Climate-induced changes in erosion during the 21st century for eight U.S. locations

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[1] Climate in the United States is expected to change during the 21st century, and soil erosion rates may be expected to change in response to changes in climate for a variety of reasons. This study was undertaken to investigate potential impacts of climate change on soil erosion by water. Erosion at eight locations in the United States was modeled using the Water Erosion Prediction Project model modified to account for the effects of atmospheric CO_2 concentrations on plant growth. Simulated climate data from the U.K. Meteorological Office's Hadley Centre HadCM3 Global Circulation Model were used. The results indicated a complex set of interactions between the several factors that affect the erosion process. Direct effects of rainfall increases and decreases to runoff and erosion increases and decreases were observed but were often not dominant. One of the key factors of change in the system was the biomass production. Changes in soil moisture, atmospheric CO_2 concentration, temperature, and solar radiation each impacted the biomass production at differing levels at the eight different sites. Different types of changes occurring at different periods of the year also complicated the response of the system. Overall, these results suggest that where precipitation increases are significant, erosion can be expected to increase. Where precipitation decreases occur, the results may be more complex due largely to interactions of plant biomass, runoff, and erosion, and either increases or decreases in overall erosion may be expected. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1815 Hydrology: Erosion and sedimentation; 1854 Hydrology: Precipitation (3354); 1860 Hydrology: Runoff and streamflow; 1866 Hydrology: Soil moisture; *KEYWORDS:* soil erosion, runoff, infiltration, climate change, GCM, soil conservation

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1. Introduction

[2] Climate in the United States is changing. Historical weather records analyzed by *Karl et al.* [1996] indicate that since 1910 there has been a steady increase in the area of the United States affected by extreme precipitation events (>50.8 mm in a 24 hour period). According to statistical analyses of the data, there is less than one chance in a thousand that this observed trend could occur in a quasi-stationary climate. *Karl et al.* [1996] also observed in the weather records an increase in the proportion of the country experiencing a greater than normal number of wet days. These climate changes that have been observed do not address the issue of causation. However, results from Coupled Atmosphere-Ocean Global Climate Models suggest that climate changes are expected to continue through the next century [*McFarlane et al.*, 1992; *Johns et al.*, 1997] as the concentration of greenhouse gasses increases in the atmosphere. Temperatures are generally expected to increase across the United States, and precipitation patterns may change in complex ways, differing from region to region in total precipitation, distributions of precipitation through the year, and precipitation intensities. The Coupled Atmosphere-Ocean Global Climate Models indicate potential future changes in both the number of wet days and the percentage of precipitation coming in intense convective storms as opposed to longer duration, less intense storms [*McFarlane et al.*, 1992; *Johns et al.*, 1997].

[3] Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, including changes in plant biomass production, plant residue decomposition rates, soil microbial activity, evapotranspiration rates, and soil surface sealing and crusting, as well as shifts in land use necessary to accommodate a new climatic regime [*Williams et al.*, 1996]. The most direct impact of climate change on erosion results from changes in precipitation. Significant changes in rainfall erosivity may occur in the United States over the next century. Results of analyses of erosivity changes as a function of precipitation changes using two Global Climate Models (GCMs) indicate the probability of increases in erosivity across much of the

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northern tier and New England states and decreases in parts of the western high plains states [*Nearing*, 2001]. A study conducted by *Pruski and Nearing* [2002] draws attention to the fact that changes in rainfall which occur due to changes in storm intensity can be expected to have a greater impact on erosion rates than those due to changes in the number of rain days alone. Results of that study suggest that in studying erosional changes, changes in precipitation under climate change must be reflected as a combination of both factors. If only the number of days of precipitation is modified to account for precipitation changes, erosional changes will be underestimated. If only intensity changes are used to reflect precipitation changes, erosional changes will be overstated. The overall results of that study suggested that, other factors being equal (e.g., temperature, CO_2 levels, and solar radiation), each 1% change in precipitation can effect a 2% change in runoff and an approximate 1.7% change in erosion. Of course, other factors do not remain constant, and the interactions which result may be very complex.

[4] Several studies have been conducted to investigate the potential effects of climate change on erosion. *Favis-Mortlock and Boardman* [1995] used the Erosion Productivity Impact Calculator (EPIC) model to evaluate potential erosion rate changes on the South Downs in the United Kingdom. The EPIC erosion model is based on the Universal Soil Loss Equation and hence is quite limited in its ability to model the complicated interactions which may occur in the erosional system as the climate changes. *Favis-Mortlock and Savabi* [1996] used the Water Erosion Prediction Project (WEPP) model [*Nearing et al.*, 1989; *Flanagan and Nearing*, 1995] with adjustments coded for atmospheric CO_2 concentration, to study the effects of changing CO_2 levels on evapotranspiration rates, water balances, and crop biomass production rates. *Savabi and Stockle* [2001] investigated the impact of CO_2 and temperature changes on soil erosion. Their study indicated sensitivity of erosion to changes in both parameters, but they did not attempt to evaluate the potential impact of precipitation changes on erosion. A study of future erosion in Mato Grosso State, Brazil, also using a CO_2-sensitive version of WEPP, estimated soil erosion changes using three different GCMs. The authors found for their case increases in soil erosion ranging from 27% to 55%, as well as a decrease of 9% for one of the GCMs [*Favis-Mortlock and Guerra*, 1999].

[5] Preindustrial levels of CO_2 in the atmosphere were probably near 280 ppm, while the current level is ~350 ppm and will undoubtedly continue to increase in the future [*Bolin et al.*, 1986]. Predictions are that global atmospheric CO_2 would double sometime near the middle of the 21st century [*Intergovernmental Panel on Climate Change-Task Group on Scenarios for Climate Impact Assessment* (*IPCC-TGCIA*), 1999]. Erosion would be indirectly affected by modifications to the growth pattern of crops resulting from increased temperature and/or atmospheric CO_2 content [*Favis-Mortlock et al.*, 1991].

[6] Reviews of experiments in controlled environments reported by *Rosenzweig and Hillel* [1998] show a wide range in the magnitude of response to a doubling CO_2, usually tested experimentally from a "current" level (300–350 ppmv CO_2) to a "doubled" level (600–700 ppmv CO_2). Most changes in crop yields have been positive, and only a few have been slightly negative. Responses to elevated CO_2 vary among different crops and even among varieties of the same crop and depend in part on water and nutrient availability and in part on genetics [*Rosenzweig and Hillel*, 1998].

[7] The combined impact of climate change and direct CO_2 effects on agricultural productivity is difficult to predict; however, the consequences of these phenomena for important agricultural regions of the United States and the world could be great [*Stockle et al.*, 1992b]. Assessments of the impact of CO_2-induced changes on agricultural productivity are needed for both scientific and policy-making purposes. The complexity of climate-crop production interactions makes simulation a useful and, probably, the only practical approach available for making the needed assessments [*Stockle et al.*, 1992a].

[8] High-temperature stress is among the least understood of all plant processes, but temperature is known to affect morphology, portioning of photosynthetic products, and the root to shoot ratio. Critical temperature parameters used empirically to describe effects on plant growth include mean, minimum, and maximum daily temperature as well as the cumulative heat load above a defined threshold during the growing period [*Rosenzweig and Hillel*, 1998]. The influence of the temperature in the biomass production is represented in the WEPP model [*Flanagan and Nearing*, 1995] by the temperature stress factor, which is computed with the equation

$$TS = \sin\left[\frac{\pi}{2}\frac{T_a - T_b}{T_o - T_b}\right], \tag{1}$$

where TS is the temperature stress factor (0–1), T_a is the average daily temperature (°C); T_b is the base temperature for the crop (°C), and T_o is the optimum temperature for the crop (°C).

[9] *Savabi and Stockle* [2001], using the WEPP model, simulated a slight increase of crop yield for corn in West Lafayette when the temperature increased ~0.8°C but when the daily temperature increased more than 0.8°C, annual crop yield was reduced. The reason presented by the authors for the initial increase was that the potential accumulation of growing degree days from planting to maturity is 1700°C days for corn, and West Lafayette's climate does not, on average, reach this value during the growing season. Global climate models can provide estimates of the number of days with temperatures that may exceed the optimal or the known threshold of tolerance for any particular crop. These may be used in the analysis of the potential impacts of high temperatures on crop yields [*Rosenzweig and Hillel*, 1998].

[10] The objective of this study was to investigate the changes expected in the runoff and erosion as a function of the climate changes estimated for the 21st century by the HadCM3 model [*Gordon et al.*, 2000; *Pope et al.*, 2000; *Wood et al.*, 1999] under corn and wheat management systems at eight locations in the United States.

2. Methods

2.1. Climate Scenarios

[11] 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. Climate files for each of these eight locations were generated with the

Climate Generator (CLIGEN) model [*Nicks and Gander*, 1994; *Flanagan and Nearing*, 1995] using input values based on historical data from each site.

[12] Data spanning 11 decades, from 1990 to 2099, were obtained from the Atmosphere-Ocean Global Climate Models developed by the U.K. Meteorological Office's Hadley Centre. HadCM3 is the third generation of Atmosphere-Ocean Global Climate Models produced by the Hadley Centre. It simulates a 1% increase in greenhouse gases for the time period studied, as well as the effects of sulphate aerosols. The model also considers the effects of the minor trace gases, CH_4, N_2O, CFC11, CFC12, and HCFC22, a parameterization of simple background aerosol climatology, and several other improvements over the previous Hadley Centre model, HadCM2. Results from the model are reported on a 2.5° latitude by 3.75° longitude grid [*Gordon et al.*, 2000; *Pope et al.*, 2000; *Wood et al.*, 1999].

[13] The data obtained from HadCM3 were the values of total precipitation, mean temperature, and total, downward, surface, shortwave solar radiation flux for each month of the 110 years studied (1990–2099). With these values we obtained the monthly mean values of precipitation, mean temperature and solar radiation for each location in the 11 decades analyzed. These values were compared with the data from the CLIGEN database [*Nicks et al.*, 1993], which were statistical representations of the historical National Weather Service records from each location.

2.2. CLIGEN File Generation and Downscaling

[14] Climate files for each of these eight locations and eleven decades were generated using the CLIGEN model [*Nicks and Gander*, 1994; *Flanagan and Nearing*, 1995]. The CLIGEN was used to generate long-term (100 year, in this case) representative, synthetic, stable-climate weather files for WEPP, which were necessary in order to determine representative erosion values for each decade's climate file [*Baffaut et al.*, 1996].

[15] In general, we took a simple approach to downscaling the GCM data for the specific locations tested. The Hadley data refer to a relatively large-scale grid (2.5° latitude by 3.75° longitude), while the CLIGEN files refer to point locations for National Weather Service stations [*Nicks and Gander*, 1994]. The current conditions for climate at the specific locations were represented by data from the CLIGEN database. Perturbations from this baseline for precipitation, temperature, and solar radiation were made, as described in sections 2.2.1, 2.2.2, and 2.2.3, based on relative changes in the GCM data. Specifically, the GCM data for the time period 1960–1989 were considered as temporally equivalent to the CLIGEN data, which are based on roughly the same time period. If, for example, the average precipitation from the GCM data for the month of June for the decade 2050–2059 was 6% greater than the correspond-ing value for the time period 1960–1989, then the CLIGEN June precipitation would be increased by 6% to represent the June precipitation for the decade 2050–2059.

Pruski and Nearing [2002]). The change in the number of days of precipitation was made by changing the probability of wet following wet and the probability of wet following dry days in the CLIGEN input file, until the desired change in total precipitation was reached. Changes in the number of days of precipitation do not translate into changes in precipitation intensity as calculated by the CLIGEN model. However, changes in the amount of precipitation on a given day do change both the average and peak intensities of precipitation in a statistically representative manner based on current knowledge of the relationships between these variables [*Nicks and Gander*, 1994]. This is because representative intensities of storms are generated by CLIGEN based on statistical relationships with storm amount and geographic region. In this study, we maintain the assumption that these relationships remain valid, though no information exists currently to either verify or refute that assumption.

2.2.2. Temperature Changes

[17] The method we chose for changing temperature due to climate change was based on altering the CLIGEN input values on a relative basis using corresponding Hadley data, as discussed above. First, the mean monthly values of temperature obtained from HadCM3 for each decade were compared with the mean temperature for the same grid for the period of 1960–1989 (also obtained from the HadCM3). Then, the ratio between these values was multiplied with both the maximum and the minimum temperature found in the CLIGEN files to reflect the relative temperature changes for the given decade to be studied. The same method was also applied to standard deviation of the maximum and minimum temperatures. Each computed value was checked to ensure that there were no problems at values of temperature near 0°C.

2.2.3. Solar Radiation Changes

[18] The same procedure used to adjust temperature was used for solar radiation, for similar reasons. The mean daily values of total downward surface short wave flux obtained from the HadCM3 for each month were compared with the values for the period of 1960–1989, and the ratio obtained was multiplied with the solar radiation values of the CLIGEN database to represent the new values of solar radiation in each decade. The same change was also applied to the values of standard deviation.

2.3. Soils, Crops, and Topography Scenarios

[19] We selected soils that were most common to each location (Table 1). The simulated crops were chisel plow corn and no-till winter wheat. The base temperature considered in the WEPP model [*Flanagan and Nearing*, 1995] for corn was 10°C and for wheat was 4°C, and the optimum temperatures for corn and wheat were 25°C and 15°C, respectively. The number of degrees day necessary for both was 1700°C d.

[20] The slope profile was S-shaped with 0% slope at the crest of the hill, 1% at the bottom of the hill, and 7% maximum gradient halfway down the slope. A slope length

Table 1. Properties of the Soils Simulated in the Study[a]

Location	Soil	Soil Texture	Sand, %	Clay, %	Organic Matter, %	Cation Exchange Capacity, meq 100 g^{-1}	Rock, %	Interrill Erodibility (K_i), 10^6 kg s^{-1} m^{-4}	Rill Erodibility (K_r) s m^{-1}	Critcal Hydraulic Shear Stress (τ_c), Pa	Baseline Green-Ampt Hydraulic Conductivity (K_b), mm h^{-1}
Atlanta	Cecil	SL	66.5	19.6	0.89	4.8	5.2	3.93823	0.0119	3.57	19.76
	Hiwasse	SL	67.7	11.6	1.25	3.4	3.6	4.8835	0.009209	2.77	13.33
	Tifton	LS	81.5	5.0	1.00	2.5	13.2	5.14494	0.01188	2.27	16.77
Cookeville	Bewley	SIL	6.4	24.5	2.00	15.8	1.3	4.70276	0.007896	3.5	1.46
	Hartsells	L	48.2	13.5	1.25	8.9	5.4	4.85687	0.009168	2.9	7.98
	Muskingun	SIL	16.9	18.1	2.00	12.6	11.9	5.05686	0.010498	3.5	2.9
Corvallis	Dayton	SIL	16.9	18.1	2.50	18.9	1.3	5.05686	0.010498	3.5	2.5
	Price	SICL	7.2	32.9	3.50	25.9	7.1	4.23838	0.007085	3.5	1.13
	Apt	SICL	7.2	32.9	6.00	30.4	2.3	4.23838	0.007085	3.5	1.02
Pierre	Highmore	SIL	6.4	24.5	3.00	20.0	1.1	4.70276	0.007896	3.5	1.25
	Onita	SIL	6.4	24.5	5.00	28.4	1.2	4.70276	0.007896	3.5	0.99
	Lowry	SIL	6.4	24.5	3.00	20.0	0.0	4.70276	0.007896	3.5	1.25
Syracuse	Pawnee	SIC	6.2	46.2	2.00	35.8	0.0	3.5096	0.006913	3.5	0.65
	Sharpsburg	L	35.1	23.6	3.50	22.7	6.0	6.11452	0.00732	3.18	4.91
	Wymore	SICL	7.2	32.9	3.00	31.6	0.0	4.23838	0.007085	3.5	1
Temple	Houston	C	29.5	44.8	3.00	41.1	1.0	3.5838	0.006917	3.5	0.73
	Branyon	C	29.5	44.8	3.00	41.1	3.8	3.5838	0.006917	3.5	0.73
	Tarrant	GR-L	48.2	13.5	2.00	10.3	21.1	4.85687	0.006269	2.9	7.79
Wichita	Blanket	SIL	6.4	24.5	2.00	18.2	1.1	4.70276	0.007896	3.5	1.33
	Farnum	L	41.0	18.9	2.00	14.9	0.0	5.31409	0.006983	3.12	6.19
	Tabler	SIL	16.9	18.1	2.00	18.0	0.0	5.05686	0.010498	3.5	2.54
West Lafayette	Drummer	SICL	7.2	32.9	6.00	27.1	1.1	4.23838	0.007085	3.5	1.1
	Crosby	SIL	16.9	18.1	2.00	12.6	1.3	5.05686	0.010498	3.5	2.9
	Starks	SIL	6.4	24.5	2.00	15.8	0.0	4.70276	0.007896	3.5	1.46
	Toronto	SIL	6.4	24.5	4.00	19.3	0.0	4.70276	0.007896	3.5	1.28

[a]Values were taken from the WEPP database for U.S. soils.

the same relationships for the effects of CO_2 on plant growth and evapotranspiration rates as the model described in section 1 [*Favis-Mortlock and Savabi*, 1996], except that the current version (99.5) of the WEPP model was modified, rather than an earlier version (95.001) as in previous studies [e.g., *Favis-Mortlock and Savabi*, 1996; *Favis-Mortlock and Guerra*, 1999; *Savabi and Stockle*, 2001]. The parameters used in the equations of the model for the CO_2 effects on plant growth and evapotranspiration rates were those proposed by *Stockle et al.* [1992b].

[22] To estimate the CO_2 level for each decade, the data of the CO_2 levels obtained by the Carbon Dioxide Information Analysis Center (CDIAC) and presented by *IPCC-TGCIA* [1999] for the period of 1960–1998 were used to develop a nonlinear regression equation to represent the change of the CO_2 as a function of time. The equation determined was $CO_2 = 1.128310^{-23}\ (\text{Year})^{7.7285}$ ($r^2 = 0.99$), where CO_2 is expressed in ppmv. The CO_2 levels used in the model for each decade were obtained with this equation for the middle of each decade and represent results quite similar to those of the Hadley model.

2.5. Simulations

[23] A total of more than 550 simulations were conducted. Each erosion simulation was made using a 100-year synthetic, steady-climate weather file in order to obtain representative, average annual erosion estimates for a given climate file that represented 1 decade at one location. All erosion values reported and discussed in this study are given in terms of average erosion rate over the portion of the slope that was predicted to experience net loss of soil. The small areas of net deposition on the bottom of the slopes as predicted by the model for these slopes were not evaluated.

2.6. Statistical Analyses

[24] For each of the eight locations, linear regression equations were computed to relate the mean annual precip-

Table 2. Regression Equations for Precipitation Amount as a Function of Year During the Period 1990–2099[a]

Location	Equation	r^2	Significance Level, %
Atlanta	0.8396 (year) − 214	0.161	74.9
Cookeville	1.4580 (year) − 1389	0.308	92.3
Corvallis	−0.4099 (year) + 1755	0.129	69.1
Pierre	−0.0931 (year) + 1014	0.008	19.9
Syracuse	−0.9056 (year) + 2843	0.274	90.1
Temple	−0.5479 (year) + 1938	0.030	38.4
Wichita	−0.7435 (year) + 2437	0.167	78.8
West Lafayette	0.3162 (year) + 714	0.031	39.5

[a]Precipitation amounts are given in millimeters.

Table 3. Regression Equations for Mean Annual Temperature as a Function of Year During the Period 1990–2099[a]

Location	Equation	r^2	Significance Level, %
Atlanta	0.0398 (year) − 61.4	0.94	100
Cookeville	0.0413 (year) − 67.0	0.94	100
Corvallis	0.0367 (year) − 62.6	0.98	100
Pierre	0.0571 (year) − 107.6	0.99	100
Syracuse	0.0553 (year) − 98.7	0.95	100
Temple	0.0414 (year) − 62.1	0.89	100
Wichita	0.0493 (year) − 83.5	0.94	100
West Lafayette	0.0508 (year) − 90.4	0.96	100

[a]Annual temperatures are given in °C.

Table 4. Regression Equations for Mean Solar Radiation as a Function of Year During the Period 1990–2099[a]

Location	Equation	r^2	Significance Level, %
Atlanta	0.0211 (year) + 153.2	0.15	76.7
Cookeville	0.0156 (year) + 157.3	0.12	69.7
Corvallis	0.0374 (year) + 81.6	0.58	99.4
Pierre	0.0329 (year) + 98.6	0.29	90.9
Syracuse	0.0385 (year) + 103.8	0.32	93.2
Temple	0.0382 (year) + 134.7	0.09	64.1
Wichita	0.0301 (year) +133.7	0.16	78.2
West Lafayette	0.0351 (year) + 104.3	0.37	95.3

[a]Solar radiation is given in W m^{-2}.

itations, mean annual temperatures, mean annual solar radiations, mean monthly precipitations, and mean monthly temperatures to time. For each combination of location, soil type, and cropping system, linear regression equations were computed to relate mean annual erosion and mean annual runoff, and erosion), though only six of the eight groups were represented in the results (Table 7).

4. Discussion

[26] The pathways whereby runoff and erosion are affected by climate changes are quite complicated [*Pruski and Nearing*, 2002; *Williams et al.*, 1996]. Factors can involve changes in plant biomass production, plant residue decomposition rates, soil microbial activity, evapotranspiration rates and associated soil moisture changes, soil surface sealing and crusting, soil roughness changes, and undoubtedly a variety of others. We found that we were able to characterize a great deal of the predicted changes in runoff and erosion predicted in this study via the mechanisms of the direct effects of precipitation on both runoff and erosion and the indirect effects of atmospheric CO_2 concentration, temperature, and precipitation on biomass production, which, in turn, impacted both runoff and erosion predictions (Figure 2). Precipitation and CO_2 levels generally have a

Table 5. Regression Equations for Annual Runoff Amount as a Function of Time Over the Period 1990 Through 2099 for the Eight Locations, Two Crops, and Various Soil Types[a]

Location	Crop	Soil	Equation	r^2	Significance Level, %
Atlanta, Georgia	corn	Cecil	0.4969 (year) − 725.6	0.333	91.9
		Hiwasse	0.5000 (year) − 715.1	0.351	92.9
		Tifton	0.4421 (year) − 671.6	0.455	96.8
	wheat	Cecil	0.2570 (year) − 294.1	0.172	76.7
		Hiwasse	0.2526 (year) − 269.7	0.174	76.9
		Tifton	0.2604 (year) − 351.7	0.346	92.6
Cookeville, Tennessee	corn	Bewley	0.6978 (year) − 1072.0	0.364	95.1
		Hartsells	0.6880 (year) − 1184.3	0.630	99.7
		Muskingun	0.6767 (year) − 1107.0	0.495	98.4
	wheat	Bewley	0.6086 (year) − 927.1	0.333	93.7
		Hartsells	0.5150 (year) − 875.3	0.592	99.4
		Muskingun	0.5494 (year) − 898.0	0.436	97.3
Corvallis, Oregon	corn	Dayton	−0.00565 (year) + 113.2	0.001	3.3
		Price	0.0754 (year) + 15.4	0.022	31.6
		Apt	−0.0683 (year) + 287.4	0.017	28.0
	wheat	Dayton	−0.0725 (year) + 253.1	0.029	36.4
		Price	−0.1079 (year) + 404.5	0.032	38.0
		Apt	−0.1622 (year) + 485.4	0.071	54.4
Pierre, South Dakota	corn	Highmore	0.02822 (year) + 80.1	0.009	20.6
		Onita	0.03223 (year) + 76.8	0.010	21.3
		Lowry	0.02696 (year) + 77.8	0.008	18.8
	wheat	Highmore	−0.1544 (year) + 427.3	0.207	81.4
		Onita	−0.1985 (year) + 495.6	0.295	89.5
		Lowry	−0.1094 (year) + 330.1	0.128	69.0
Syracuse, Nebraska	corn	Pawnee	−0.1252 (year) + 498.0	0.031	39.4
		Shapsburg	−0.0478 (year) + 276.5	0.008	28.2
		Wymore	−0.1168 (year) + 457.2	0.030	38.7
	wheat	Pawnee	−0.4870 (year) + 1187.6	0.426	97.1
		Shapsburg	−0.2216 (year) + 585.7	0.235	87.0
		Wymore	−0.4366 (year) + 1066.3	0.408	96.5
Temple Texas	corn	Houston	−0.0866 (year) + 504.4	0.003	13.0
		Branyon	−0.0875 (year) + 484.5	0.003	13.5
		Tarrant	−0.1284 (year) + 445.3	0.016	28.6
	wheat	Houston	0.5398 (year) − 823.5	0.138	73.9
		Branyon	0.4591 (year) − 693.6	0.114	69.1
		Tarrant	0.2305 (year) − 310.8	0.065	55.1
Wichita, Kansas	corn	Blanket	−0.0534 (year) + 294.2	0.007	18.6
		Farnum	−0.0253 (year) + 214.4	0.002	10.2
		Tabler	−0.0757 (year) + 321.0	0.015	27.7
	wheat	Blanket	−0.1999 (year) + 548.4	0.156	77.0
		Farnum	−0.0762 (year) + 268.4	0.043	45.9
		Tabler	−0.1459 (year) + 411.7	0.114	69.1
West Lafayette, Indiana	corn	Drummer	−0.0643 (year) + 393.8	0.009	21.3
		Crosby	0.1106 (year) − 19.2	0.044	46.2
		Starks	0.0379 (year) + 167.7	0.004	13.9
		Toronto	− 0.0138 (year) + 278.8	0.001	4.9
	wheat	Drummer	−0.3418 (year) + 911.4	0.209	84.2
		Crosby	−0.1037 (year) + 366.4	0.050	49.2
		Starks	−0.2818 (year) + 794.7	0.163	78.2
		Toronto	−0.3119 (year) + 850.2	0.191	82.1

[a]Runoff amounts are given in millimeters.

study where precipitation increases were predicted by the Hadley model. For the case of West Lafayette, Indiana, the

during a rainfall as the surface layer of soil wets downward. A greater proportion of the total rainfall depth is used in this

Table 6. Regression Equations for Annual Erosion as a Function of Time Over the Period 1990 Through 2099 for the Eight Locations, Two Crops, and Various Soil Types[a]

Location	Place	Crop	Soil	Equation	r^2	Significance Level, %
Atlanta, Georgia	Atlanta	corn	Cecil	0.07132 (year) − 126.0	0.466	97.0
			Hiwasse	0.08930 (year) − 155.0	0.433	96.1
			Tifton	0.04984 (year) − 83.0	0.393	94.8
		wheat	Cecil	0.00691 (year) − 10.6	0.541	98.5
			Hiwasse	0.00892 (year) − 13.1	0.488	97.5
			Tifton	0.00748 (year) − 10.8	0.440	96.3
Cookeville, Tennessee	Cookeville	corn	Bewley	0.1424 (year) − 268.0	0.809	100.0
			Hartsells	0.16767 (year) − 315.0	0.804	100.0
			Muskingun	0.17042 (year) − 319.0	0.780	100.0
		wheat	Bewley	0.01376 (year) − 24.0	0.716	99.9
			Hartsells	0.01435 (year) − 24.8	0.627	99.6
			Muskingun	0.01465 (year) − 25.4	0.654	99.7
Corvallis, Oregon	Corvallis	corn	Dayton	−0.00123 (year) + 4.6	0.023	32.6
			Price	−0.00128 (year) + 5.9	0.011	22.6
			Apt	−0.00125 (year) + 4.8	0.019	29.8
		wheat	Dayton	0.00154 (year) − 2.0	0.137	70.8
			Price	0.00217 (year) − 2.9	0.172	76.6
			Apt	0.00182 (year) − 2.7	0.228	83.7
Pierre, South Dakota	Pierre	corn	Highmore	0.0795 (year) − 143.4	0.632	99.4
			Onita	0.0824 (year) − 149.0	0.646	99.5
			Lowry	0.0766 (year) − 138.1	0.624	99.4
		wheat	Highmore	−0.000936 (year) + 4.0	0.028	35.7
			Onita	−0.0014 (year) + 4.9	0.066	52.5
			Lowry	−0.000836 (year) + 3.6	0.022	31.8
Syracuse, Nebraska	Syracuse	corn	Pawnee	0.08045 (year) − 139.2	0.388	95.9
			Shapsburg	0.08224 (year) − 138.9	0.309	92.4
			Wymore	0.08579 (year) − 150.8	0.417	96.8
		wheat	Pawnee	−0.002154 (year) + 6.1	0.156	77.0
			Shapsburg	−0.005218 (year) + 14.5	0.149	75.9
			Wymore	−0.001918 (year) + 06.0	0.125	71.4
Temple, Texas	Temple	corn	Houston	0.01589 (year) + 0.2	0.008	20.8
			Branyon	0.01733 (year) − 3.8	0.010	23.1
			Tarrant	−0.014 (year) + 57.4	0.006	18.0
		wheat	Houston	0.01806 (year) − 32.9	0.490	98.4
			Branyon	0.0269 (year) − 51.6	0.739	99.9
			Tarrant	0.01473 (year) − 25.4	0.244	87.8
Wichita, Kansas	Wichita	corn	Blanket	0.06167 (year) − 99.2	0.150	76.1
			Farnum	0.06517 (year) − 105.3	0.147	75.6
			Tabler	0.06618 (year) − 105.7	0.130	72.4
		wheat	Blanket	−0.00012 (year) + 2.9	0.001	3.6
			Farnum	−0.0014 (year) + 6.0	0.017	29.3
			Tabler	−0.00015(year) + 2.7	0.001	5.0
West Lafayette, Indiana	W Lafayette	corn	Drummer	0.108 (year) − 199.6	0.638	99.7
			Crosby	0.121 (year) − 221.1	0.600	99.5
			Starks	0.108 (year) − 198.2	0.623	99.6
			Toronto	0.112 (year) − 206.2	0.625	99.6
		wheat	Drummer	0.0037 (year) − 4.9	0.239	87.3
			Crosby	0.00358 (year) − 4.5	0.219	85.3
			Starks	0.00413 (year) − 5.4	0.227	86.2
			Toronto	0.00392 (year) − 5.0	0.217	85.2

[a]Erosion amounts are given in t ha^{-1}.

soil, a lesser soil water suction, and decreased infiltration. Thus more rainfall increases runoff disproportionately via soil moisture effects and vice versa.

[29] Greater amounts and rates of rainfall and runoff, other factors being equal, will tend to cause an increase in erosion. Increased runoff causes an increase in the shear stresses of overland and rill flow, which, in turn, increases the detachment capability and the sediment transport capacity of the flow. Splash and interrill erosion also tend to increase with increased rain. The simulation results for group 1 conditions showed a general increase in erosion with increases in precipitation, and the changes were proportionally greater than for runoff. For the cases of Atlanta, Georgia, and Cookeville, Tennessee, where the precipitation changes were relatively greater and more statistically significant than for West Lafayette, Indiana, both the runoff and the erosion changes were disproportionately greater than were the changes for precipitation (Table 7).

4.2. Group 2

[30] Group 2 characterizes situations where the precipitation, runoff, and erosion decreased. Essentially, this is the opposite set of results as for group 1. This group included results for wheat from Pierre, South Dakota; Syracuse, Nebraska; Corvallis, Oregon; and Wichita, Kansas (Table 7). One would perhaps expect that the results might be essentially opposite for the cases where precipitation decreases significantly as for when precipitation in-

Table 7. Precipitation, Runoff, and Erosion Estimated for 1990 and Changes (Δ) Estimated for the Period of 1990–2099

Location	Crop	Soil	Precipitation 1990, mm	Runoff 1990, mm	Erosion 1990, t ha^{-1}	Δ Precipitation		Δ Runoff, %	Δ Erosion, %	Group[a]
						Millimeters	Percent			
Atlanta, Georgia	corn	Cecil	1456.7	263.2	15.93	92.4^{d}	63^{d}	20.8^{f}	49.3^{f}	1
		Hiwasse		279.9	22.71			19.7^{f}	43.3^{f}	1
		Tifton		208.2	16.18			23.4^{f}	33.9^{f}	1
	wheat	Cecil		217.3	3.15			13.0^{e}	24.1^{f}	1
		Hiwasse		233.0	4.65			11.9^{e}	21.1^{f}	1
		Tifton		166.5	4.09			17.2^{f}	20.1^{f}	1
Cookeville, Tennessee	corn	Bewley	1511.5	316.6	15.38	160.4^{f}	10.6^{f}	24.2^{f}	101.9^{f}	1
		Hartsells		184.8	18.66			41.0^{f}	98.8^{f}	1
		Muskingun		239.6	20.14			31.1^{f}	93.1^{f}	1
	wheat	Bewley		284.0	3.38			23.6^{f}	44.8^{f}	1
		Hartsells		149.6	3.76			37.9^{f}	42.0^{f}	1
		Muskingun		195.3	3.75			30.9^{f}	42.9^{f}	1
Corvallis, Oregon	corn	Dayton	939.2	101.9	2.15	-45.1^{d}	-4.8^{d}	-0.6^{b}	-6.3^{c}	2
		Price		165.4	3.35			5.0^{c}	-4.2^{b}	6
		Apt		151.5	2.31			-5.0^{c}	-6.0^{c}	2
	wheat	Dayton		108.8	1.06			-7.3^{c}	15.9^{d}	4
		Price		189.8	1.42			-6.3^{c}	16.8^{e}	4
		Apt		162.6	0.95			-11.0^{d}	21.0^{e}	4
Pierre, South Dakota	corn	Highmore	828.6	136.3	14.81	-10.2^{b}	-1.2^{b}	2.3^{b}	59.1^{f}	8
		Onita		140.9	14.98			2.5^{b}	60.5^{f}	8
		Lowry		131.5	14.33			2.3^{b}	58.8^{f}	8
	wheat	Highmore		120.0	2.14			-14.2^{e}	-4.8^{c}	2
		Onita		100.6	2.11			-21.7^{e}	-7.3^{d}	2
		Lowry		112.4	1.94			-10.7^{d}	-4.8^{c}	2
Syracuse, Nebraska	corn	Pawnee	1040.5	248.9	20.90	-99.6^{f}	-9.6^{f}	-5.5^{c}	42.4^{f}	4
		Shapsburg		181.4	24.76			-2.9^{c}	36.5^{f}	4
		Wymore		224.8	19.92			-5.7^{c}	47.4^{f}	4
	wheat	Pawnee		218.5	1.81			-24.5^{f}	-13.1^{e}	2
		Shapsburg		144.7	4.12			-16.8^{e}	-13.9^{e}	2
		Wymore		197.5	2.18			-24.3^{f}	-9.7^{d}	2
Temple, Texas	corn	Houston	847.5	332.1	31.84	-60.3^{c}	-7.1^{c}	-2.9^{b}	5.5^{b}	4
		Branyon		310.4	30.69			-3.1^{b}	6.2^{b}	4
		Tarrant		189.8	29.54			-7.4^{c}	-5.2^{b}	2
	wheat	Houston		250.7	03.04			23.7^{d}	65.4^{f}	8
		Branyon		220.0	01.93			23.0^{d}	153.2^{f}	8
		Tarrant		147.9	3.91			17.1^{d}	41.4^{e}	8
Wichita, Kansas	corn	Blanket	957.5	187.9	23.52	-81.8^{e}	-8.5^{e}	-3.1^{b}	28.8^{e}	4
		Farnum		164.1	24.39			-1.7^{b}	29.4^{e}	4
		Tabler		170.4	26.00			-4.9^{c}	28.0^{d}	4
	wheat	Blanket		150.6	2.64			-14.6^{e}	-0.5^{b}	2
		Farnum		116.8	3.21			-7.2^{c}	-4.8^{c}	2
		Tabler		121.4	2.43			-13.2^{d}	-0.7^{b}	2
West Lafayette, Indiana	corn	Drummer	1343.5	265.8	15.32	34.8^{c}	2.6^{c}	-2.7^{b}	77.6^{f}	5
		Crosby		200.9	19.69			6.1^{c}	67.6^{f}	1
		Starks		243.1	16.72			1.7^{b}	71.1^{f}	1
		Toronto		251.3	16.68			-0.6^{b}	73.9^{f}	5
	wheat	Drummer		231.2	2.46			-16.3^{e}	16.5^{e}	5
		Crosby		160.0	2.59			-7.1^{c}	15.2^{e}	5
		Starks		233.9	2.80			-13.3^{e}	16.2^{e}	5
		Toronto		229.5	2.80			-15.0^{e}	15.4^{e}	5

[a] Group 1 is characterized by increase in precipitation, runoff, and erosion. Group 2 is characterized by decrease in precipitation, runoff, and erosion. Group 3 is characterized by increase in precipitation and runoff and decrease in erosion. Group 4 is characterized by decrease in precipitation and runoff and increase in erosion. Group 5 is characterized by increase in precipitation, decrease in runoff, and increase in erosion. Group 6 is characterized by decrease in precipitation, increase in runoff, and decrease in erosion. Group 7 is characterized by increase in precipitation and decrease in runoff and erosion. Group 8 is characterized by decrease in precipitation and increase in runoff and erosion.

[b] Significance level is 0–24.9%.

[c] Significance level is 25–49.9%.

[d] Significance level is 50–74.9%.

[e] Significance level is 75–89.9%.

[f] Significance level is 90–100%.

creases significantly; however, the picture was slightly more complicated than that. For results for Syracuse, Nebraska, for example, precipitation decreases were significant at the 90% level (Table 5); however, only the wheat fell into group 2. The reasons for this are discussed below when we present group 4 results. Where group 2 results were found, the pathway of decreased precipitation causing a direct effect on runoff and erosion (pathways A and B, Figure 2) was the dominant process of change in the system behavior.

4.3. Group 4

[31] Group 4 presented a decrease in the annual precipitation and runoff and an increase in erosion. This situation was observed for wheat in Corvallis, Oregon, and for corn

in Syracuse, Nebrasks; Wichita, Kansas; and Temple, Texas (Table 7). A typical example for this condition was observed for corn in Syracuse, Nebraska, on a Pawnee soil. The decrease expected in precipitation was 99.6 mm ($\Delta = -9.6\%$, $F = 90.1\%$, where F represents statistical significance of the change), the reduction in runoff was 5.5% ($F = 39.4\%$), and the increase in erosion was 42.4% ($F = 45.9\%$). The key factor in this case was that the crop yield for corn decreased by 41%. This decrease was a result of the decrease in precipitation, particularly through the growing season in the months of June, July, and August (Figure 1). The biomass reduction had more significant effect on the erosion than on runoff, which produced the results whereby erosion increased even while runoff decreased. Pathways A, C, and E were dominant (Figure 2).

[32] The reason this occurred was discussed previously by *Pruski and Nearing* [2002]. Both runoff and erosion are sensitive to biomass changes, but erosion is more so 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 subsurface roots and decaying residue, which mechanically hold the soil in place and provide a medium for microorganisms to thrive. The decrease of biomass production with decreased rainfall thus counteracted the decreased erosivity of the rain and runoff for group 4 results.

4.4. Group 5

[33] Group 5 represents conditions with increases in the annual precipitation and erosion and decreases in annual runoff (Table 7). This situation was observed only in West Lafayette, Indiana, where the precipitation changes were relatively small (2.6%, Table 7) and had a low significance level ($F = 39.5\%$, Table 2). 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 (Figure 1), and the changes in monthly runoff and erosion were dissimilar as well.

[34] As an example, we take the cases of corn growing on the Drummer and Crosby soils. The case of the Drummer soil fell into group 5, while the Crosby soil fell into group 1 (Table 7). For both cases the decreases of precipitation during the growing season of June through September effected reductions in overall runoff and little or no changes in erosion, while increases in precipitation in April and May caused large increases in both runoff and erosion (Table 8). March saw an increase in precipitation (Figure 1) and very little change in erosion but a decrease in runoff of 22.5 mm for the Drummer soil and 4.8 mm for the Crosby soil (Table 8). It was the 22.5 mm decrease in runoff in March that placed that condition into group 5, in other words, which shifted the annual balance of runoff to the negative range, even though precipitation and erosion increased. March represents the period of the spring thaw. With warmer temperatures during the winter months occurring under climate change through the century, the winter months saw a predicted increase in runoff. This would be due to the warmer temperatures decreasing the influence of frozen layers in the soil which inhibit infiltration, as well as less

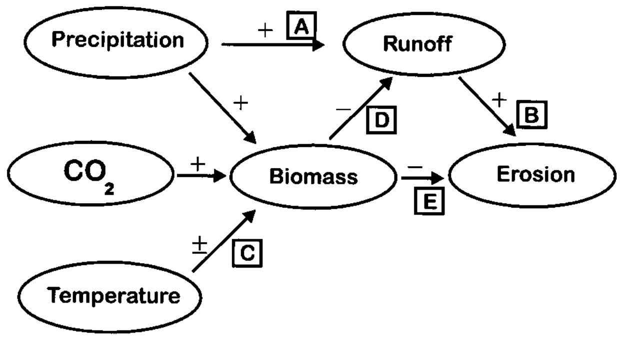

Figure 2. Schematic diagram of primary pathways whereby changes in precipitation, temperature, and atmospheric CO_2 concentrations may impact runoff and erosion. Plus signs indicate expected positive correlations between causes and effect, and minus signs signify expected negative correlations. Pathways are lettered for reference to the text.

carryover of snow into March to be made available for snowmelt runoff. The increase in runoff for March was greater for the silty clay loam Drummer soil than for the silt loam Crosby (Table 8), perhaps for reasons related to the lower hydraulic conductivity rate of the Drummer (Table 1).

4.5. Group 6

[35] Group 6 represents conditions with decrease in the precipitation and erosion but with runoff increase, i.e., exactly the opposite trends as for group 5. This situation was found only in one particular condition, for corn in Corvallis, Oregon, on the Price soil, where the significance levels were 69.1% for precipitation, 31.6% for runoff, and 22.6% for erosion. In other words, predicted changes in runoff and erosion were not highly significant for this treatment. For this case the changes in runoff and erosion were consistent on a month to month basis. Some months saw increases in predicted runoff and erosion, and others saw decreases, but for each individual month the trend was the same for both (Table 8). Furthermore, the months that showed increases for the Price soil also showed increases for the other soils, such as the Dayton (Table 8). It just so happened that the proportion of change in runoff and erosion was not the same when summed over all the months, so for the Price soil, where the predicted changes were not dramatic to begin with, the increases in runoff outweighed the decreases, while the predicted decreases in erosion outweighed the predicted increases.

4.6. Group 8

[36] Group 8 is characterized by conditions where the precipitation decreased but the runoff and the erosion both increased. In the cases of group 8 found in this study the results are explained in terms of biomass production. Dominant mechanisms of change corresponded to pathway C-D for runoff and C-E and C-D-B for erosion (Figure 2). A typical example of this situation corresponds to wheat in Temple, Texas. Temple is the location with the highest temperature and with one of the lowest annual precipitation values. The decrease in the precipitation (Table 5) produced an increase in the water stress, and the increase in the temperature (Table 6) produced the increase in the temper-

Table 8. Changes in Average Monthly Runoff and Soil Loss Over the Simulation Period 1990–2099 for Selected Cases[a]

Location	Soil	Variable	Janurary	February	March	April	May	June	July	August	September	October	November	December
West Lafayette, Indiana	Drummer	runoff, mm	8.6	0.3	−22.5	17.6	3.3	−14.5	−6.5	−1.1	−3.6	7.1	−0.8	5.1
		erosion, t ha^{-1}	0.0	0.1	0.2	6.7	4.7	−0.8	0.1	0.3	0.2	0.2	0.1	0.1
	Crosby	runoff, mm	6.4	2.7	−4.8	15.9	4.1	−13.4	−6.1	−1.4	−2.6	7.3	0.3	3.8
		erosion, t ha^{-1}	0.1	0.1	0.3	7.6	5.8	−1.2	0.1	0.3	0.3	0.2	0.1	0.1
Corvallis, Oregon	Price	runoff, mm	20.7	−1.9	3.4	−1.5	−3.4	−3.1	0.0	0.0	0.3	1.6	2.1	−14.7
		erosion, t ha^{-1}	0.02	0.0	0.1	0.1	−0.3	−0.4	0.0	0.0	0.0	0.1	0.1	0.0
	Dayton	runoff, mm	13.9	−1.9	1.1	−0.5	−1.3	−1.2	0.0	0.0	0.3	1.6	2.1	−14.7
		erosion, t ha^{-1}	0.02	0.0	0.0	0.0	−0.2	−0.2	0.0	0.0	0.0	0.0	0.1	−0.1

[a]The crop was corn in all cases shown.

ature stress. Both stresses acted to decrease the biomass production and crop yield, and less biomass translated to increases in both runoff and erosion.

[37] A similar situation was found for corn in Pierre, South Dakota, where the annual changes in the precipitation and runoff were small (Table 8), while erosion changes were great and highly significant ($F > 99\%$, Table 6). Although Pierre, South Dakota, had a only a small decrease in the annual precipitation (Table 5), the decreases in the precipitation during the corn-growing season were significant, occurring mainly in July (−37.3 mm) and August (−30.8 mm). Significant increases in temperature (Table 6) also were found during the corn-growing season. The combination of these two effects produced the significant reduction in the biomass production and, consequently, an increase in erosion and to a lesser extent runoff (Table 7).

5. Implications for the Future

[38] The results of this study suggested that in locations where precipitation increases are significant, we can expect runoff and erosion rates to increases at an even greater rate than the precipitation. Our study was limited in terms of the number of sites tested, so it is possible that there may be exceptions to this in certain cases. 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.

[39] We recognize that our analysis of the plant growth aspects of the system under temperature changes is limited. For example, there appears to be a wide range of resistance to high-temperature stress both within and among crop species what suggests a potential for genetic improvement, but which is difficult to currently model. To adapt to an environment of higher temperature, plant breeders may select cultivars that exhibit heat tolerance during reproductive development, high harvest indices, high photosynthetic capacities per unit leaf area, small leaves, and low leaf area per unit ground area (to reduce heat load) [*Hall and Allen*, 1993]. Smaller leaves may translate to lesser canopy and ground cover, even were crop yields to remain level.

[40] In essence, we have studied here the "dumb farmer" scenario [*Easterling et al.*, 1992a] rather than the "smart farmer" scenario [*Easterling et al.*, 1992b]. The "dumb farmer" scenario assumes no farmer adaptation to ameliorate against negative impacts, or take maximum advantage of positive impacts, of climate change. In the "smart farmer" scenario, *Easterling et al.* [1992b] concluded that "the simulations show(ed) that earlier planting, longer-season cultivars and the use of furrow diking for moisture conservation would offset some of the yield losses induced by climate change in warm-season crops. Longer-season varieties of wheat (a cool-season crop) and shorter-season varieties of the perennials wheatgrass and alfalfa were also effective." The next step in the process of evaluating erosional impacts of climate change will be to similarly consider farmer adaptations through the means available and appropriate for various regions and crops. Since these factors vary greatly across our study samples, we expect that the "smart farmer" approach will involve several studies based on either region or crop type. In *Easterling et al.*'s [1992a, 1992b] studies the region was limited to Missouri, Iowa, Nebraska, and Kansas.

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