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Climate change impacts on soil erosion in Midwest United States with changes in crop management

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Abstract

This study investigates potential changes in erosion rates in the Midwestern United States under climate change, including the adaptation of crop management to climate change. Previous studies of erosion under climate change have not taken into account farmer choices of crop rotations or planting dates, which will adjust to compensate for climate change. In this study, changes in management were assigned based on previous studies of crop yield, optimal planting date, and most profitable rotations under climate change in the Midwestern United States. Those studies predicted future shifts from maize and wheat to soybeans based on price and yield advantages to soybeans. In the results of our simulations, for 10 of 11 regions of the study area runoff increased from +10% to +310%, and soil loss increased from +33% to +274%, in 2040–2059 relative to 1990–1999. Soil loss changes were more variable compared to studies that did not take into account changes in management. Increased precipitation and decreasing cover from temperature-stressed maize were important factors in the results. The soil erosion model appeared to underestimate the impact of change in crop type, particularly to soybeans, meaning that erosion increases could be even higher than simulated. This research shows that future crop management changes due to climate and economics can affect the magnitude of erosional impacts beyond that which would be predicted from direct climate change

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alone. Prediction of future soil erosion can help in the management of valuable cropland and suggest the need for continually changing soil conservation strategies.

Keywords: Soil erosion; Climate change; Runoff; Land management; Agriculture; Water Erosion Prediction Project

1. Introduction

The consensus of atmospheric scientists is that climate change is occurring, both in terms of air temperature and precipitation. For instance, the year 1998 was likely the warmest of the last 1000 years in the Northern Hemisphere (IPCC, 2001), the year 2001 was second warmest on record (NCDC, 2002), and globally 9 of the 10 warmest years since 1860 have occurred since 1990 (WMO, 2001). Karl and Knight (1998) found that from 1910 to 1996, total precipitation over the contiguous U.S. increased, and 53% of the increase came from the upper 10% of precipitation events (the most intense precipitation). The percent of precipitation coming from 50-mm-or-more rain days also increased. Mean streamflow in U.S. watersheds also increased by approximately 1/6 from 1939 to 1999, and has been related to increasing precipitation (Groisman et al., 2001). Summarizing from over 30 climate and soil erosion related studies for the U.S., SWCS (2003) determined that the research pointed to increasing soil erosion and runoff in the future. They determined that the potential impacts were serious enough to warrant increased attention by conservationists on changing policies to prepare for the anticipated impacts of more severe erosion and runoff on soil and water resources.

Increasing air temperatures affect soil erosion indirectly in several ways. Warmer temperatures mean faster accumulation of the necessary growing degree-days for crop maturity, which can increase biomass production rates. In other cases warmer temperatures can limit crop production because of excessive temperatures (Pruski and Nearing, 2002a,b). Temperature also impacts microbial activity levels, and hence residue decomposition rates. The level of carbon dioxide in the air also has a direct impact on the amount of biomass produced by various crops via direct CO_2 fertilization effects (Stockle et al., 1992). Such biomass changes affect canopy and ground residue cover, which affect erosion rates. Increased CO_2 can also enhance stomatal resistance, suppress transpiration, and lead to a moister soil, conducive to greater runoff-induced erosion (Schulze, 2000). Temperature can also influence evapo-transpiration rates, which impact soil moisture, which in turn may influence infiltration and runoff amounts and rates (Pruski and Nearing, 2002b).

Climate changes are also likely to be accompanied by changes in crop management, as farmers adapt their management practices to the new climate (Southworth et al., 2000, 2002a,b,c; Pfeifer and Habeck, 2002; Pfeifer et al., 2002). For instance, decreased crop yields may lead the farmer to plant a new crop, or farmers may change planting dates of maize to take advantage of increased warmth or to avoid high temperatures during silking. Farmers may also plant crop varieties of different maturity type, thus affecting the timing and duration of soil cover. All of these changes in management affect the impacts of climate change on erosion, but have so far received little attention in the literature.

Several researchers have examined erosion under climate change without taking into account farmer adaptation. Favis-Mortlock and Boardman (1995), using the Erosion Productivity Impact Calculator (EPIC) model (Williams and Sharpley, 1989), found a 7% increase in precipitation could lead to a 26% increase in erosion in the United Kingdom. Lee et al. (1996), also applying EPIC, found that for the U.S. Corn Belt, a 20% precipitation increase gave a predicted 37% increase in erosion and a 40% increase in runoff. Panagoulia and Dimou (1997) predicted increases in both the length and frequency of flood episodes (double and triple average streamflow) in Greece, based on precipitation outputs from the GISS climate change model, which they linked to possible increased bed and bank erosion. Schulze (2000), using the CERES-Maize and ACRU models, predicted a 10% increase in precipitation would lead to a 20–40% increase in runoff in South Africa. With continuous soybeans in Brazil, Favis-Mortlock and Guerra (1999) predicted a −9% to +55% change in sediment yield for the year 2050 from three climate models, with the Hadley Centre climate model (HadCM2) showing a 22–33% increase in mean annual sediment yield with a 2% increase in annual precipitation, and monthly sediment yield increasing by up to 103%. Nearing (2001) predicted significant changes in mean annual erosivity over the U.S. for the 21st century using output from both the Canadian global coupled climate model (CGCM1) and the revised Hadley Centre climate model (HadCM3).

Pruski and Nearing (2002a) used HadCM3 model predictions coupled with the Water Erosion Prediction Project-Carbon Dioxide (WEPP-CO_2) model (Flanagan and Nearing, 1995; Favis-Mortlock and Savabi, 1996; Nearing et al., 1989), and determined soil loss and runoff rates for the 21st century for eight locations in the United States. Their results indicated that in every case where precipitation was predicted to increase significantly, erosion increased significantly. In the locations where decreases in precipitation were predicted, erosion decreased in some cases and increased in others. Cases of predicted erosion increasing where precipitation decreased were attributed to large reductions in crop biomass production levels. These are prime examples where farmer adaptation should be accounted for. It is unlikely that a farmer will continue to grow a crop if production levels decrease greatly.

So far, few studies of erosion under climate change have looked at changes in crop management. This is important, because the impacts of management practices on erosion can be greater than the impacts of precipitation or air temperature, and many farmers will likely change crop rotations during this century. In South Africa, Schulze (2000) found with the ACRU model that time evolution of land cover significantly changed the rainfall–runoff relationship, from a combination of agricultural and urban land use changes. Focusing on cropland specifically, Schulze noted that changes in tillage type, planting date, and plant density could have a larger influence on hydrological responses than the conversion to another crop. In Denmark, Leek and Olsen (2000) found the proportion of annual erosivity contributed in the month of September to increase from 8% to 17%, as precipitation increased by 24–78% over the period of record. Government-mandated changes in cropping to autumn cereals over this period increased the percentage of bare soil in Denmark during this month, resulting in an intensified risk of erosion from the combination of climate change and crop management change.

In Ohio, USA, West and Wali (2002) found with the U.K. Meteorological Office GCM and the REM model (calibrating its empirical soil erosion component to 15 plots) that mined areas reclaimed with grassland or hayland would benefit from decreasing sediment yield under climate change (to the year 2050), related to increased biomass and surface litter from enhanced carbon dioxide levels. In northern China, Gao et al. (2002) found that 40 years of historical climate change alone would have decreased water erosion, but land use changes from grasslands to dry crop fields more than compensated for climate, increasing water erosion by at least a factor of eight, and intensifying the already increased wind erosion associated with rising air temperature.

In this study, changes in future crop management are taken into account, in addition to changes in climate, to investigate impacts of climate change on erosion in the Midwestern United States. Crops included maize (*Zea mays* L.), soybeans (*Glycine max* Merrill), and wheat (*Triticum aestivum* L.). The investigation was performed using the results of the yield and market profitability studies conducted by Southworth et al. (2000, 2002a,b,c), Pfeifer and Habeck (2002) and Pfeifer et al., (2002). Soil loss and runoff were then predicted with an erosion model and a climate model for 2040–2059, and results were compared to crop and climate conditions for 1990–1999. Economically viable crop rotations and optimal planting dates were used for erosion simulations under future climate scenarios.

2. Materials and methods

2.1. Study area and time period

The study area was five states of the Midwestern U.S.: Illinois, Indiana, Michigan, Ohio, and Wisconsin. These were divided into 11 regions (Fig. 1), as used by Southworth et al. (2000), corresponding roughly to the Land Resource Regions of the Natural Resources Conservation Service (NRCS). In the simulation of soil erosion and climate, the years 1990–1999 were considered for baseline conditions, while 2040–2059 were used for future climate change.

2.2. Crop rotations

The crops accounted for in this study were maize, soybeans, and wheat. In 2001, the area planted in maize, soybeans, and winter wheat comprised 87% of the non-idle cropland in the study region (USDA-NASS, 2002). Baseline conditions were represented with current crop rotations (Table 1), which came from a database developed by the NRCS (Natural Resources Conservation Service) (Weesies, 2000) for the Revised Universal Soil Loss Equation (Renard et al., 1997). The Revised Universal Soil Loss Equation database was based on information from the National Agricultural Statistics Service, NRCS records of cropping rotations, and university extension bulletins. This information was supplemented with farm survey information collected for a previous study (Pfeifer and Habeck, 2002; Pfeifer et al., 2002). Percent area of each crop rotation was calculated from Wu's (2000) analysis of state-level data from NRCS' 1992 National Resources Inventory.

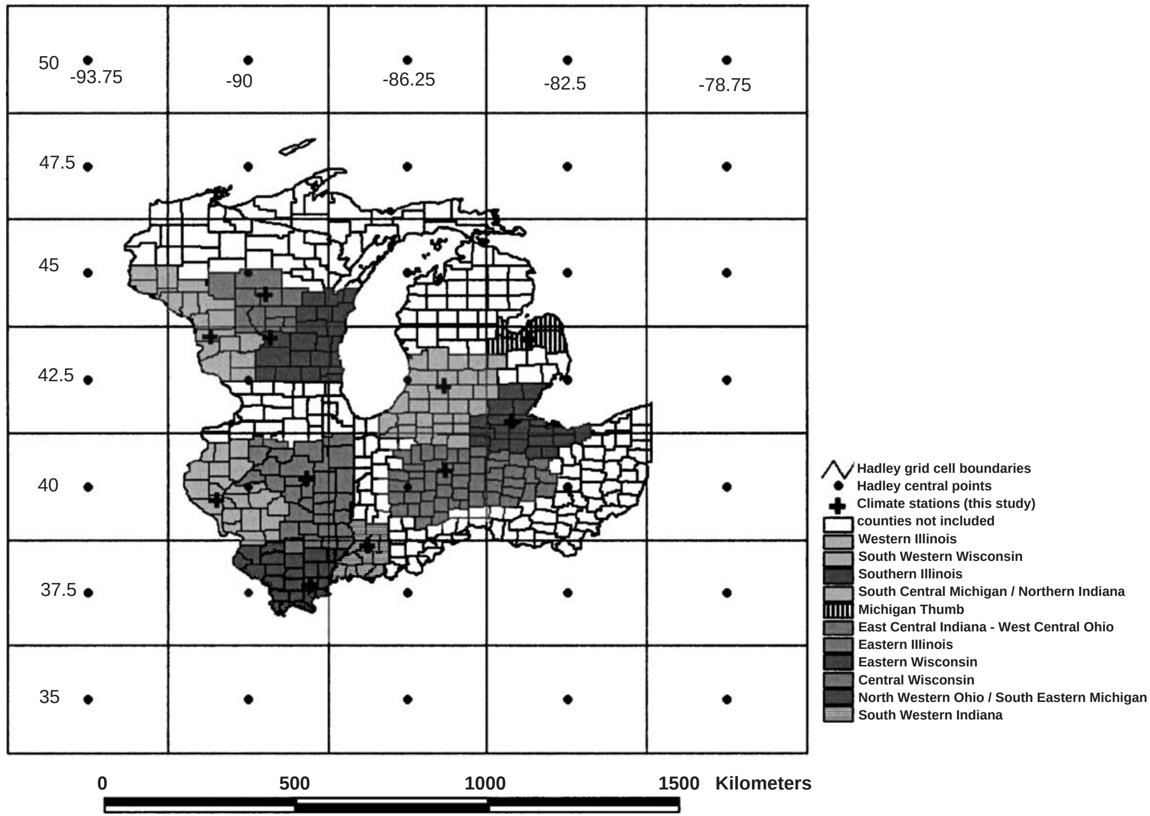

Fig. 1. Eleven regions used in this study (after Southworth et al., 2000), overlain with Hadley Centre model grid latitudes and longitudes (from DKRZ, 2001).

Table 1
Baseline-climate and future-climate crop rotations used, and percentage of total cropped area assumed, for agricultural regions of the Midwestern U.S.

Agricultural region	Baseline crop rotations[a] (1990–1999)	Percent of acreage[b]	Future crop rotations[c] (2040–2059)	Percent of acreage[c]
Central Wisconsin[d]	Maize/soybean	100	Maize/soybean	95
			Soybean, continuous	5
East Central Indiana/ West Central Ohio	Maize/soybean	91	Maize/soybean	100
	Soybeans, continuous	7		
	Soybean/wheat (2-year)	2		
Eastern Illinois	Maize/soybean	79	Maize/soybean	100
	Maize/wheat/soybean (double-cropped)	20		
	Soybean/wheat (2-year)	1		
Eastern Wisconsin	Maize/soybean	94	Maize/soybean	95
	Wheat, continuous	6	Soybean, continuous	5
Michigan Thumb	Maize/soybean	87	Maize/soybean	65
	Wheat, continuous	13	Soybean, continuous	35
North Western Ohio/South Eastern Michigan	Maize/soybean	86	Maize/soybean	90
	Soybeans, continuous	9	Soybean, continuous	10
	Wheat, continuous	5		
South Central Michigan/ Northern Indiana	Maize/soybean	96	Soybean, continuous	100
	Wheat, continuous	4		
Southern Illinois	Maize, continuous	12	Maize/soybean	95
	Maize/soybean	69	Maize/wheat/soybean (double-cropped)	5
	Maize/wheat/soybean (double-cropped)	18		
	Soybean/wheat (2-year)	1		
South Western Indiana	Maize, continuous	19	Maize/soybean	100
	Maize/soybean	64		
	Maize/wheat/soybean (double-cropped)	17		
	Soybean/wheat (2-year)	1		
South Western Wisconsin	Maize/soybean	98	Maize/soybean	55
	Soybean/wheat (2-year)	2	Soybean, continuous	45
Western Illinois[d]	Maize/soybean	99	Maize/soybean	100
	Soybean/wheat (2-year)	1		

[a] Adapted from Weesies (2000).
[b] Calculated from Wu (2000)'s analysis of state-level data from the 1992 USDA-NRCS National Resources Inventory.
[c] Adapted from Pfeifer and Habeck (2002), who found these rotations to be profit optimizing from PC-LP economic analysis for 2050–2059 HadCM2-SUL climate.
[d] PC-LP analysis not performed on these regions by Pfeifer and Habeck (2002) because of earlier problems with DSSAT runs; profit optimal crops of an adjacent region were used (Eastern Wisconsin for Central Wisconsin, Eastern Illinois for Western Illinois).

Future crop rotations (Table 1) are the economically viable crops for the years 2050–2059 under future climate as determined Southworth et al. (2000, 2002a,b,c), who performed a series of studies to examine future yield changes and optimal planting dates under climate change in the Midwest, and Pfeifer and Habeck (2002), who expanded on these results to determine the most economically viable crop rotations for future farmers under climate change. To determine the most profitable future rotations they used the Purdue University Crop/Livestock Linear Programming model (PC/LP) (Dobbins et al., 1994) to model six crop rotations with various combinations of varieties. They assumed constant crop prices from the 1981–1990 average: \$94 per metric ton for maize, $\$220 \cdot \text{ton}^{-1}$ for soybeans, $\$118 \cdot \text{ton}^{-1}$ for wheat.

As part of their results, Pfeifer et al. (2002) also determined the optimum percent area for each crop rotation. They found an increase in the planted area of soybeans and a decrease in the area planted to wheat, as a maize–soybean rotation would continue to be profitable nearly everywhere, continuous soybeans would become profitable in several regions, and wheat would no longer be profitable in most regions (Table 1).

2.3. Planting and harvest dates

Current planting and harvest dates, used to represent baseline conditions (Table 2), came from the Revised Universal Soil Loss Equation database (Weesies, 2000),

Table 2
Baseline-climate and future-climate planting dates used in this study for agricultural regions of the Midwestern U.S.

Agricultural region	Baseline planting dates[a] (1990–1999)			Future planting dates[b] (2040–2059)		
	Maize	Soybeans	Wheat	Maize	Soybeans	Wheat
Central Wisconsin	May 10	May 25	–	May 3	Apr 12	–
East Central Indiana/ West Central Ohio	May 1	May 5–May 16	Oct 20	May 14	Apr 23	–
Eastern Illinois	Apr 25–May 1	May 15–Jun 24[c]	Oct 10–Oct 20	May 14	May 28	–
Eastern Wisconsin	May 10	May 25	Oct 1	May 3	Apr 12	–
Michigan Thumb	May 10	May 25	Oct 1	May 21	Apr 19–Apr 23	–
North Western Ohio/South Eastern Michigan	May 10	May 5–May 25	Oct 1	May 31	Apr 19	–
South Central Michigan/ Northern Indiana	May 10	May 25	Oct 1	–	Apr 19	–
Southern Illinois	Apr 22–May 1	May 5–Jun 24[c]	Oct 8–Oct 10	May 14	May 24–Jun 28*	Oct 2
South Western Indiana	Apr 25–May 1	May 5–Jun 22[c]	Oct 4–Oct 10	May 14	May 14	–
South Western Wisconsin	May 10	May 25	Oct 5	May 31	Apr 12–Apr 16	–
Western Illinois	May 1	May 15–May 16	Oct 20	May 3	May 24	–

[a] Adapted from Weesies (2000).
[b] Determined from crop simulations that had been performed by Southworth et al. (2000, 2002b,c). Except for double-cropped wheat and soybeans, dates were those that produced maximum yield from DSSAT crop simulations, prior to June 1.
[c] Double-cropped with wheat.

adapted to fit within the ranges of the U.S. Department of Agriculture-National Agricultural Statistics Service's "Usual Planting and Harvest Dates" (USDA-NASS, 1997). This was supplemented with dates for double-cropped soybeans and wheat from Tony Vyn and Ellsworth Christmas (Purdue University Department of Agronomy, personal communications, 8 March 2002). Future planting dates were based on the crop simulations of Southworth et al. (2000, 2002a,b,c). Future planting dates for maize depended on the relative yields from short season vs. medium season varieties, which led in many regions to a later optimal planting date for maize because of the relatively greater increase in yields for the medium season varieties (Southworth et al., 2002a). Similarly, predicted optimum soybean yields changes were cultivar dependent, with late- and mid-maturing varieties producing large yield increases in some areas.

2.4. Tillage

Tillage consisted of chisel ploughing followed by field cultivation before planting for both baseline and future conditions. Baseline tillage dates were based on the Weesies (2000) database. Future tillage dates were adjusted to the new planting dates, assuming the same number of days between tillage and planting.

2.5. Crop yields

Calibration of the erosion model for crop yields was done by changing the energy to biomass conversion factor in the crop growth model of WEPP. The crop growth model in WEPP is basically the same as that used in the EPIC model (Williams and Sharpley, 1989). The model includes the effects of temperature and moisture stresses on crop growth and yields, and hence is sensitive to climate (long-term) and weather (intra- and inter-annual) changes.

For current conditions, the erosion model was calibrated to match 1990–1999 dry yields, within 0.03 $kg \cdot m^{-2}$ (5 bushels per acre). These target yield values were calculated as the mean over all counties in each region, based on yield data from the National Agricultural Statistics Service ⟨ftp://www.nass.usda.gov/pub/nass/county/⟩, adjusting for standard moisture content.

For future conditions, the erosion model was calibrated to match expected yields for 2040–2059, to within 0.03 $kg \cdot m^{-2}$ or as close as possible. These expected yields were estimated by Southworth et al. (2000, 2002a,b,c) using the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 1999) yield simulations. In order to normalize yield changes for valid comparisons, the ratio of future yields (based on 2050–2059 HadCM2 climate) to baseline yields (based on current Vegetation/Ecosystem Modeling and Analysis Project [VEMAP] climate data) (Kittel et al., 1996) was multiplied by the 1990–1999 observed yields from the National Agricultural Statistics Service, to obtain the yield for 2040–2059. Baseline DSSAT simulations were based on current planting dates, and future DSSAT simulations were based on the yield-optimizing planting dates previously determined. Appropriate varieties (short, medium, or long season) were selected for each crop.

2.6. Climate modeling

For baseline conditions, 100-year simulations were performed with the CLIGEN climate generator (Nicks et al., 1995), version 5.109 (Meyer, 2001), for a representative climate station in each region, taken as close as possible to the interpolated data locations of the previous studies used. Each CLIGEN station had at least 32 years of record, from which monthly parameters were obtained. These parameters consisted of mean and standard deviation of maximum and minimum air temperature, mean and standard deviation of solar radiation, mean and standard deviation and skewness of precipitation per wet day, probability of a wet day given that the previous day was dry, probability of a wet day given that the previous day was wet, relative time to peak rainfall intensity, and maximum 30-minute precipitation.

For future climate, the Hadley Centre model HadCM3 (Gordon et al., 2000; Pope et al., 2000) was used, with the GGa1 (greenhouse gases) version (Viner, 2001), as applied to a mid-range greenhouse gas emissions scenario, IS95a (also called IS92a). The IS95a scenario assumes that global population doubles over the 21st century, total economic output is raised by a factor of 10, world energy growth is increased by a factor of 4, and the contribution of non-fossil-fuel energy sources increases from 10% to 40% of all energy (MacCracken et al., 2001). Carbon dioxide concentrations for this scenario came from Taylor et al. (1995). The appropriate model output files were obtained from the LINK project at ⟨http://www.cru.uea.ac.uk/link⟩.

To obtain climate inputs to the erosion simulations, the total change in precipitation indicated by the climate model was split halfway between a change in the number of rain days and the change in the precipitation per day, as recommended by Pruski and Nearing (2002b).

2.7. Erosion modeling

The Water Erosion Prediction Project-Carbon Dioxide (WEPP-CO_2) model (Favis-Mortlock and Savabi, 1996) was used for erosion modeling. WEPP-CO_2 is a modified form of WEPP (Nearing et al., 1989; Flanagan and Nearing, 1995), using the carbon dioxide–plant growth relationships from Stockle et al. (1992). Limitations of this model will be discussed in the Discussion section. All erosion simulations included two tillage events: chisel ploughing, then field cultivation, before planting. In each case, a constant S-shaped slope was used, with maximum 7% gradient at the mid-slope. Pruski and Nearing (2002a) showed that estimated relative changes in erosion (using WEPP-CO_2) as a function of climate change were not particularly sensitive to the hillslope gradient used in the simulations within a wide range of slopes tested.

Three soil types were used for each region (Table 3), reflecting where crops were actually grown, according to county Soil Surveys from the U.S. Department of Agriculture. Simulations were made with the crop types and rotations chosen from the previous economic study (Pfeifer and Habeck, 2002; Pfeifer et al., 2002), with the erosion model calibrated to future yields corresponding to optimal planting dates under climate change, as determined from crop modeling results of Southworth et al. (2000, 2002a,b,c), with harvest and tillage dates adjusted accordingly, and running the climate

Table 3
Soil types used for erosion modeling in this study

Agricultural region	Soil types used for erosion modeling[a]
Central Wisconsin	Kert silt loam
	Meadland loam
	Rozzellville loam
East Central Indiana/West Central Ohio	Blount silt loam
	Glynwood silt loam
	Pewamo clay loam
Eastern Illinois	Catlin silt loam
	Ipava silt loam
	Sable silty clay loam
Eastern Wisconsin	Dodge silt loam
	Mt. Carroll silt loam
	Seaton silt loam
Michigan Thumb	Guelph loam
	Londo loam
	Tappan loam
North Western Ohio/South Eastern Michigan	Fulton silt loam
	Latty silty clay loam
	Lenawee silty clay loam
South Central Michigan/Northern Indiana	Kalamazoo loam
	Riddles loam
	Sleeth loam
Southern Illinois	Hurst silt loam
	Patton silty clay loam
	Zipp silty clay
South Western Indiana	Alford silt loam
	Iva silt loam
	Ragsdale silt loam
South Western Wisconsin	Downs silt loam
	Fayette silt loam
	Worthen silt loam
Western Illinois	Atterberry silt loam
	Downs silt loam
	Tama silty clay loam

[a] Based on county Soil Surveys from U.S. Department of Agriculture, soils on which crops are successfully grown.

generator based on the HadCM3-GGa1 climate scenarios. Soil loss and runoff estimates for each region were taken from a weighted mean of the soil loss and runoff for each rotation, weighted according to the percentage of area expected under that rotation, and as an average for the three soils used at each location. In each case, the eight groupings of Pruski and Nearing (2002a) were used to separate directions of change among precipitation, runoff, and soil loss (see Table 4). Interactions between variables did not allow a complete separation of the effects of climate change and management, but a rough estimate of the relative contribution of each was obtained from examining WEPP-CO_2 runs with continuous soybeans and a maize–soybeans rotation.

Table 4
Precipitation, runoff, and erosion estimated for 1990–1999, and changes estimated for 2040–2059 with changes in crop management

Region	1990–1999				2040–2059				
	Crop rotations[a]	Precipitation (mm)	Runoff[b] (mm)	Soil loss[b] (tons · ha^{-1})	Crop rotations[a]	Change in precipitation (%)	Change in runoff[b] (%)	Change in soil loss[b] (%)	Group[c]
Central Wisconsin	(MS)	792.4	54.9	3.3	(MS, S)	0.5	53.8	150.0	1
East Central Indiana/West Central Ohio	(MS, S, SW)	889.2	85.6	3.8	(MS)	10.2	9.9	34.4	1
Eastern Illinois	(MS, MWS, SW)	867.5	117.8	6.3	(MS)	8.7	16.4	32.6	1
Eastern Wisconsin	(MS, W)	800.3	59.5	3.8	(MS, S)	−1.1	125.4	129.3	8
Michigan Thumb	(MS, W)	730.8	38.6	1.9	(MS, S)	14.2	49.2	105.0	1
North Western Ohio/South Eastern Michigan	(MS, S, W)	826.4	58.2	1.9	(MS, S)	13.8	309.5	273.7	1
South Central Michigan/ Northern Indiana	(MS, W)	885.6	49.6	3.5	(S)	6.8	−26.1	−3.0	7
Southern Illinois	(M, MS, MWS, SW)	1106.6	205.2	11.5	(MS, MWS)	9.6	18.6	37.5	1
South Western Indiana	(M, MS, MWS, SW)	1106.2	143.1	8.4	(MS)	8.4	6.3	18.2	1
South Western Wisconsin	(MS, SW)	802.9	97.8	5.5	(MS, S)	−2.1	120.8	147.2	8
Western Illinois	(MS, SW)	933.7	119.1	8.2	(MS)	7.9	7.7	18.9	1

[a] M = maize, S = soybeans, W = wheat; single letter = continuous crop, multiple letters = rotation.
[b] Runoff and soil loss are averaged over all crop rotations, averaged over all three soil types for each region. All changes are relative to baseline conditions (1990–1999).
[c] After Pruski and Nearing (2002a).

Group	Precipitation	Runoff	Soil loss
1	↑	↑	↑
2	↓	↓	↓
3	↑	↑	↓
4	↓	↓	↑
5	↑	↓	↑
6	↓	↑	↓
7	↑	↓	↓
8	↓	↑	↑

3. Results

3.1. Climate modeling

Eight of the 11 regions had over 5% increased predicted annual precipitation in 2040–2059 relative to the baseline (Table 4). Every region showed a decrease in July precipitation and an increase in October precipitation for 2040–2059 relative to the baseline time period (monthly data not presented).

3.2. Erosion modeling

Runoff and soil loss increased in the future scenarios compared to the baseline. WEPP-CO_2 predicted increases in 10 of the 11 regions of +10% to +274% in soil loss, with a wider range of increase in runoff (Table 4). Soil loss and runoff patterns frequently followed those of annual precipitation. In regions where precipitation, runoff, and soil loss all increased, i.e., group 1 of Pruski and Nearing's (2002b) groupings (Table 4), the direct effect of increasing rainfall probably played the key role in the increase of erosion. Wetter soil from rainfall means decreased infiltration rates due to decreased soil water suction and increased surface sealing, both of which may increase runoff rates and amounts. The greater runoff causes increased shear stress, which increases the detachment capability of the flow, and therefore increases erosion (Pruski and Nearing, 2002a). All of these processes are explicitly accounted for in the WEPP model.

Predicted maize yield decreased under climate change, which caused decreased predicted soil residue cover, which leads to increased erosion. In almost every case, predicted soybean yields were increasing while maize yields were decreasing. Changes in 2040–2059 yields at optimal planting dates were −31% to +18% for maize and +9% to +101% for soybeans relative to the baseline. The drop in maize yield appeared to lead to increased erosion even when precipitation decreased. In eastern Wisconsin, where predicted annual precipitation decreased but predicted runoff and soil loss increased (Pruski and Nearing's group 8), predicted July precipitation (important to maize's silking period) decreased, and predicted maize yield decreased (Table 4). Therefore, the predicted loss of crop cover undoubtedly caused predicted increase of runoff and soil loss.

3.3. Comparison of results from previous studies

The erosion simulations had more widely varying results than other studies not taking into account changes in management. The increases in erosion were greater than those predicted with the EPIC model for the U.K. by Favis-Mortlock and Boardman (1995) and Favis-Mortlock and Savabi (1996), and with the WEPP-CO_2 model for eight locations in the United States (Pruski and Nearing, 2002b). In contrast with Lee et al. (1996), who found (using EPIC) for the U.S. Corn Belt a 20% increase in precipitation to be associated with a 37–40% increase in runoff and soil loss, this study found a 10–20% increase in annual precipitation to be associated with up to an approximate +300% change in runoff and soil loss (Table 4). It made sense that the results of this study would be more widely ranging because of the variation in management and planting dates in addition to climate.

4. Discussion

Soil properties, changes in the timing of precipitation, and changes in planting date may intensify, lessen, or reverse the general pattern of changes in soil loss and runoff. For example, soils with higher hydraulic conductivity may show a greater percentage increase in runoff as a function of increased precipitation than soils with lower conductivities. Earlier soybean planting dates provide crop cover during the spring. May and July modeled precipitation was less for 2040–2059 for east central Indiana compared to the baseline time, while the relative increase in August precipitation was greater than the average for the year. Thus, the simulated greater rainfall occurred when the soil was not protected from runoff by crop canopy cover as it had been during the baseline scenarios.

The results of sensitivity testing with planting date showed that soil loss increased substantially with later planting dates for maize and soybeans, but not for wheat. For southern Illinois, where runoff and soil loss increased (Table 4), examination of monthly soil loss showed a clear May peak which increased significantly from the baseline to 2040–2059. Maize was being planted 2 weeks later (May 14), soybeans 1 week later (May 24), than 1990–1999, so the delayed planting date caused a longer time for soil to remain uncovered during April and May rains, which intensified predicted soil loss. Favis-Mortlock and Guerra (1999) found a similar importance of timing, with increased runoff and consequent risk of erosion early in the growing season when the soybean crop did not yet cover the soil.

Increases in future runoff and soil loss would likely have been even larger if the effect of changing from maize–soybeans to continuous soybeans could have been more accurately modeled. Using the same climate input with two different rotations (Table 5) showed that the change from maize–soybeans to continuous soybeans could either increase or decrease predicted runoff and soil loss, from -23% to $+23\%$ for the future scenarios. However, erosion research literature has shown that continuous soybeans will undoubtedly increase soil loss relative to rotational soybeans with maize (Laflen and Moldenhauer, 1979; Laflen and Colvin, 1981). Comparing results for continuous soybeans and maize–soybean rotation for two sample regions for each time period showed that while continuous soybeans had less canopy cover than maize–soybeans, continuous soybeans had greater ground cover, when averaged over the time periods studied. Thus, WEPP-CO_2 predicted a decrease in erosion because of increased soybean ground cover. The reason that WEPP-CO_2 did not accurately model the soybean cover effect on erosion is because the functions in the model do not differentiate the effectiveness of residue type on erosion impact.

Given that a decrease in soil loss for continuous soybeans would not be expected, and the soil loss estimates in Table 4 could actually underestimate soil loss increases. South central Michigan/northern Indiana was the only region to have only soybeans without maize, and modeled future soybean yields there increased markedly (over 90%). This was also the only region to consistently show a decrease in future soil loss. As a consequence, even in the one region with a predicted decrease in soil loss, the result is in doubt because the soybeans should probably have resulted in greater predicted erosion. The change in rotation made the greatest contribution to soil loss and runoff changes in this region, relative to the change in climate, yield, and planting date. In the other regions, the

Table 5
Separate effects of climate change (interacting with yield and planting date) and management on runoff and soil loss, for 1990–1999 and 2040–2059, climates with changes in crop management

Region	Effect of climate change	Same rotation under different climates: percent change relative to 1990–1999 for same rotation		Effect of management	Same climate under different rotations: percent change for continuous soybeans relative to maize–soybeans for same climate			
	Rotation[a]	2040–2059		Rotation[a]	1990–1999		2040–2059	
		% Change in runoff	% Change in soil loss		% Change in runoff	% Change in soil loss	% Change in runoff	% Change in soil loss
Central Wisconsin	(MS)	54.1	147.2	from (MS) to (S)	–	–	−3.0	23.0
East Central Indiana/ West Central Ohio	(MS)	10.3	37.8	from (MS) to (S)	5.7	51.3	–	–
Eastern Illinois	(MS)	17.6	26.7	from (MS) to (S)	–	–	–	–
Eastern Wisconsin	(MS)	124.1	118.0	from (MS) to (S)	–	–	−0.7	10.1
Michigan Thumb	(MS)	49.4	98.6	from (MS) to (S)	–	–	−6.2	−5.2
North Western Ohio/South Eastern Michigan	(MS)	309.6	290.8	from (MS) to (S)	7.0	80.2	0.6	−7.5
South Central Michigan/ Northern Indiana	(MS)[b]	−7.5	−23.3	from (MS)[b] to (S)	–	–	−11.4	9.8
Southern Illinois	(MS)	19.4	26.4	from (MS) to (S)	–	–	–	–
South Western Indiana	(MS)	8.0	6.4	from (MS) to (S)	–	–	–	–
South Western Wisconsin	(MS)	116.7	131.4	from (MS) to (S)	–	–	4.4	13.7
Western Illinois	(MS)	7.7	18.2	from (MS) to (S)	–	–	–	–

Soil loss and runoff estimates are the average of all three soil types (Table 2) of each region.
[a] MS = maize–soybean rotation; S = continuous soybeans.
[b] Extra runs made for MS in 2040–2059 even though zero acreage predicted for this rotation.

contribution of changing climate/yield/planting date to soil erosion was over twice as much as that of the change in rotation.

The loss of wheat in rotations also probably contributed to the predicted increase in soil erosion. Despite the relatively small area of wheat, it may be expected that the loss of wheat from rotations had an impact on soil loss comparable to that of the adoption of continuous soybeans (Laflen and Colvin, 1981; Edwards and Owens, 1991). In a separate set of erosion simulations that were performed by applying the baseline conditions, calibrations, crop rotations, and planting dates to future climate conditions, soil loss under continuous wheat was 1/6 to 1/3 that of continuous soybeans (data not shown).

4.1. Uncertainty of results

Many factors contribute to the uncertainty of these results, including uncertainty in farmer response, the possibility of development of new, as yet unknown, plant cultivars, the uncertainty of the climate model results used to make the predictions, and our assumptions in the study.

Unknown factors that could affect the accuracy of model predictions include the nature of a producer's decision-making process and the necessary criteria (in terms of, for instance, decreased crop yield) that lead the producer to change crop type or planting date. Also, it is not yet known how future varieties, including new cultivars responsive to increased carbon dioxide, might improve yields beyond what can be modeled from calibration data or change a crop system's erosional response.

The fertilization effect of increased carbon dioxide on crop yield is another area of major uncertainty. The carbon dioxide-yield component of WEPP-CO_2 may be too simple for the complexity of real crop responses (Favis-Mortlock and Guerra, 1999), and its yield sensitivity to CO_2 fertilization is greater than other models and observations (Favis-Mortlock and Savabi, 1996). However, CO_2 fertilization effects are uncertain for other crop models as well (Schulze, 2000). For this study, a possible overestimation of C3 plants' (soybeans, wheat) crop yield with WEPP-CO_2 would tend to result in an underestimation of soil erosion for continuous soybeans. Therefore, the absolute magnitude of soil erosion could be somewhat greater than modeled.

The prediction of future crop management is a key element of uncertainty that could benefit from more research studies in this area. Price and the substitutability of crops are two controlling factors of future crop rotations. Future crop prices determine the relative desirability of growing crops. For the 1981–1990 prices Pfeifer and Habeck (2002) used, soybeans were twice as valuable as maize for the same volume, and were 86% more valuable than wheat, so (all else being equal) soybeans were more profitable to grow. Consequently, there was very little wheat in the economically viable crop rotations of future years, and no continuous maize. As of writing, the Indiana Agricultural Statistics Service showed that the soybean price was still more than double the price of maize, and higher than wheat. A future change in relative prices could lead to vastly different rotations and areas of each crop grown, which would impact erosion rates.

It is also uncertain whether Midwest U.S. farmers would adapt to continuous soybeans, as the economic modeling indicates. This rotation has little history behind it to recommend it, as producers have been reluctant to plant even a second year of soybeans in succession.

Three main reasons for not planting continuous soybeans are crop disease problems from monoculture cropping, a breakdown of soil aggregates associated with low root mass, and a relative lack of soil cover both during and after the growing season. In Brazil, Favis-Mortlock and Guerra (1999) found that 10 years of continuous soybeans stripped the soils of their A horizon and created gullying and crusting problems. However, the soybean yield increases predicted by the crop model under climate change are unprecedented in history, and are coupled with maize yield decreases, so it is unknown whether the economics could outweigh agronomic considerations for producers.

New crop markets could change which crops can be substituted under climate change. Although the maize–soybeans–wheat stronghold in the eastern U.S. Corn Belt has been maintained for many years, a substantial decrease in maize yield could alter it. Barley and cotton, for instance, performed very well in simulations using Hadley and Canadian Climate Centre models of future climate, by the National Assessment Synthesis Team (2000), and could enter the Midwest U.S. market. Irrigation could also become a factor, if precipitation stress leads producers to supplement rainfall. However, Southworth et al. (2002a) studied soybean and maize irrigation across the study region, and found that under maximum allowable irrigation for future climate, yields increased only 5% for maize, and up to 15–20% for soybeans (Pfeifer and Habeck, 2002). Water was not the limiting factor, and maximum temperature limited plant growth.

The results of this study are further dependent on the climate model. Although models are becoming more accurate, small regional scale prediction is subject to disagreement between models. Nearing (2001) found that the Canadian global coupled model showed increased erosivity over California for the year 2080, while the Hadley Centre model showed a decrease. Addition of another model to such analyses would help validate the results. Regional differences among models suggest that future improvements are needed to make them more reliable.

Other limitations of this study include the reliance upon results of earlier studies, which were already completed and not available to modify; using rotations based on a single set of relative crop prices; a single slope shape and angle; the restriction to only three crops; and the inability to consider pests or diseases in the crop model. Consideration of these factors would require much more extensive research. Also, the crop simulation models showed optimal maize planting dates later than current accepted practices; these later dates were not used, but led to the use of a June 1 cutoff for maize planting. More extensive calibration data would be required to test the validity of this result.

Similar studies in other regions such as in rangelands or in cotton growing areas would be valuable. Future studies might also examine multiple types of tillage and consider different slopes. Consideration of pests and diseases will require more extensive study.

5. Conclusions

Soil loss and runoff were predicted to increase throughout nearly all of the eastern U.S. Corn Belt for the period from 1990–1999 to 2040–2059 based on a series of simulations using the Water Erosion Prediction Project-Carbon Dioxide (WEPP-CO_2) erosion model with climate from the Hadley Centre model (HadCM3-GGa1) and yield prediction from a previous climate change study using the Decision Support System for Agrotechnology Transfer (DSSAT). The erosion simulations included a prediction of changes in future crop management under climate change. This involved the most profitable crop rotations as determined from a previous economic study. These future changes in management involved mainly an increase in soybean crop area and a decrease in the area of planted wheat. The erosion modeling showed that soil loss and runoff could increase significantly in all but one region of the eastern U.S. Corn Belt in 2040–2059 relative to the period 1990–1999.

Results were comparable to other studies of erosion under climate change for the same area, but had more variation because of the different rotations, regions, and planting dates being considered. This suggested that the change in management could have a significant effect on the accuracy of predicted soil loss under climate change.

Increases in soil losses were sometimes associated with increased precipitation, and sometimes more likely associated with decreased crop cover from lowered maize yields, brought about by extreme heat or drought under climate change. Planting date changes had an additional effect on erosion, e.g., later planting dates for maize increased soil loss.

The results relied heavily on the simulation of management under future climate, which in turn relied on relative prices between viable alternative crops and the relationship of climate with crop yield. The future crop rotations reflected the combined effect of soybeans having more positive yield effects from climate change than maize, and soybeans being more highly priced than maize or wheat. Growing maize and soybeans instead of wheat is predicted to lead to increased erosion. The single region that consistently showed a decrease in runoff and soil loss was also the only region with just soybeans in the future crop mix. WEPP-CO_2 showed less soil loss and runoff with continuous soybeans than with a maize–soybean rotation, while our current understanding of the system would suggest the opposite. Therefore, even in this region, runoff and soil loss may have been underestimated.

Many assumptions were required to assess management under future climate change. To achieve a wider range of results, additional testing with different tillage types, relative crop prices, slopes, and climate models is recommended. However, the results suggest potential erosion increases in the rest of the 21st century, and suggest more research needs to be done to identify management adaptations to climate change.

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