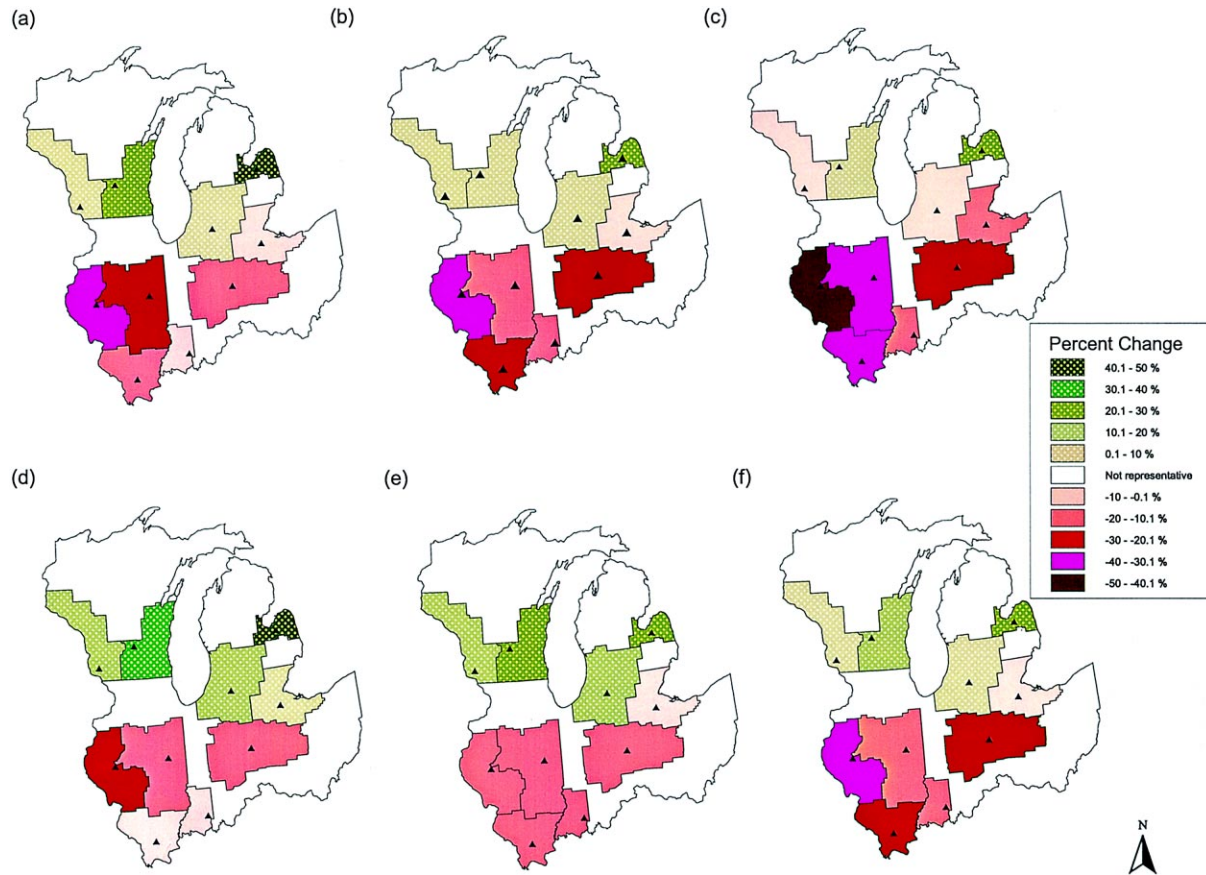
Fig. 3. Percent change in mean maximum decadal yield for long-season maize, compared to VEMAP yields, for (a) halved variability HadCM2-GHG, (b) HadCM2-GHG, (c) doubled variability HadCM2-GHG, (d) halved variability HadCM2-SUL, (e) HadCM2-SUL, and (f) doubled variability HadCM2-SUL.

5.1 to 35%. This difference in pattern may be due to different factors than the changes in yield of medium and long-season maize, perhaps related to the strong east-west precipitation gradient or differences in soils at this location.

3.2. Mean maximum decadal yield versus planting dates

The impact of changing climate on planting dates in terms of the mean maximum decadal yields (Figs. 3–5) illustrates that under future climate change scenarios later planting dates produced higher yields. In almost all cases (Table 3) the highest mean maximum decadal yield occurs at a later planting date under future climate change, which explains why

medium-season maize varieties frequently have higher total yields than the longer season maize. The later planting dates for all maize varieties have the most beneficial impact on medium-season maize. The productivity induced shift to later planting dates is past the current optimal planting dates for longer season varieties and into the medium-season maize optimal planting dates. Such delays in planting dates also have been found by other researchers under future climate change scenarios (Jones et al., 1999).

3.3. Spring freezes

In future climate scenarios, the frequency of maize-killing freeze events will decrease although under doubled variance scenarios the intensity of the freeze event
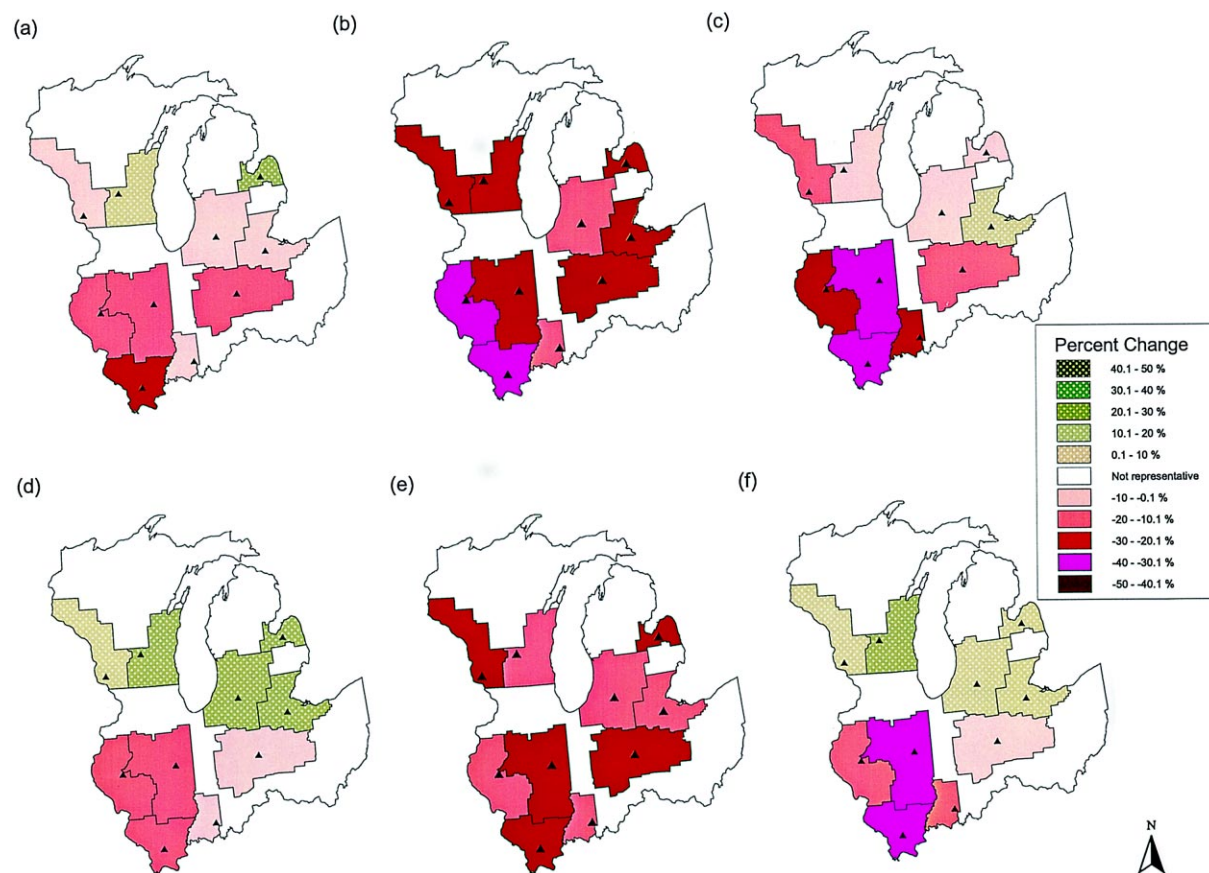
Fig. 4. Percent change in mean maximum decadal yield for medium-season maize, compared to VEMAP yields, for (a) halved variability HadCM2-GHG, (b) HadCM2-GHG, (c) doubled variability HadCM2-GHG, (d) halved variability HadCM2-SUL, (e) HadCM2-SUL, and (f) doubled variability HadCM2-SUL.

will increase (Fig. 6). This implies that increased frost tolerance is not an important issue for future climate change and maize growth as initially expected.

4. Discussion

4.1. Crop yield changes by region

The future climate scenarios, with increased temperatures and precipitation, resulted in significantly altered maize yields, at each of the 10 agricultural areas in the study region.

Across the southern areas yields generally decreased due to the daily maximum temperatures

becoming too high and hence, resulting in yield decline. Western Illinois had yield decreases of −10 to −50% for long-season maize, −10 to −40% for medium-season maize, and −10 to +40% for short-season maize. For short-season maize western Illinois was the only location with yield increases, although these increases only occurred under the HadCM2-SUL scenarios and the halved variability HadCM2-GHG scenario, i.e. the less extreme climates. Eastern Illinois had yield decreases of −10 to −40% for long and medium-season maize, and −30 to −50% decreases for short-season maize. Southern Illinois yield decreases ranged from 0 to −40% for long-season maize, −10 to −40% for medium-season maize, and −30 to −40% for short-season maize.

Table 3
Mean maximum decadal yield planting dates (Julian days) under VEMAP current climate and future HadCM2GHG (halved variability (0.5)/unchanged variability (1.0)/doubled variability (2.0)) and HadCM2SUL (halved variability (0.5)/unchanged variability (1.0)/doubled variability (2.0)) climate scenarios for maize varieties

Site[a]	VEMAP[b]	HadCM2GHG[c]			HadCM2SUL[d]		
		0.5	1.0	2.0	0.5	1.0	2.0
A							
LSC[e]	130 (260[f])	186 (204)	186 (212)	179 (173)	179 (227)	186 (223)	179 (210)
MSC[g]	158 (261)	207 (218)	207 (185)	74 (165)	193 (215)	200 (194)	81 (178)
SSC[h]	179 (235)	195 (132)	207 (138)	218 (125)	200 (159)	207 (147)	200 (139)
B							
LSC	123 (252)	186 (215)	179 (196)	158 (181)	172 (218)	172 (221)	158 (200)
MSC	144 (272)	193 (234)	200 (201)	144 (218)	186 (255)	186 (212)	172 (248)
SSC	158 (208)	144 (136)	207 (127)	151 (122)	207 (164)	207 (138)	144 (148)
C							
LSC	116 (241)	179 (224)	172 (218)	165 (213)	158 (243)	158 (228)	144 (217)
MSC	123 (267)	179 (262)	179 (205)	165 (268)	172 (312)	172 (217)	144 (292)
SSC	158 (198)	137 (176)	137 (151)	165 (157)	172 (190)	172 (164)	158 (181)
D							
LSC	137 (212)	165 (220)	172 (219)	114 (208)	137 (236)	151 (235)	144 (227)
MSC	137 (274)	179 (272)	186 (222)	144 (269)	165 (303)	172 (232)	151 (299)
SSC	158 (208)	130 (169)	137 (156)	151 (171)	165 (182)	172 (177)	172 (184)
F							
LSC	151 (258)	200 (219)	186 (199)	193 (176)	186 (234)	186 (207)	186 (198)
MSC	165 (258)	207 (181)	207 (167)	81 (160)	200 (215)	200 (195)	200 (174)
SSC	179 (195)	130 (124)	102 (118)	130 (121)	207 (136)	207 (126)	116 (124)
G							
LSC	151 (256)	186 (247)	186 (218)	186 (218)	179 (246)	165 (230)	172 (217)
MSC	165 (255)	200 (232)	207 (207)	200 (192)	193 (250)	193 (209)	193 (212)
SSC	151 (201)	207 (167)	207 (143)	207 (144)	207 (194)	207 (162)	200 (158)
H							
LSC	123 (184)	179 (233)	158 (190)	172 (196)	165 (243)	151 (223)	151 (218)
MSC	144 (252)	193 (265)	193 (189)	186 (238)	186 (299)	172 (214)	172 (280)
SSC	158 (224)	193 (151)	144 (145)	179 (140)	193 (190)	179 (162)	186 (168)
J							
LSC	123 (213)	172 (214)	179 (205)	172 (192)	165 (234)	158 (228)	144 (215)
MSC	151 (272)	186 (264)	193 (200)	186 (232)	179 (284)	179 (217)	165 (277)
SSC	165 (233)	193 (155)	207 (139)	186 (139)	207 (174)	186 (172)	172 (174)
K							
LSC	137 (261)	74 (168)	186 (166)	74 (150)	179 (199)	186 (216)	88 (165)
MSC	137 (219)	81 (179)	102 (149)	81 (155)	74 (188)	200 (180)	81 (185)
SSC	137 (122)	109 (150)	102 (112)	109 (117)	95 (164)	109 (130)	116 (140)
L							
LSC	137 (171)	179 (242)	165 (218)	158 (212)	151 (240)	130 (215)	158 (220)
MSC	137 (269)	186 (300)	179 (207)	179 (262)	179 (307)	151 (213)	158 (286)
SSC	137 (209)	200 (176)	200 (163)	193 (162)	193 (192)	186 (171)	186 (168)

[a] A: eastern Illinois; B: east-central Indiana; C: north-west Ohio; D: south-central Michigan; F: southern Illinois; G: south-west Indiana; H: eastern Wisconsin; J: south-west Wisconsin; K: western Illinois; and L: Michigan thumb.
[b] VEMAP dataset for current climate data.
[c] HadCM2GHG is the Hadley Center data for 2050–2059 from the greenhouse gas only run.
[d] HadCM2SUL is the Hadley Center data for 2050–2059 from the greenhouse gas and sulphate run.
[e] LSC: long-season maize.
[f] Maize yields are given in bu/ac.
[g] MSC: medium-season maize.
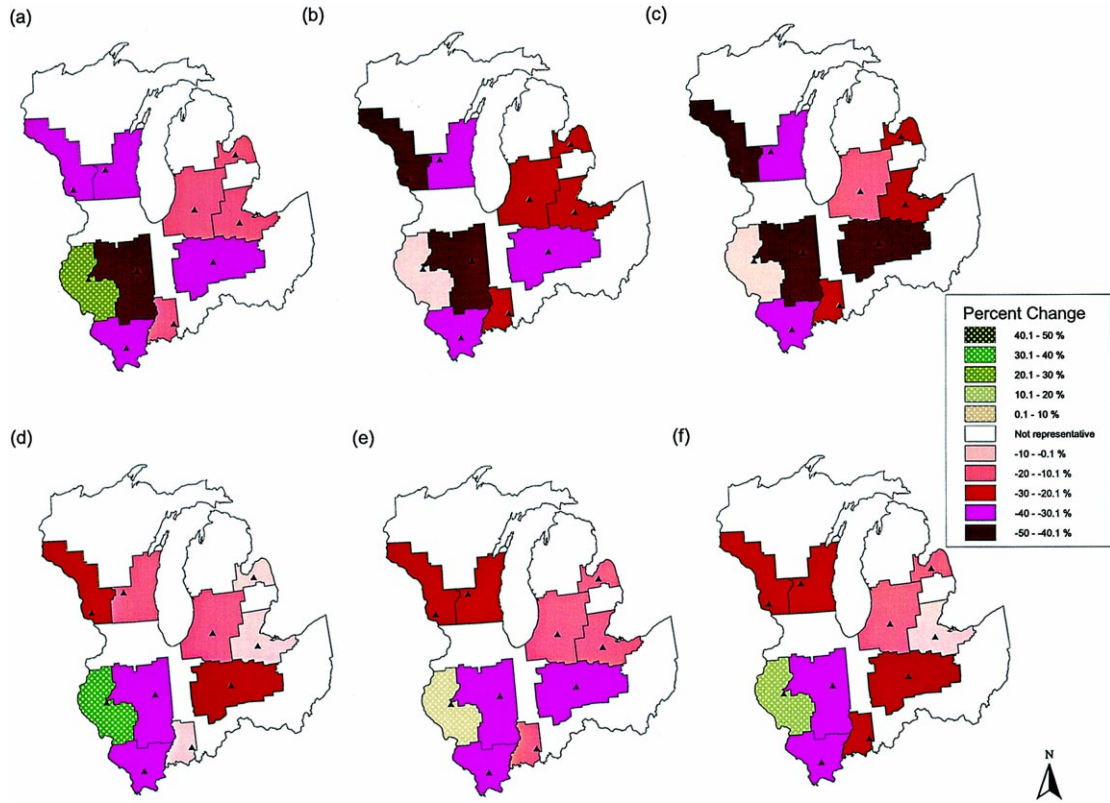[h] SSC: short-season maize.

Fig. 5. Percent change in mean maximum decadal yield for short-season maize, 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.
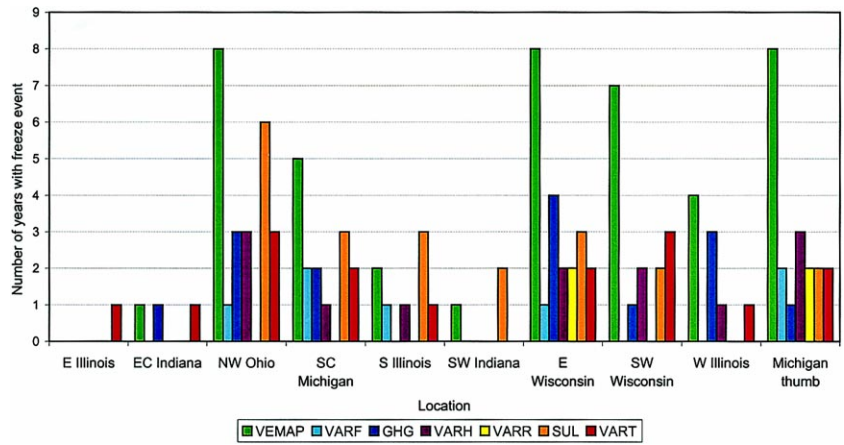

Fig. 6. Number of years across the decade of analysis, with a spring freeze event, for the seven climate scenarios: current climate (VEMAP), halved variability HadCM2-GHG (VARF), HadCM2-GHG (GHG), doubled variability HadCM2-GHG (VARH), halved variability HadCM2-SUL (VARR), HadCM2-SUL (SUL), doubled variability HadCM2-SUL (VART).

Results were very consistent across climate scenarios. Southwest Indiana yields decreased between 0 and −20% for long-season maize, 0 and −30% for medium-season and short-season maize. East-central Indiana had yield decreases of −10 to −30% for long-season maize, 0 to −30% for medium-season maize, and −20 to −50% for short-season maize.

Agricultural areas in the northern states of the study region typically experienced more increased yields under the six future climate scenarios, especially for long-season maize. Northwest Ohio had yield changes of +10 to −20% for long-season maize, +20 to −30% for medium-season maize, and 0 to −30% for short-season maize. South-central Michigan yield changes ranged from +20 to −10% for long-season maize, +20 to −20% for medium-season maize, and −10 to −30% for short-season maize. The Michigan thumb area experienced the greatest yield increases for long-season maize, with +20 to +50% increases above current yields, for medium-season maize +20 to −30% changes in yield, and 0 to −30% decreases for short-season maize. Southwest Wisconsin had +20 to −10% changes in yield for long-season maize, +10 to −30% for medium-season maize, and −20 to −50% changes for short-season maize. Finally, eastern Wisconsin, had yield changes of 0 to +40% for long-season maize, +20 to −30% for medium-season maize, and −10 to −40% for short-season maize.

The results across all 10 agricultural areas have some significant and consistent patterns. The two main patterns are (1) short-season maize has low yields compared to current yields under changed climate scenarios except in western Illinois, and (2) the halved variability climate scenarios produced both the highest maize yield increases and some of the lowest decreases in agricultural areas in the southern states, indicating that changes in future climate variability, producing more extreme climatic events, will be detrimental to future agricultural production. Hence, as this research illustrates, it is extremely important to model both changes in mean and variability of future climate.

Our results indicate that the currently grown (predominant) maize hybrid (long-season maize) will have increased or better yields under future climate conditions, compared to current yields, than will the medium and short-season maize hybrids. However, in terms of actual yield, medium-season maize yields are frequently greater than those obtained from longer-season maize for the same climate scenario due to the later planting dates under climate change. Short-season maize does not appear to be as viable under changed climate conditions across the study region.

Spatially, results show that the agricultural areas in the northern states (southwest Wisconsin, eastern Wisconsin, south-central Michigan, northwest Ohio, and the Michigan thumb) will experience increases in maize yields as a result of climate change, while those in the southern and central regions (western Illinois, eastern Illinois, southern Illinois, southwest Indiana, and east-central Indiana) will show a clearly decreasing trend. The more extreme climate scenario, as represented by HadCM2-GHG, results in greater reduction of maize yields than HadCM2-SUL. The HadCM2-GHG scenario produces mean monthly summer temperatures that are 1–4°C warmer than the HadCM2-SUL scenarios. Increased surface air temperatures result in a reduction in agricultural productivity in many crops due to earlier flowering and a shortening of the grain-fill period. The shorter the crop duration, the lower yield per unit area (Lal et al., 1998), as is seen in results in central and southern locations in the study region. However, in northern locations of the study area, where low temperatures currently limit the grain fill period, increases in temperatures due to climate change will result in the grain filling period lengthening and increased yields.

4.2. Daily maximum temperatures

High temperatures affect agricultural production directly through the effects of heat stress at critical phenological stages in the crop's growth. In maize, high temperatures at the stages of silking or tasseling result in significant decreases in yield. Both the CERES-maize and another crop model, EPIC, use the temperature-sum approach to calculate developmental time, where $GDD = [(T_{max} - T_{min})/2] - T_{base}$. In the case of the EPIC model, the only condition is that GDD cannot be <0. This has an important implication for climate change studies, because increasing the daily mean temperature in the EPIC model will never directly slow the developmental rate. In the case of CERES-maize, if the maximum daily temperature (T_{max}) is above 44°C or the minimum daily temperature (T_{min}) is less than the base temperature, then the

average 3-h temperature is calculated for eight periods of the day using an interpolation scheme. If this 3-h temperature is greater than the base temperature or $<44°C$, then the 3-h temperature contributes to the daily temperature to be summed. In addition, if the 3-h temperature is $>34°C$, then the developmental rate is assumed to decrease. Using the CERES-maize model, when the maximum daily temperature exceeds $44°C$, then the developmental rate will be slowed due to high temperatures. In addition, if the amplitude of daily temperature fluctuations increases to the extent that the maximum daily temperature is exceeding $44°C$ or the minimum daily temperature is less than the base temperature, the developmental rate will decrease, even if the mean daily temperature stays the same. In contrast, with the standard GDD approach, such as that used in the EPIC model, only the mean daily temperature effects developmental time, not the amplitude of daily temperature. Again, this has implications for climate change studies, where daily temperature amplitude may change as the climate changes (Riha, 1999; personal communication). This inclusion of both the amplitude and the mean temperature is an important reason for the selection of the CERES-maize model.

Using regression analyses, Rosenzweig (1993) found that daily maximum temperatures greater than $33.3°C$ in July and August were negatively correlated with maize yield in the US Maize Belt and that daily maximum temperatures $>37.7°C$ caused severe damage to maize. The future climate scenarios used had maximum daily temperatures $>35°C$ on several days during July and August (Table 4). Results in this table match closely with yield changes with an increased number of days with temperatures greater than $35°C$ within a given climate scenario, resulting in decreased yields.

Hoogenboom et al. (1995), using the CERES-maize model, found that no maize growth occurred at air temperatures below $8°C$; maximum crop growth and grain fill occurred at daily temperatures of $34°C$; and growth was reduced at higher temperatures up until $44°C$, above which no growth occurred. Due to this temperature sensitivity, maximum daily temperature will become important in the future climate scenarios, as will the frequency and duration of such occurrences.

Table 4

Number of days in the growing season (1 May–30 September) with maximum daily temperatures 35.0–39.9°C, and 40.0–44.9°C under VEMAP current climate and future HadCM2GHG (halved variability (0.5)/unchanged variability (1.0)/doubled variability (2.0)) and HadCM2SUL (halved variability (0.5)/unchanged variability (1.0)/doubled variability (2.0)) climate scenarios for the year 2055

Site[a]	VEMAP[b]		HadCM2GHG[c]: 2055						HadCM2SUL[d]: 2055					
	Maximum temperature >35°C	Maximum temperature >40°C	Maximum temperature >35°C			Maximum temperature >40°C			Maximum temperature >35°C			Maximum temperature >40°C		
			0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0	0.5	1.0	2.0
A	5	0	92	80	95	13	28	28	44	45	37	0	5	0
B	1	0	62	69	56	6	9	3	12	18	14	0	0	0
C	1	0	20	34	35	0	1	1	6	5	6	0	0	0
D	0	0	15	12	10	0	0	0	2	2	0	0	0	0
F	9	0	89	83	93	22	28	30	32	44	44	0	1	0
G	4	0	60	65	69	4	9	7	8	17	19	0	0	0
H	0	0	43	35	44	1	4	0	2	4	4	0	0	0
J	0	0	55	48	45	1	3	2	1	7	1	0	0	0
K	3	0	87	80	91	30	28	39	44	45	47	0	5	0
L	0	0	15	16	22	0	1	0	0	1	0	0	0	0

[a] A: eastern Illinois; B: east-central Indiana; C: north-west Ohio; D: south-central Michigan; F: southern Illinois; G: south-west Indiana; H: eastern Wisconsin; J: south-west Wisconsin; K: western Illinois; and L: Michigan thumb.

[b] VEMAP dataset for current climate data.

[c] HadCM2GHG is the Hadley Center data for 2050–2059 from the greenhouse gas only run.

[d] HadCM2SUL is the Hadley Center data for 2050–2059 from the greenhouse gas and sulphate run.

The US Environmental Protection Agency (EPA) found a decrease in maize yields under conditions of future climate change of 4–42% due to temperatures rising above the range of tolerance for the maize crops (EPA, 1998). Saarikko and Carter (1996) found that the thermal suitability for spring wheat in Finland could shift northwards by 160–180 km per 1°C increase in mean annual temperature. In areas of current growth the timing of crop development under a warmer climate shifts to earlier in the year, thus shortening the development phase, resulting in decreased yields. In northwest India, Lal et al. (1998) found a reduction of 54% in wheat yields with a 4°C rise in mean daily temperatures. Using a doubled atmospheric CO_2 concentration (720 ppmv) from present day and a 5°C rise in mean daily temperatures, the decrease in yield was only 32% from current conditions. These results are similar in terms of pattern and trend to those of this research, with increasing summer maximum temperatures resulting in decreased yields.

4.3. Impacts of CO_2 fertilization

This approach, using the CERES-maize model, enables us to model the predicted future climate, and CO_2 levels based on this future climate, and to evaluate the crop response. This research used a future atmospheric CO_2 concentration of 555 ppmv, compared to 360 ppmv for current conditions. For maize, a C4 crop, this response is not as important as for C3 crops such as soybeans. C4 crops are more efficient photosynthetically than C3 plants and show less response to increasing atmospheric CO_2 concentration, which provides a future potential agricultural adaptation of C3 crops over C4 crops due to their enhanced growth functions with higher concentrations of CO_2 (Rosenzweig and Hillel, 1998; Rosenzweig, 1993). Assessment of both the effects increased atmospheric CO_2 concentrations and climatic change impacts on agricultural production is a crucial area of research because the two factors occur together.

4.4. Climate variability impacts on maize yields

The halved variability climate scenarios produced maize yields with the greatest increases in yield for long-season maize. In addition, decreases in yield for the agricultural areas in the southern states, and for the medium-season and short-season maize varieties were much less extreme. These results were expected for the halved variability scenarios which resulted in less extreme events, e.g. fewer spring freezes (Fig. 6) and a decreased number of extreme temperature events (Table 4).

The doubled climate variability scenarios represent the most extreme climate scenarios modeled. In addition, a doubling of current or future variability conditions is probably at the maximum limit of likely changes in climate variability. As such, these doubled variability scenarios probably represent the most extreme variability changes that might occur by 2050. Under the doubled variability scenarios, particularly the doubled variability HadCM2-GHG scenario, the greatest decreases in maize yields for long-season maize are found. Medium-season and short-season maize also experience large decreases in yield under these scenarios. The doubled variability scenario also results in highly variable year-to-year variability in maize yields across the 10 years modeled and studied. These results are in accordance with those found by other research groups, and are not surprising given the high incidence of days with extreme temperatures, compared to the halved variability scenarios (Table 4). When evaluating all six future climate scenarios in terms of their impacts on midwestern maize yields it is quite evident that the most detrimental agricultural impacts would arise from a future climate similar to the HadCM2-GHG doubled variability scenario.

More extreme weather events and increased variability of the weather will result in lower maize yields. Phillips et al. (1996) studied climate impacts on crop yields in the United States and found that changes in variability affected mean yields less than changes in mean climate, but did affect changes in inter-annual yield variability. Mearns et al. (1996, 1997) found that increases in climate variability, on a scale of doubling current variability, resulted in substantially decreased crop yields for wheat. In addition, they found decreased variability to have little effect on mean yield. Wolf et al. (1996) and Semenov et al. (1996) found that higher temperatures in Rothamsted, UK and in Seville, Spain, resulted in lower grain yields for spring wheat. In addition, a doubling of temperature variability resulted in an additional decrease in yield (using the models CERES, AFRCWHEAT and NWHEAT,

but not for SIRIUS which had no change) across all sites, which was related to an increased number of days at sub-optimal temperatures. For the same locations Semenov and Barrow, (1997) found that when changes in climate variability are included in a climate change analysis the results found are quite different. For wheat yields, a decrease in yield of 20% was observed when variability was doubled. Again, these results are similar to those reported in this research.

4.5. Potential adaptations to climatic change

Another important area of research concerns possible adaptation strategies to climate change and the effects of those strategies. The most obvious adaptations identified in this research are (1) the development of a more heat tolerant hybrid of long-season maize and (2) switching from maize (a C4 crop) to soybeans (a C3 crop) to take advantage of increased atmospheric CO_2 concentrations promoting increased growth and greater tolerances for hot temperatures (although how realistic this may be will be dependent on market factors). In fact, increased heat tolerance in short and medium-season maize varieties may provide the opportunity to manipulate planting dates of these hybrids and provide adaptation equal or superior to adaptation of long term varieties under some conditions, which is illustrated by the use of shorter season maize varieties rather than sorghum in recent years in the southwestern United States. Under increased climate variability and increased 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.

5. Conclusions

Our primary conclusions are:
- A lengthened growing season, dominated by a central period of high maximum daily temperatures, is a critical inhibitor to maize yields. Late spring and early fall frosts do not affect maize yields.

- The north-south temperature gradient in the midwestern Great Lakes states is extremely important in influencing patterns of maize yield under future climate conditions.
- Climate variability is a significant factor influencing maize yields because increased climate variability results in the largest decreases in future maize yields.

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. Continuing research will incorporate crop modeling of soybeans (DSSAT SOYGRO) and wheat (DSSAT CERES-wheat), both in terms of the potential mean changes in future climate and the potential changes in climate variability. These results will be 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 are fed back into the crop model for further adjustment to crop production modeling. This will allow the development of farm level strategies to be created and then tested by running back through the model scenarios with the adaptations incorporated.

The approach taken in this research examines adaptation at the farm level. Other research has examined agricultural response to climate change primarily on a regional or national basis. Both are important. However, 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 reality. This research hopes to provide the basis for strategic planning and risk management by farmers and the agricultural infrastructure to better adapt to changing conditions.

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