Expected climate change impacts on soil erosion rates: A review

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ABSTRACT: Global warming is expected to lead to a more vigorous hydrological cycle, including more total rainfall and more frequent high intensity rainfall events. Rainfall amounts and intensities increased on average in the United States during the 20th century, and according to climate change models they are expected to continue to increase during the 21st century. These rainfall changes, along with expected changes in temperature, solar radiation, and atmospheric CO_2 concentrations, will have significant impacts on soil erosion rates. The processes involved in the impact of climate change on soil erosion by water are complex, involving changes in rainfall amounts and intensities, number of days of precipitation, ratio of rain to snow, plant biomass production, plant residue decomposition rates, soil microbial activity, evapotranspiration rates, and shifts in land use necessary to accommodate a new climatic regime. This paper reviews several recent studies conducted by the authors that address the potential effects of climate change on soil erosion rates. The results show cause for concern. Rainfall erosivity levels may be on the rise across much of the United States. Where rainfall amounts increase, erosion and runoff will increase at an even greater rate: the ratio of erosion increase to annual rainfall increase is on the order of 1.7. Even in cases where annual rainfall would decrease, system feedbacks related to decreased biomass production could lead to greater susceptibility of the soil to erode. Results also show how farmers' response to climate change can potentially exacerbate, or ameliorate, the changes in erosion rates expected.

Keywords: Climate change, runoff, sediment, soil erosion, soil loss

The consensus of atmospheric scientists is that climate change is occurring, both in terms of global air temperature and precipitation patterns. For instance, the year 1998 was likely the warmest of the last 1000 years in the Northern Hemisphere (IPCC, 2001), and the year 2001 was second warmest on record (NCDC, 2002). Globally, 9 of the 10 warmest years since 1860 have occurred since 1990 (WMO, 2001). Warmer atmospheric temperatures associated with greenhouse warming are expected to lead to a more vigorous hydrological cycle, including more extreme rainfall events (IPCC, 1995). Karl and Knight (1998) reported that from 1910 to 1996 total precipitation over the contiguous U.S. increased, and that 53% of the increase came from the upper 10% of precipitation events (the most intense precipitation). The percent of precipitation coming from days of precipitation in excess of 50 mm has also increased significantly.

Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, the most direct of which is the change in the erosive power of rainfall (Nearing, 2001; Pruski and Nearing, 2002a). A second dominant pathway of influence by climate change on erosion rates is through changes in plant biomass. The mechanisms by which climate changes affect biomass, and by which biomass changes impact runoff and erosion, are complex (Pruski and Nearing, 2002b) For example, anthropogenic increases in atmospheric carbon dioxide concentrations cause increases in plant production rates and changes in plant transpiration rates (Rosenzweig and Hillel, 1998), which translate to an increase in soil surface canopy cover and, more importantly, biolo-gical ground cover. On the other hand, increases in soil and air temperature and moisture will likely cause faster rates of residue decomposition due to an increase in microbial activity. More precipitation may also lead to an increase in biomass production. Higher temperatures may translate to higher evaporation rates, while more rainfall would tend to lead to higher soil moisture levels.

Temperature changes also affect biomass production levels and rates in complex ways. Corn biomass production may increase with increasing temperature, particularly if the growing season is extended, but then may decrease because of temperature stresses as the temperature becomes too high (Rosenzweig and Hillel, 1998). Again, biomass changes impact soil surface cover, which greatly impacts erosion. Another potential impact of climate change is associated with the changes from snowfall to rainfall. If decreased days of snowfall translates correspondingly to increases in days of rainfall, erosion by storm runoff is liable to increase. Even changes in soil surface conditions, such as surface roughness, sealing, and crusting, may change with shifts in climate, hence impacting erosion rates.

A more complex, but perhaps dominant factor in the equation, is the potential for shifts in land use necessary to accommodate a new climatic regime (Williams et al., 1996). As farmers adapt cropping systems, the susceptibility of the soil to erosive forces will change. Farmer adaptation may range from shifts in planting, cultivation, and harvest dates to changes in crop type (Southworth et al., 2000, 2002a, b; Pfeifer and Habeck, 2002).

The purpose of this paper is to present and interpret the principal results of four recent studies conducted by the authors in order to show the potential impact of climate change on soil erosion rates, which in turn has significant implications for conservation planning. As a whole, these studies provide a good overview of both the mechanisms whereby climate change is expected to affect soil ero-

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sion rates and the magnitudes of change that we might expect from climate change. We will discuss first the effects and mechanisms whereby precipitation change itself influences erosion response, and then look at some case studies using output data from Global Circulation Models to assess more complicated interactions involving precipitation, biomass production, and other system factors. We will then overview a case study of potential impacts of farmers' response to climate change for the Midwestern United States.

In most of the studies discussed in this paper, the Water Erosion Prediction Project (WEPP) model was utilized (Flanagan and Nearing, 1995; Nearing et al., 1989). The WEPP model accounts for most of the processes and interactions whereby climate change impacts runoff and erosion. In the WEPP model, plant biomass production is influenced by changes in temperature and soil moisture, and the model was modified to include the effects of changes in atmospheric carbon dioxide concentrations on biomass production. Residue decomposition rates in the model are sensitive to soil moisture and temperature. Soil moisture is sensitive to rainfall inputs and evapo-transpiration rates, which are sensitive to air temperature. Infiltration rates are impacted by residue cover and soil consolidation. Canopy and ground cover are modeled as dynamic variables, and influence infiltration, runoff, and erosion in different and interactive ways. The model is well suited for studying the complex interactions involved in assessing climate change impacts on erosion.

The results of the studies on climate change and erosion show that the anticipated effects of climate change on both runoff and erosion are significant and important. The interactions involved are complex because of the many interactions between the processes involved. The trend for the United States is for increased erosion on average, with significant geographic heterogeneity. This has important implications for conservation programs.

Potential changes in rainfall erosivity

Rainfall erosivity is, in general terms, the ability or power of rain to cause soil loss. It is most generally thought of in terms of the R-factor in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), hence it was originally derived based on data from natural runoff plots located throughout the eastern part of the United States. It has since been found to be a robust parameter in many parts of the world (Larionov, 1993; Schwertmann et al., 1990; Yun et al., 2002). Rainfall erosivity is correlated to the product of total rainstorm energy and maximum 30 minute rainfall intensity during a storm (Wischmeier and Smith, 1978). The relationship first derived by Wischmeier and Smith is still used today in the Revised Universal Soil Loss Equation (Renard et al., 1997), which is the current technology applied in the United States for conservation planning and compliance. Studies using a physically-based, continuous simulation model of erosion have also substantiated the geographic trends of published R-factors for many parts of the United States, including western states (Baffaut et al., 1996).

Estimations of future climate change provided by Global Circulation Models (GCMs) do not provide the type of detailed storm information needed to directly calculate predicted R-factor changes. Hence, statistical relationships between monthly and annual precipitation and the R-factor must be used to analyze the GCM output relative to erosivity changes (Nearing, 2001).

Renard and Freimund (1994) evaluated erosivity at 155 locations within the continental United States, and developed statistical relationships between the R-factor and both total annual precipitation at the location and a modified Fournier coefficient (Fournier, 1960; Arnoldus, 1977), F, calculated from monthly rainfall amounts as:

$$F = \frac{\sum_{i=1}^{12} p_i^2}{P} \qquad [1]$$

where:
p_i (mm) = average monthly precipitation, and
P (mm) = average annual precipitation.

The derived relationships between R-factor and P developed by Renard and Freimund (1994) were:

$$\text{R-factor} = 0.04830P^{1.610} \quad (r^2 = 0.81) \qquad [2]$$

and

$$\text{R-factor} = 587.8-1.219P+0.004105P^2 \quad (r^2 = 0.73) \qquad [3]$$

and the relationships between R-factor and F were

$$\text{R-factor} = 0.7397F^{1.847} \quad (r^2 = 0.81) \qquad [4]$$

and

$$\text{R-factor} = 95.77-6.081F+0.04770F^2 \quad (r^2 = 0.75) \qquad [5]$$

where: the R-factor is in units of (MJ mm ha^{-1} $year^{-1}$). (Note that Equation 13 in the paper of Renard and Freimund (1994), which corresponds to Equation 4 in this paper, contained a misprint.) Equations 2 and 4 provided a better fit on the lower end of the data range, and Equations 3 and 5 fit better on the upper end; therefore Renard and Freimund (1994) recommended using Equation 2 when P was less than 850 mm and Equation 3 when P was greater than 850 mm. Likewise, they recommended using Equation 4 when F was less than 55 mm and *Equation 5 when* F was greater than 55 mm.

Using these relationships, precipitation output from GCMs can be analyzed for trends in R-factor changes. Nearing (2001) used output from two coupled Atmosphere-Ocean Global Climate Models, one developed by the U.K. Meteorological Office's Hadley Centre (Gordon et al., 2000; Pope et al., 2000; Wood et al., 1999) and the other from the Canadian Centre for Climate Modeling and Analysis (Boer et al., 2000; Reader and Boer, 1998; McFarlane et al., 1992).

Changes in rainfall erosivity for the two models were computed for two time intervals. In the first case, erosivity values from 2040 to 2059 were compared to those from 2000 to 2019, and in the second case erosivity values from 2080 to 2099 were compared to those from 2000 to 2019. Erosivity changes were computed in two ways: i) as a function of change in average annual precipitation for the twenty year periods using Equations 2 and 3, and ii) as a function of the Fournier coefficient for the twenty year periods using Equations 4 and 5.

Erosivity results calculated from the Hadley Centre model analyses indicated a general increase in rainfall erosivity over large parts of the eastern United States, including most of New England and the mid-Atlantic states as far south as Georgia, as well as a general increase across the northern states of the United States and southern Canada. Hadley Centre results also indicated a tendency for erosivity increases over parts of Arizona and New Mexico. Decreases in erosivity were indicated in other parts of the southwestern United States, including parts of California, Nevada, Utah, and western Arizona. Decreases were also shown over eastern Texas and a large portion of the southern central plains from Texas to Nebraska.

Table 1. Average magnitudes (absolute values) of erosivity change calculated for the United States during the 21st century (from Nearing, 2001).

	Average magnitude of change	
Climate model	40 Yr. time interval	80 Yr. time interval
	(%)	(%)
Hadley Centre	17	21
Canadian Centre	29	58

Erosivity results calculated from the Canadian Centre for Climate Modeling and Analysis model also showed an increase in erosivity across the northern United States, including New England, and southern Canada. The Canadian Centre model results also indicated a reduction in erosivity across much of the southern plains, again from Texas to Nebraska. The Canadian Centre model did not show consistent results for the southeastern United States. Results of the computations using annual precipitation indicated changes in parts of the southeast United States tending toward lower erosivity, while results of the erosivity computations using the Fournier coefficient indicated the possibility of little change or increases over part of that region. This suggests a change in the distribution of monthly rainfall patterns through the year.

Erosivity results calculated from the Canadian Centre for Climate Modeling and Analysis show major differences compared to the results from the Hadley results in the southwestern United States, including California, Arizona, Nevada, and Utah. Whereas the Hadley Centre model results suggest a definite trend towards lower erosivity in this area, the Canadian Centre for Climate Modeling and Analysis model results suggest a definite, strong trend toward greater erosivity through the 21st century in this area.

The overall results indicated that changes may be significant, though varying widely from region to region. From the most conservative of the four methods used, Nearing (2001) estimated that the average magnitude of change (as either increase or decrease) over the country as a whole would be 17% (Table 1) different from current erosivity at the location. At the other extreme, one of the four methods used predicted an average magnitude of change of 58% from current conditions. Regardless of which method is used, the results suggest that changes in erosivity will be geographically variable and quite large at certain locations.

Effects of precipitation changes on runoff and erosion

Changes in total rainfall amount at a given location may occur in different ways, primarily either because of an increase in the number of precipitation (wet) days or because of increased average precipitation per wet day. Corresponding to a change in the average amount of rainfall during wet days is generally a change in rainfall intensities. In other words, the distribution of rainfall amounts per day is generally correlated to the distribution of rainfall intensities. These two factors of rainfall change will influence runoff and erosion in different ways.

Pruski and Nearing (2002a) conducted a modeling study specifically to assess the relative influence of these two mechanisms of rainfall change on runoff and erosion. They used the WEPP model to simulate runoff and erosion using a combination of three soil classes (silt loam, sandy loam, and clay), three slope gradients, four cropping systems, and three locations (Corvallis, Oregon; Temple, Texas; and West Lafayette, Indiana). The model was calibrated to provide reasonable cropping, soil moisture, erosion, and runoff responses for the 108 different (3x3x4x3) scenarios.

Precipitation inputs for the scenarios were adjusted in the following way. Total annual precipitation was modified by 0%, ± 10%, and ± 20% relative to the historical values for each of the three locations studied. The relative amount of rainfall per month was maintained at historical (baseline) levels. The modifications were made in three ways: 1) The number of days of precipitation was increased or decreased by the desired amount (0%, ± 10%, and ± 20%), with the average amount of rainfall per day remaining constant. This modification was done by adjusting the transitional probabilities of wet following wet (P:W/W) and wet following dry (P:W/D) days for input to the climate generator, CLIGEN (Nicks et al., 1995). 2) The average amount of precipitation per wet day was modified by the desired amount, maintaining the number of wet days as a constant. In this case, using CLIGEN, changes in the average amount of precipitation per day also change the precipitation intensities in a statistically representative manner based on relationships between these variables for general geographic areas (Nicks and Gander, 1994). Thus rainfall intensities were adjusted appropriately with rainfall amount. 3) Half the change was made by changing the number of wet days, and half the change by the amount of rain per day. For example, for the precipitation scenario of +10% from the baseline, +5% change was a result of increased number of precipitation days, and +5% was a result of the amount of precipitation per day.

The overall average responses to precipitation change are reported in Table 2 as sensitivity values, i.e., the average percent change in runoff or soil loss for each one percent change in precipitation. In every case studied, both runoff and erosion increased with increasing precipitation (and vice versa), and in all but one case the change was greater than linear. Overall, runoff was more sensitive to precipitation change than was erosion. In the case of soil loss for the precipitation scenario of changing wet days only, erosion increased with increasing precipitation (and vice versa), but with a sensitivity less than one. The reason for this has to do with biomass feedbacks. With other factors equal, increased precipitation caused an increase in biomass production, which increases the resistance of the system to erosion. This acts as a partial compensating factor in regards to the precipitation influence on erosion. Runoff is influenced by biomass, but less strongly than is erosion.

Table 2. Sensitivities of changes in runoff and erosion to changes in average annual precipitation: the ratio of % _ runoff or erosion to % _ change in precipitation (from Pruski and Nearing, 2002a).

	Average normalized sensitivity to changes in average annual precipitation		
	Number of wet days	Amount of rain per day	Combined
Runoff	1.28	2.50	1.97
Erosion	0.85	2.38	1.66

The sensitivity analyses showed that both soil loss and runoff were much more impacted by annual precipitation change when the change in precipitation came in the form of amount and intensity of rainfall per day, rather than the number of days of rainfall. Pruski and Nearing (2002b) assessed the results relative to the empirical equations derived by Renard and Freimund (1994) for the R-factor, discussed above, and determined that using the combination of both changing the number of days of rain and the rainfall amount (and implicitly intensity, as well) gave a result that followed the empirical data most closely. Thus we conclude that, other factors not considered, we can expect about a 2% and 1.7% change in runoff and erosion, respectively, for each 1% change in total precipitation under climate change. Table 2 reports average sensitivity values for all the system scenarios studied. Individual scenarios varied a bit from the mean. For runoff, where the average sensitivity for the combined case was 2.0, the values for the scenarios ranged from 1.6 to 2.2. For erosion the corresponding values ranged from 1.5 to 2.0.

Runoff and erosion at selected locations

The complex interactions of climate change impacts on runoff and erosion rates become evident when looking at the modeling results using specific examples of climate change scenarios. Pruski and Nearing (2002b) investigated the changes expected in runoff and erosion as a function of the climate changes estimated for the 21st century using output from the Hadley Centre model (Gordon et al., 2000; Pope et al., 2000; and Wood et al., 1999) under corn and wheat management systems at eight locations in the United States. Climate data from eight locations were studied: Atlanta, Georgia; Cookeville, Tennessee; Corvallis, Oregon; Pierre, South Dakota; Syracuse, Nebraska; Temple, Texas; West Lafayette, Indiana; and Wichita, Kansas.

Data spanning eleven decades, from 1990 to 2099, were obtained from the Global Circulation Models developed by the U.K. Meteorological Office's Hadley Centre (Gordon et al., 2000; Pope et al., 2000; and Wood et al., 1999). The data obtained from the Hadley model were the monthly values of total precipitation, mean temperature, and total, downward, surface, short-wave, solar radiation flux, from which monthly mean values of precipitation, mean temperature and solar radiation were computed. Perturbations from the historical data for precipitation, temperature, solar radiation, and atmospheric carbon dioxide levels were then made, as described in more detail by Pruski and Nearing (2002b). Soils were chosen from the most common at each location, and the simulated crops were chisel plow corn and no-till winter wheat.

The pathways whereby modeled runoff and erosion rates were affected by the climate change inputs were quite complicated. The basic results from the study of Pruski and Nearing (2002b) are shown in Table 3. In terms of annual values, there are eight (2x2x2) possible combinations (Groups) of trends in changes for precipitation, runoff, and erosion; for example, increasing precipitation accompanied by increasing runoff and increasing erosion is one possibility (see bottom of Table 3). Six of the eight possible combinations (Groups) were observed in the modeling results.

Only three of the eight locations studied involved increasing precipitation, and for one of those (West Lafayette, Indiana), the change was small (2.6%). For the two sites where the precipitation trend was positive and where the significance level of the change was greater than 50%, the modeling data fell into results Group 1: increasing precipitation accompanied by both increasing runoff and soil loss (Table 3). For the West Lafayette site, several of the soil/cropping scenarios modeled fell into results Group 5 (Table 3): increasing precipitation, decreasing runoff, and increasing erosion. The explanation for these results is related to the seasonal distributions of the changes in precipitation, runoff, and erosion through the year. The predicted changes in precipitation for West Lafayette, Indiana, as with several of the other locations, were not similar on a month to month basis, and the changes in monthly runoff and erosion were dissimilar as well. As an example, for the case of corn growing on the Drummer soil modeled precipitation decreased during the growing season of June through September, which caused reductions in runoff and erosion, while increases in precipitation in April and May caused increases in both runoff and erosion. The net result was a decrease in annual runoff with an increase in annual erosion.

For the sites where modeled precipitation decreased, the situation was a bit more complex. Some of the results fell into results Group 2, where decreases in precipitation led directly to decreases in runoff and erosion. In these cases the decreased hydrologic driving forces of erosion dominated the processes of change. In other cases biomass reductions due to moisture stresses from less rainfall led to increased modeled runoff and/or erosion. The biomass reduction had a more significant effect on the erosion than on runoff, which produced Group 4 results whereby erosion increased even while runoff decreased. Both runoff and erosion are sensitive to biomass changes, but erosion is affected more than is runoff. Erosion is affected by plant canopy, which reduces the impact energy of rainfall; by crop residues, which protect the soil from raindrop impact and drastically reduce rill detachment rates and sediment transport capacities; and by sub-surface roots and decaying residue, which mechanically hold the soil in place and provide a medium for micro-organisms to thrive. The decrease of biomass production with decreased rainfall thus counteracted the decreased erosivity of the rain and runoff for Group 4 results.

The results of this study (Pruski and Nearing, 2002b) suggested that in locations where precipitation increases are significant, we can expect runoff and erosion rates to increase at an even greater rate than the precipitation. The results also point out that erosional response to climate change may be very complex. Where rainfall decreases were predicted, predicted erosion rates were just as likely to increase as to decrease. Given these results, along with the likelihood of overall increases in heavy storms during the next century (Karl et al., 1996), the overall story is one of increased erosion rates under climate change for the coming century.

Influence of farmers' response to climate change

As climate and economic conditions change, farmers will respond with changes in their crops and cropping practices. Such changes may have a dramatic influence on erosion rates, and predicting what those changes might be is a complicated process.

Southworth et al. (2000, 2002a, b) performed a series of studies to examine future yield changes and optimal planting dates under climate change in five states of the Midwest United States. Pfeifer and Habeck (2002) expanded on these results to determine the most economically viable crop rotations for farmers under climate change.

Table 3. Precipitation, runoff and erosion estimated for 1990, and changes (Δ) estimated for the period of 1990-2099 (from Pruski and Nearing, 2002b).

Location	Crop	Soil	Prec 1990 (mm)	Runoff 1990 (mm)	Erosion 1990 ($t\ ha^{-1}$)	Δ Precipitation	Δ Runoff	Δ Erosion (%)	Group
Atlanta GA	Corn	Cecil	1456.7	263.2	15.93	92.4 mm	20.8 (e)	49.3 (e)	1
		Hiwasse		279.9	22.71	6.3%	19.7 (e)	43.3 (e)	1
		Tifton		208.2	16.18	(c)	23.4 (e)	33.9 (e)	1
	Wheat	Cecil		217.3	3.15		13.0 (d)	24.1 (e)	1
		Hiwasse		233.0	4.65		11.9 (d)	21.1 (e)	1
		Tifton		166.5	4.09		17.2 (e)	20.1 (e)	1
Cookeville TN	Corn	Bewley	1511.5	316.6	15.38	160.4 mm	24.2 (e)	101.9(e)	1
		Hartsells		184.8	18.66	10.6%	41.0 (e)	98.8 (e)	1
		Muskingun		239.6	20.14	(e)	31.1 (e)	93.1 (e)	1
	Wheat	Bewley		284.0	3.38		23.6 (e)	44.8 (e)	1
		Hartsells		149.6	3.76		37.9 (e)	42.0 (e)	1
		Muskingun		195.3	3.75		30.9 (e)	42.9(e)	1
Corvallis OR	Corn	Dayton	939.2	101.9	2.15	-45.1 mm	-0.6 (a)	-6.3(b)	2
		Price		165.4	3.35	-4.8%	5.0 (b)	-4.2(a)	6
		Apt		151.5	2.31	(c)	-5.0 (b)	-6.0(b)	2
	Wheat	Dayton		108.8	1.06		-7.3 (b)	15.9(c)	4
		Price		189.8	1.42		-6.3 (b)	16.8(d)	4
		Apt		162.6	0.95		-11.0(c)	21.0(d)	4
Pierre SD	Corn	Highmore	828.6	136.3	14.81	-10.2 mm	2.3 (a)	59.1(e)	8
		Onita		140.9	14.98	-1.2%	2.5 (a)	60.5(e)	8
		Lowry		131.5	14.33	(a)	2.3 (a)	58.8(e)	8
	Wheat	Highmore		120.0	2.14		-14.2(d)	-4.8(b)	2
		Onita		100.6	2.11		-21.7(d)	-7.3(c)	2
		Lowry		112.4	1.94		-10.7(c)	-4.8(b)	2
Syracuse NE	Corn	Pawnee	1040.5	248.9	20.90	-99.6 mm	-5.5 (b)	42.4(e)	4
		Shapsburg		181.4	24.76	-9.6%	-2.9 (b)	36.5(e)	4
		Wymore		224.8	19.92	(e)	-5.7 (b)	47.4(e)	4
	Wheat	Pawnee		218.5	1.81		-24.5(e)	-13.1(d)	2
		Shapsburg		144.7	4.12		-16.8(d)	-13.9(d)	2
		Wymore		197.5	2.18		-24.3(e)	-9.7(c)	2
Temple TX	Corn	Houston	847.5	332.1	31.84	-60.3 mm	-2.9(a)	5.5(a)	4
		Branyon		310.4	30.69	-7.1%	-3.1(a)	6.2(a)	4
		Tarrant		189.8	29.54	(b)	-7.4(b)	-5.2(a)	2
	Wheat	Houston		250.7	03.04		23.7(c)	65.4(e)	8
		Branyon		220.0	01.93		23.0(c)	153.2(e)	8
		Tarrant		147.9	3.91		17.1(c)	41.4(d)	8
Wichita KS	Corn	Blanket	957.5	187.9	23.52	-81.8 mm	-3.1(a)	28.8(d)	4
		Farnum		164.1	24.39	-8.5%	-1.7(a)	29.4(d)	4
		Tabler		170.4	26.00	(d)	-4.9(b)	28.0(c)	4
	Wheat	Blanket		150.6	2.64		-14.6(d)	-0.5(a)	2
		Farnum		116.8	3.21		-7.2(b)	-4.8(b)	2
		Tabler		121.4	2.43		-13.2(c)	-0.7(a)	2
W Lafayette IN	Corn	Drummer	1343.5	265.8	15.32	34.8 mm	-2.7(a)	77.6(e)	5
		Crosby		200.9	19.69	2.6%	6.1(b)	67.6(e)	1
		Starks		243.1	16.72	(b)	1.7(a)	71.1(e)	1
		Toronto		251.3	16.68		-0.6(a)	73.9(e)	5
	Wheat	Drummer		231.2	2.46		-16.3(d)	16.5(d)	5
		Crosby		160.0	2.59		-7.1(b)	15.2(d)	5
		Starks		233.9	2.80		-13.3(d)	16.2(d)	5
		Toronto		229.5	2.80		-15.0(d)	15.4(d)	5

Group	Precipitation	Runoff	Erosion	Significance levels:
1	↑	↑	↑	(a) 0 - 24.9%
2	↓	↓	↓	(b) 25 - 49.9%
3	↑	↑	↓	(c) 50 - 74.9%
4	↓	↓	↑	(d) 75 - 89.9%
5	↑	↓	↑	(e) 90 - 100%
6	↓	↑	↓	
7	↑	↓	↓	
8	↓	↑	↑	

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. From these studies they predicted a large increase in the planted area of soybeans and a decrease in the area planted to wheat across much of the study area.

The Southworth et al. (2000, 2002a, b) and Pfeifer and Habeck (2002) studies investigated how these predicted changes in cropping might impact erosion rates. They applied simulation methods similar to those described above used by Pruski and Nearing (2002b), including the application of the CO_2 sensitive WEPP model and Hadley Centre climate scenarios for the 21st century.

The study results indicated that both runoff and soil loss increased in future scenarios compared to current conditions for 10 of the 11 Midwestern regions studied (Table 4). The WEPP model predicted increases of +18% to +274% in soil loss, with associated increases in runoff. Soil loss and runoff patterns frequently followed those of annual precipitation.

The studies of Southworth et al. (2000, 2002a, b) predicted that corn yield would decrease under climate change, which caused decreased predicted soil residue cover and hence led to increased predicted erosion. In almost every case, however, soybean yields were predicted to increase while the corn yields were decreasing. Changes in 2040 to 59 yields at optimal planting dates were -31% to +18% for corn and +9% to +101% for soybeans relative to the baseline. The drop in corn yield appeared to lead to increased erosion even when precipitation decreased. In eastern Wisconsin and southwestern Wisconsin, where annual precipitation decreased but runoff and soil loss increased (Pruski and Nearing's Group 8), July precipitation (important to corn's silking period) decreased, and predicted corn yield decreased (Table 4). Therefore, the predicted loss of crop cover caused the predicted increase of runoff and soil loss.

Increases in future runoff and soil loss would likely have been even larger if the effect of changing from corn-soybeans to continuous soybeans had been more accurately modeled. Looking at the same climate with two different rotations showed that the change from corn-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 increase soil loss relative to rotational soybeans (Laflen and Moldenhauer, 1979; Laflen and Colvin, 1981). Comparing results for continuous soybeans and the corn-soybean rotation for two sample regions for each time period showed that while continuous soybeans had less canopy cover than corn-soybeans, continuous soybeans had greater ground cover, when averaged over the 100 years. Thus, WEPP predicted a decrease in erosion because of increased soybean ground cover. Given our current understanding of the system, such a decrease would not be expected (Laflen and Moldenhauer, 1979; Laflen and Colvin, 1981). Therefore, the soil loss estimates in Table 4 could actually underestimate soil loss, since the WEPP model was apparently over-accounting for the erosional impact of increase in soybean cover. South central Michigan and northern Indiana were the only regions to have soybeans without corn, and modeled future soybean yields there increased markedly (over 90% per period). This was also the only region to consistently show a decrease in predicted 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 caused greater erosion. The reason that WEPP did not accurately model the soybean cover effect on erosion is because the functions in the model do not adequately differentiate the effectiveness of residue type on erosion impact.

The loss of wheat in rotations also probably contributed to the 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).

The results of sensitivity testing with planting date showed that soil loss increased substantially with later planting dates for corn 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 2040-59. Corn was being planted 2 weeks later (May 14) and soybeans 1 week later (May 24) than 1990-99, so the delayed planting date caused a longer time for soil to remain uncovered during April and May rains, which could have intensified soil loss. In Wisconsin, however, where soybean planting occurred 4 to 6 weeks earlier in 2040-59 than the baseline, the extended period of crop cover could have been reducing the soil loss from an even greater increase than might have occurred otherwise.

The erosion simulations from this study had more widely varying results than other studies not taking into account changes in management. This makes sense, considering that changes in crop types and cropping practices such as planting dates would have a major influence on erosion rates.

Results and Discussion

The data generated from Global Circulation Models, which is used for input for many of the studies described in this paper, are definitive neither in terms of precise magnitude of climate change expected nor in terms of the geographical distribution of the expected changes. This is evident, for example, when one compares the results from the study of Nearing (2001) that uses both the Hadley Centre and the Canadian Centre for Climate Modeling and Analysis results. The Canadian model suggests greater magnitudes of change (Table 1), and results for California for the two models are opposite in sign. The important aspects, therefore, of the results of the studies described here relate to recognizing that change in climate will result in change in erosion rates and in understanding the processes and factors that dominate the erosional changes.

All of the erosion/climate change studies to date suggest that increased rainfall amounts and intensities will lead to greater rates of erosion, and there appears to be little doubt that both average rainfall amounts and intensities are on the rise nationally. Thus, there appears to be little doubt that erosion will also be on the increase nationally, unless amelioration measures are taken.

In terms of processes, rainfall amounts and intensities are certainly the most direct and important factors controlling erosional changes under climate change. The results of

Table 4. Precipitation, runoff, and erosion estimated for 1990-99, and changes estimated for 2040-59 and 2080-99 with changes in crop management.

Region	Crop rotations[a]	Precipitation (mm)	Runoff[b] (mm)	Soil loss[b] ($t \cdot ha^{-1}$)	Crop rotations[a]	Change in precipitation (%)	Change in runoff[b] (%)	Change in soil loss[b] (%)	Group[c]	Change in precipitation (%)	Change in runoff[b] (%)	Change in soil loss[b] (%)	Group[c]
	1990-99	1990-99	1990-99	1990-99	2040-59 and 2080-99	2040-59	2040-59	2040-59	2040-59	2080-99	2080-99	2080-99	2080-99
Central Wisconsin	(MS)	792.4	54.9	3.3	(MS, S)	0.5	53.8	150.0	1	0.2	57.7	122.0	1
East Central Indiana/ West Central Ohio	(MS, S, SW)	889.2	85.6	3.8	(MS)	10.2	9.9	34.4	1	8.4	5.0	18.7	1
Eastern Illinois	(MS, MWS, SW)	867.5	117.8	6.3	(MS)	8.7	16.4	32.6	1	2.1	16.6	68.9	1
Eastern Wisconsin	(MS, W)	800.3	59.5	3.8	(MS, S)	-1.1	125.4	129.3	8	-6.6	112.7	119.3	8
Michigan Thumb	(MS, W)	730.8	38.6	1.9	(MS, S)	14.2	49.2	105.0	1	9.7	41.6	67.9	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	7.9	284.9	225.5	1
South Central Michigan / Northern Indiana	(MS, W)	885.6	49.6	3.5	(S)	6.8	-26.1	-13.0	7	0.9	-37.9	-38.0	7
Southern Illinois	(M, MS, MWS, SW)	1106.6	205.2	11.5	(MS, MWS)	9.6	18.6	37.5	1	9.8	18.8	33.6	1
South Western Indiana	(M, MS, MWS, SW)	1106.2	143.1	8.4	(MS)	8.4	6.3	18.2	1	11.8	10.6	30.8	1
South Western Wisconsin	(MS, SW)	802.9	97.8	5.5	(MS, S)	-2.1	120.8	147.2	8	-6.2	118.1	134.7	8
Western Illinois	(MS, SW)	933.7	119.1	8.2	(MS)	7.9	7.7	18.9	1	1.2	3.1	24.5	1

[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 (1990-99).**

[a] **M = corn, S = soybeans, W = wheat; single letter = continuous crop, multiple letters = rotation.**

[c] **After Pruski and Nearing (2002a).**

simulation studies suggest that erosion will increase approximately 1.7% for each 1% change in annual rainfall. This result is in basic agreement with our understanding of the relationship between rainfall erosivity and rainfall amounts that we know from measured erosion data. The results also indicate that the dominant factor related to the change in erosion rate is the amount and intensity of rain that falls in the storm, rather than the number of days of precipitation in a year.

The second dominant process related to erosion and climate change is biomass production. Biomass levels will change under climate change due to changes in temperature, moisture, and atmospheric carbon dioxide levels, and biomass ranks right next to rainfall in terms of its impact on erosion rates (Nearing et al. 1990). The change in erosion rates as a function of biomass is perhaps the most complex to understand because of the many interactions and counter-effects, and to the greater effect of biomass on erosion compared to runoff.

The third major process of erosion rate changes under climate change, and the wild card, is land use. Detailed land use changes as a function of future climates (both weather related and economic climates) are nearly impossible to predict with any degree of accuracy. Nonetheless, the study conducted by O'Neal et al. (in press) is suggestive that land use changes will occur and that they will impact erosion rates. The trend from those results suggests that erosion will increase as a function of future land use changes in the Midwest United States, largely because of a general shift away from wheat and corn towards soybean production. Other scenarios are possible that would lead to different results.

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