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Impact of climate change on soil erosion, runoff, and wheat productivity in central Oklahoma

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Abstract

The potential for global climate changes to increase the risk of soil erosion is clear, but the actual damage is not. The objectives of this study were to evaluate the potential impacts of climate change on soil erosion, surface runoff, and wheat productivity in central Oklahoma. Monthly projections were used from the Hadley Centre's general circulation model, HadCM3, using scenarios A2a, B2a, and GGa1 for the periods of 1950–1999 and 2070–2099. Projected changes in monthly precipitation and temperature distributions between the two periods were incorporated into daily weather series by means of a stochastic weather generator (CLIGEN) with its input parameters adjusted to each scenario. The Water Erosion Prediction Project (WEPP) model was run for four climate scenarios including a recent historical climate and three tillage systems (conventional tillage, conservation tillage, and no-till). HadCM3-projected mean annual precipitation during 2070–2099 at El Reno, Oklahoma decreased by 13.6%, 7.2%, and 6.2% for A2a, B2a, and GGa1, respectively; and mean annual temperature increased by 5.7, 4.0, and 4.7 °C, respectively. Predicted average annual soil loss in the tillage systems other than no-till, compared with historical climate (1950–1999), increased by 18–30% for A2a, remained similar for B2a, and increased by 67–82% for GGa1. Predicted soil loss in no-till did not increase in the three scenarios. Predicted mean annual runoff in all three tillage systems increased by 16–25% for A2a, remained similar for B2a, and increased by 6–19% for GGa1. The greater increases in soil loss and runoff in GGa1 were attributed to greater variability in monthly precipitation as projected by HadCM3. The increased variability led to increased frequency of large storms. Small changes in wheat yield, which ranged from a 5% decrease in B2a to a 5% increase in GGa1, were because the adverse effects of the temperature increase on winter wheat growth were largely offset by CO_2 rise as well as the bulky decrease in precipitation occurred outside the growing

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season. The overall results indicate that no-till and conservation tillage systems will be effective in combating soil erosion under projected climates in central Oklahoma.

Keywords: Climate change; Erosion assessment; Soil conservation

1. Introduction

Analysis of climatology throughout the contiguous U.S. has revealed an upward trend in total precipitation and a bias toward more intense rainfall events during the last century (SWCS, 2003). More importantly, all general circulation models (GCMs) considered in the SWCS report have projected that globally averaged temperature, precipitation, and intensity of rainfall events will increase in the future with increased greenhouse gases (IPCC Working Group I, 2001; U.S. NAST, 2001). This trend toward precipitation occurring in more extreme events must be adequately simulated for soil erosion assessment, because most soil loss is caused by infrequent severe storms (Edwards and Owens, 1991). Under climate changes, the potential for such projected changes to increase the risk of soil erosion and related environmental consequences is clear, but the actual damage is not known and needs to be assessed (SWCS, 2003). These insights are needed to determine (i) whether a change in soil and water conservation practices is warranted under changed climate and (ii) what practices should be taken to adequately protect soil and water resources if a change is warranted.

Impacts of projected changes in precipitation, temperature, and CO_2 on crop productivity have been evaluated by many researchers (e.g., Rosenzweig and Parry, 1994; Semenov and Porter, 1995; Mearns et al., 1997; Mavromatis and Jones, 1998). Mean and variance changes in both precipitation and temperature were considered in those studies, and some results indicated that changes in climate variability (as measured by variance) could have profound effects on crop productivity.

Impacts of global climate change on soil erosion and surface runoff have been evaluated by considering changes in precipitation intensity or frequency. The change in mean precipitation has been assumed to take place by a change in storm frequency alone, intensity alone, or a combination of the two (Favis-Mortlock et al., 1991; Boardman and Favis-Mortlock, 1993; Savabi et al., 1993; Pruski and Nearing, 2002a,b). Pruski and Nearing (2002a) compared the effects of changes in storm frequency and/or intensity by allocating mean precipitation changes to changes in storm frequency alone, changes in storm intensity alone, or changes in both. They found that a change in precipitation amount and intensity had a much greater effect on soil erosion and runoff generation than a change in storm frequency. Specifically, a 1% change in precipitation resulted in, on average, a 2.4% change in soil loss and a 2.5% change in runoff if a change in precipitation amount and intensity accounted for all of the change, and resulted in a 0.9% change in soil erosion and a 1.3% change in runoff if a change in frequency accounted for all of the change. Other studies conducted in the U.S. (Savabi et al., 1993) and Great Britain (Favis-Mortlock et al., 1991) showed that average soil erosion increased by 2–4% for a 1% increase in precipitation if changes in storm intensity accounted for all the increase.

Zhang et al. (2004) developed a downscaling method that can be used to directly incorporate changes in monthly precipitation and temperature distributions including mean and variance into daily weather series using a stochastic weather generator (CLIGEN) developed by Nicks and Gander (1994). In the proposed method, future transitional probabilities of precipitation occurrence were estimated from linear relationships developed using historical transitional probability and monthly precipitation at a station of interest. Mean and variance ratios of GCM-projected monthly precipitation between a target and a control period were directly multiplied by mean and variance of daily precipitation at the station for use in daily weather generation. Their simulation results indicated that an increase in precipitation variance, which increased the occurrence frequency of large storms, substantially increased predicted soil loss and surface runoff in conventional tillage winter wheat in Oklahoma. They also reported that an increase in mean temperature significantly reduced wheat yield and therefore considerably increased soil loss and runoff.

Climate change scenarios used in this study were from the recent climate change experiments conducted using a third generation general circulation model (HadCM3) at the Hadley Centre, UK (Wood et al., 1999; Gordon et al., 2000; Pope et al., 2000). The HadCM3 climate change experiments issued monthly forecasts for the next 100 years for the entire globe. The greenhouse gas emissions scenarios of A2a, B2a, and GGa1 were selected to represent a wide range of CO_2 increases. Selection of the HadCM3 model was subjective, and other GCM models and emissions scenarios may also be used.

The objectives of this study were to evaluate the potential impacts of HadCM3-projected climate changes during 2070–2099 under A2a, and B2a, and GGa1 forcing on soil loss, surface runoff, and winter wheat productivity under three common tillage systems on a central Oklahoma site using a newly developed downscaling method that incorporates both mean and variance changes in projected monthly precipitation and temperatures into generated daily weather series.

2. Materials and methods

2.1. Projected climate change scenarios

Climate change experiments conducted by the UK Meteorological Office's Hadley Centre using the HadCM3 model used the emissions scenarios reported in the Special Report on Emissions Scenarios (SRES, 2000) by the Intergovernmental Panel on Climate Change (IPCC, http://www.cru.uea.ac.uk/link/emissions/sres.html). A set of four families of emissions scenarios was formulated based on future production of greenhouse gases and aerosol precursor emissions. Each scenario described one possible demographic, politico–economic, societal, and technological future. The SRES scenarios of A2a, B2a, and GGa1 were used in this study. Scenario B2a emphasized more environmentally conscious, more regionalized solutions to economic, social, and environmental sustainability. Compared with B2a, scenario A2a also emphasized regionalized solutions to economic and social development, but it was less environmentally conscious. Scenario GGa1 used the historical increase in the individual greenhouse gases from 1860–1990 in forcing, and then used the individual increases in greenhouse gases till 2099 as described in the IS92a emissions scenario, which assumed a 1% per year compound rise in radiative forcing. Based on the above emissions scenarios, CO_2 concentration by the year 2085 would increase to 867 ppmv (parts per million by volume) for A2a, 546 ppmv for B2a, and 640 ppmv for GGa1. It should be noted that the IS92a scenario, which was used in the GGa1 forcing, was widely used in the past, and was considered benchmark in the impact studies.

The grid cell of HadCM3 experiments is 2.5° by 3.75° (latitude by longitude). The two grid cells (between 35° N and 37.5° N and from 101.25° W to 93.25° W) selected in this study cover most parts of Oklahoma. Monthly precipitation, mean maximum and minimum temperatures of these two cells between 1950 and 2099 were extracted from the model output. Projected data between 1950 and 1999 were used as control, and data from 2070 to 2099 were referred to as changed climate. Overall means and variances of monthly precipitation and temperatures were calculated for each period and cell. Mean temperature shifts, temperature variance ratios, precipitation ratios, and precipitation variance ratios between the two periods were calculated for each month and cell. Since the study site is near the middle grid line of the two cells, the calculated quantities of the two cells were further averaged, as if they were weighted by distance. It should be pointed out that the weighting is not a true downscaling, but it does provide a reasonable first approximation for the El Reno location, particularly given the strong east–west gradient of precipitation and the flat topography in the region. The weighted quantities were either added to (in case of shift) or multiplied by (in case of ratio) their respective baseline parameter values derived from daily weather records between 1950 and 1999 for the El Reno station (see Zhang et al., 2004 for detailed method description). Modified parameters were then input into CLIGEN (V5.111), and 200 years of daily weather daily were generated for each of three emission scenarios. In addition, 200 years of baseline climate were generated using unmodified baseline parameter values.

2.2. Watershed description and management systems

Experimental watersheds, located at the U.S. Department of Agriculture, Agricultural Research Service, Grazinglands Research Laboratory, 7 km west of El Reno, Oklahoma, were used in the study. The watersheds are 80 m wide and 200 m long with a drainage area of 1.6 ha each. The longitudinal slope of the watersheds is approximately 3–4%. Soils are predominantly silt loam with an average of 23% sand and 56% silt in the A horizon. Three watersheds were in wheat production under contrasting management and tillage systems including conventional tillage, conservation tillage, and no-till since 1978. Wheat productivity, precipitation, surface runoff, sediment, and soil moisture (intermittent) were monitored. Measured data and actual management practices were used to calibrate and improve the WEPP water balance and plant growth components (Zhang, 2004). The three erodibility parameters (i.e., inter-rill and rill erodibility and rill critical shear stress) in the WEPP erosion component were further calibrated using measured sediment data from three watersheds. Since soil physical properties in the three watersheds were similar, only one set of erodibility parameters was derived. The measured average annual soil losses between 1983 and 1995 were 5712, 2262, and 269 kg/ha for conventional tillage, conservation tillage, and no-till; and the calibrated soil losses were 5600, 2240, and 224 kg/ha, respectively.

The WEPP model is a physically based, continuous daily simulation model (Flanagan and Nearing, 1995). It simulates surface hydrology, plant growth, soil erosion, daily soil water balance, and residue decomposition. It requires four input files (i.e., slope, soil, climate, and crop management). Measured slope profile and soil properties were used to build the slope and soil input files. A common regional cropping system (annual winter wheat–summer fallow) and three contrasting tillage systems (conventional, conservation, and no-till) were used. In the simulation, winter wheat was planted on October 15 and harvested on June 20 of the following year in the baseline climate scenario. However, a new planting date of November 1 and a harvest date of June 1, which were selected from north Texas where the present temperature regime is similar to the projected temperature for the period of 2070–2099 at El Reno, were used in the three changed climate scenarios to accommodate the increased temperature. It is worth noting that planting and harvest dates have a dramatic impact on biomass production and grain yield of winter wheat. Four tillage operations, one moldboard plow and three disk operations, approximately one month apart in the summer, were used in the conventional tillage, while three disk operations were used in the conservation tillage treatment. Using the same slope, soil, and crop management input files, a CO_2-sensitive version of the WEPP model as described by Favis-Mortlock and Savabi (1996) was run for 200 years for each combination of the tillage systems and climate scenarios.

3. Results and discussion

Five-year moving averages of historical and projected annual precipitation (average of the two grid cells) at El Reno for the period of 1950–1999 are plotted in Fig. 1. The

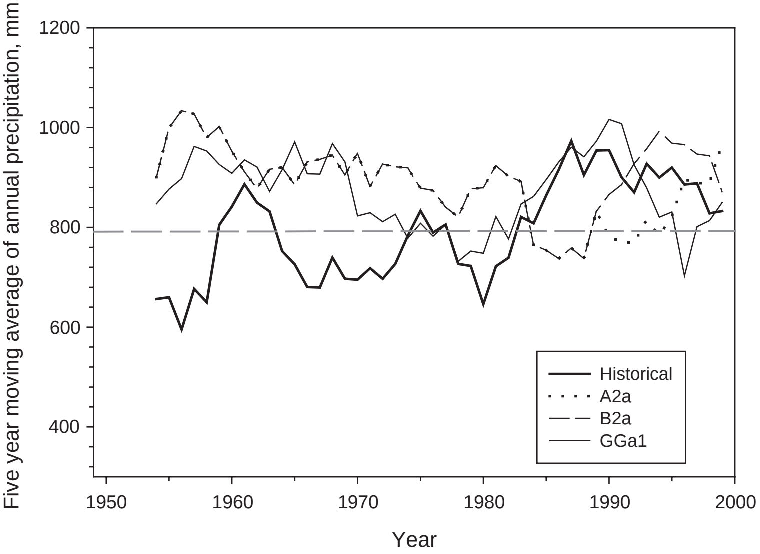

Fig. 1. Five-year moving average of historical and HadCM3-projected annual precipitation using A2a, B2a, and GGa1 forcing at El Reno for the period of 1950–1999 (Horizontal line indicates the historical mean).

moving averages of projected annual precipitation in the GGa1 scenario, which was forced using the historical increase in the individual greenhouse gases from 1860 to 1990, agreed well with those of historical data after 1975 except for a projected drier

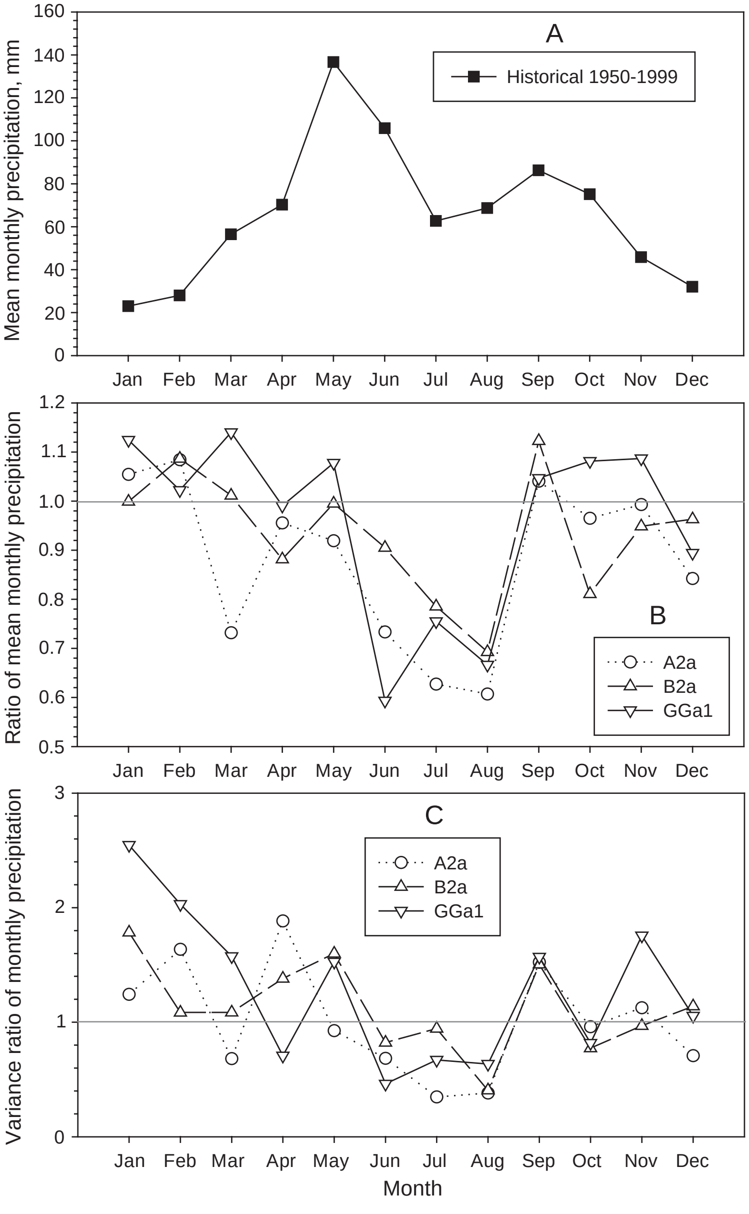

Fig. 2. (A) Historical mean monthly precipitation at El Reno during 1950–1999; (B) Ratio of HadCM3-projected mean monthly precipitation between 1950–1999 and 2070–2099 at El Reno for three emissions scenarios; (C) Variance ratios of projected monthly precipitation between 1950–1999 and 2070–2099.

spell near 1995. The simulated patterns after 1980 in the B2a scenario resembled the historical patterns measured after 1975, indicating a five-year time lag with the projected data in this scenario. Among the three emissions scenarios, the A2a scenario, which predicted the most increases in temperature and CO_2, produced the least agreement with the historical trends. It should be pointed out that the disagreement might have also stemmed from the inadequate "downscaling" of HadCM3's monthly projections from a grid scale to a particular location. As mentioned earlier, the weighting by averaging the two adjacent grid cells as used in this paper was not a true downscaling but a first approximation.

The measured average annual precipitation between 1950 and 1999 at El Reno was 791 mm (Fig. 2A). The projections of HadCM3 for the location (after "downscaling") called for decreases of 13.6%, 7.2%, and 6.2% for the A2a, B2a, and GGa1 scenarios, respectively, for the period of 2070–2099. However, the average reduction generated by CLIGEN was 13.4%, 6.7%, and 4.8% for scenarios A2a, B2a, and GGa1 respectively, showing a 1.4% overprediction for the GGa1 scenario. The discrepancy between the HadCM3 projections and the CLIGEN generations might be caused by the model

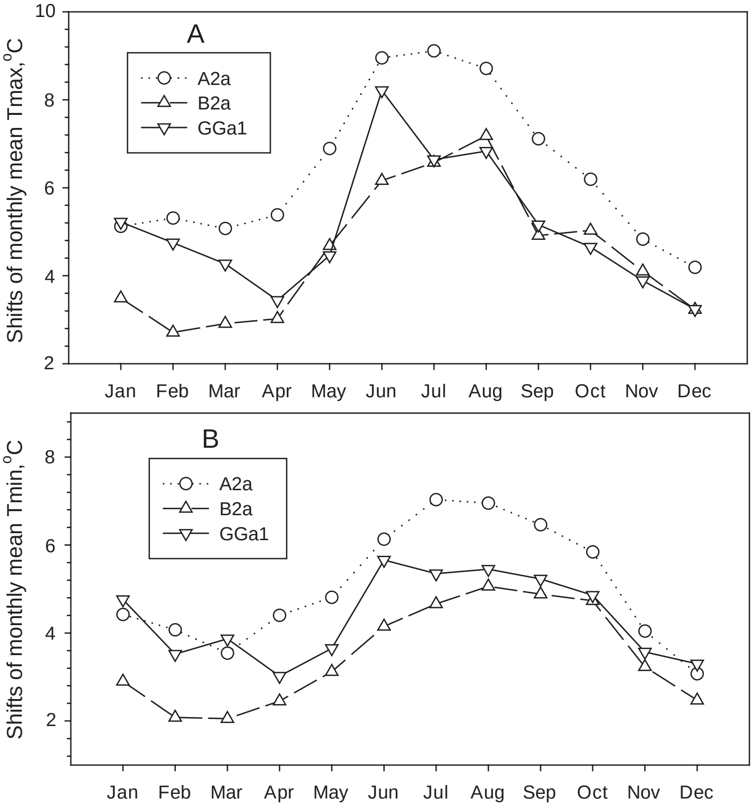

Fig. 3. HadCM3-projected shift of monthly mean temperature between 1950–1999 and 2070–2099 at El Reno for three emissions scenarios (A) maximum temperature, $T_{\max}$; (B) minimum temperature, $T_{\min}$.

approximation of precipitation distribution as well as model roundup errors. However, the discrepancy can be further reduced, if desired, by readjusting the monthly mean precipitation parameters. All three scenarios predicted a decrease in precipitation in June, July, and August, but slight increases during September and the winter months of January and February (Fig. 2B). Variances of monthly precipitation projected in all three scenarios were also lower in these three months, but were somewhat higher or unchanged in the remaining months (Fig. 2C). The mean annual temperature increases projected by HadCM3 were 5.7 °C for A2a, 4.0 °C for B2a, and 4.7 °C for GGa1, and those generated by CLIGEN were 4.9, 3.5, and 4.4 °C, respectively. The CLIGEN-generated mean increases were slightly less than these called for by HadCM3 for all three scenarios due to model approximation errors. The projected monthly increases for both maximum and minimum temperatures were greater in the warmer months than in the cooler months (Fig. 3). This trend is consistent with the drier summer as projected by HadCM3. The lesser temperature rise during the growing-season would have a less adverse impact on wheat production, because for each degree increase in the mean growing-season temperature grain yield of winter wheat would decrease by some 10% on the study site (Zhang et al., 2004).

With the A2a scenario, average annual precipitation during 2070–2099 decreased by approximately 13% compared with the baseline climate, while CO_2 concentration increased by 148% by year 2085. Predicted surface runoff decreased by 16–25% in all

Table 1
Simulated average annual precipitation, runoff, soil loss, wheat yield, and their percent changes relative to the baseline climate at the elevated CO_2 levels for the changed climate scenarios

Tillage systems	Precipitation		Runoff		Soil loss		Wheat yield	
	Depth (mm)	Change (%)	Depth (mm)	Change (%)	Rate (kg/ha)	Change (%)	Rate (kg/m^2)	Change (%)
Baseline scenario at 350 ppmv CO_2								
Conv.	795	NA	91	NA	6048	NA	0.249	NA
Cons.	795	NA	79	NA	2464	NA	0.250	NA
NT	795	NA	66	NA	224	NA	0.241	NA
Scenario A2a at 867 ppmv CO_2								
Conv.	688	−13.4	69	−25.0	7840	29.6	0.257	3.2
Cons.	688	−13.4	66	−16.1	2912	18.2	0.257	2.8
NT	688	−13.4	53	−19.2	0	NA	0.246	2.1
Scenario B2a at 546 ppmv CO_2								
Conv.	742	−6.7	86	−5.6	6272	3.7	0.237	−4.8
Cons.	742	−6.7	79	0	2464	0	0.237	−5.2
NT	742	−6.7	66	0	224	0	0.231	−4.2
Scenario GGa1 at 640 ppmv CO_2								
Conv.	757	−4.8	97	5.6	10,080	66.7	0.263	5.6
Cons.	757	−4.8	91	16.1	4480	81.8	0.263	5.2
NT	757	−4.8	79	19.2	224	0	0.254	5.4

Conv. = conventional tillage, Cons. = conservation tillage, NT = no-till, ppmv = parts per million by volume, NA = not appropriate.

three tillage systems (Table 1). The greater decrease in runoff than in precipitation was partially attributed to increased evaporative demands stemming from increased temperature as well as better crop growth due to CO_2 rise. Contrary to the runoff decrease, predicted soil loss was increased by 30% in the conventional tillage system and by 18% in the conservation tillage system. The increase in soil loss was caused by increased variability of daily precipitation, which was imparted by the increased variability of monthly precipitation as projected by HadCM3 (Fig. 2C). Greater variability in daily precipitation distribution led to increased occurrence of large storms and therefore greater soil loss.

With the B2a scenario, annual precipitation decreased by 7% during 2070–2099 and CO_2 concentration increased by 56% by year 2085. Runoff and soil loss were similar to those of the baseline climate scenario (Table 1). Compared with A2a, the increase in runoff was due to the lesser increase in temperature and the poorer growth of winter wheat, which together lowered evaporative demands. The decrease in wheat grain yield was attributable to the lesser increase in CO_2 concentration. Zhang et al. (2004) reported that for each 10% increase in CO_2, wheat yield increased by approximately 5% on the same study site.

With the GGa1 scenario, annual precipitation decreased by 5% and CO_2 increased by 80%. Predicted surface runoff, contrary to the decrease in precipitation, increased by 6%, 16%, and 19% in the conventional tillage, conservation tillage, and no-till, respectively, compared with the baseline climate, because of an increase in precipitation variability. As a result, soil losses increased by 67% in the conventional tillage and by 82% in the conservation tillage. Another important reason for the greater increase in soil loss, compared with scenarios A2a and B2a, was the larger increase in precipitation variability

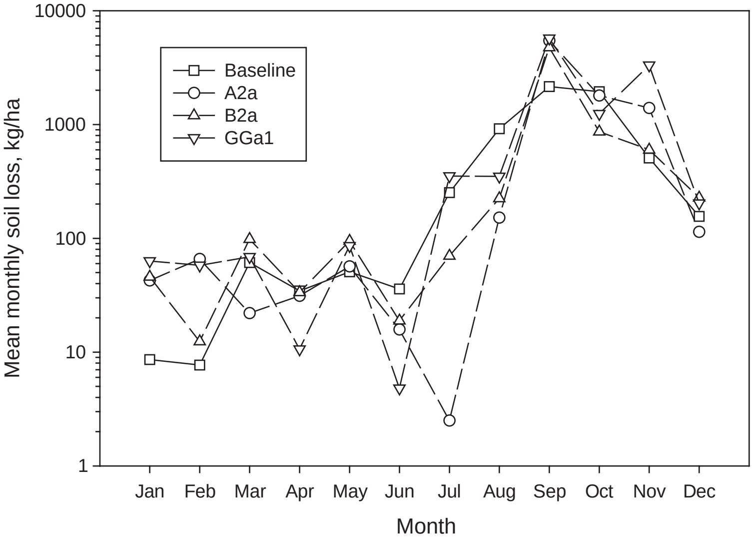

Fig. 4. WEPP-simulated mean monthly soil loss in the conventional tillage system under the baseline and three changed climate scenarios during 2070–2099 at El Reno.

(Fig. 2C). In contrast to the soil loss increases in the conventional and conservation tillage systems, there was no predicted soil loss increase in the no-till system. This result suggests that the no-till system would be effective in controlling soil erosion under the changed climates as assumed here. The best wheat yields were predicted for the GGa1 scenario, which was an integrated result of the minimal reduction in precipitation and the moderate increases in both CO_2 and temperature as compared to A2a and B2a, since temperature increase and CO_2 rise play an offsetting role in determining wheat growth and grain yield.

Mean monthly soil loss in conventional tillage during 2070–2099 is plotted on a logarithmic *Y*-axis (Fig. 4). Substantial soil loss increases were predicted for September in all three-climate change scenarios. This was attributable to the increased precipitation variability (Fig. 2C) as well as favorable surface conditions for erosion in which soils were intensely tilled during seedbed preparation and the soil surfaces were unprotected by any cover. There was a close correlation between changes in precipitation variability and changes in monthly soil loss. An increase in precipitation variability was often accompanied by an increase in soil loss, and vice versa. These results indicate that soil loss prediction is sensitive to changes in precipitation variability.

4. Implications

The Hadley Centre model (HadCM3) predicts a general decrease in annual precipitation for the region near El-Reno, OK over the century, but those decreases in rainfall may not result in reductions in wheat yields. This may be due to the fact that the decrease in annual rainfall is primarily predicted for the summer months, while the rainfall during the growing season months of September through April is relatively constant or, in some months, increasing, and the fact that the negative impact of the temperature increase is largely offset by the positive effect of the CO_2 rise. Regarding soil erosion and conservation concerns, the results indicate a possibility for increasing erosion despite the predicted decrease in annual precipitation. This is due to a predicted increase in rainfall, and particularly of the large events as reflected by a greater variability of daily rainfall amount, during the critical fall period when cover is low and the soils are more susceptible to erosion. The good news is, however, that it appears that the use of no-till and conservation tillage is sufficient to maintain low erosion levels and thus protect the soil.

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References

Boardman, J., Favis-Mortlock, D.T., 1993. Climate change and soil erosion in Britain. The Geographical Journal 159 (2), 179–183.

Edwards, W.M., Owens, L.B., 1991. Large storm effects on total soil erosion. J. Soil and Water Conservation 46 (1), 75–78.

Favis-Mortlock, D.T., Savabi, M.R., 1996. Shifts in rates and spatial distribution of soil erosion and deposition under climate change. In: Anderson, M.G., Brooks, S.M. (Eds.), Advances in Hillslope Processes. John Wiley, New York, pp. 529–560.

Favis-Mortlock, D.T., Evans, R., Boardman, J., Harris, T.M., 1991. Climate change, winter wheat yield, and soil erosion on the English South Downs. Agricultural Systems 37, 415–433.

Flanagan, D.C., Nearing, M.A. (Eds.), 1995. USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10. USDA-ARS Nat. Soil Erosion Research Lab, West Lafayette, Ind.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, F.B., Wood, R.A., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16, 147–168.

IPCC (Intergovernmental Panel on Climate Change) Working Group I, 2001. Climate Change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Mavromatis, T., Jones, P.D., 1998. Comparison of climate change scenario construction methodologies for impact assessment studies. Agricultural and Forest Meteorology 91, 51–67.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1997. Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. Climatic Change 35, 367–396.

Nicks, A.D., Gander, G.A., 1994. CLIGEN: A weather generator for climate inputs to water resource and other models. Proceedings of the 5th International Conference on Computers in Agriculture. American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 3–94.

Pope, V.D., Gallani, M.L., Rowntree, P.R., Stratton, R.A., 2000. The impact of new physical parameterizations in the Hadley Centre Climate Model-HadAM3. Climate Dynamics 16, 123–146.

Pruski, F.F., Nearing, M.A., 2002a. Runoff and soil-loss responses to changes in precipitation: a computer simulation study. Journal of Soil and Water Conservation 57 (1), 7–16.

Pruski, F.F., Nearing, M.A., 2002b. Climate-induced changes in erosion during the 21st century for eight U.S. locations. Water Resources Research 38 (12) (art. 1298).

Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. Nature 367, 133–137.

Savabi, M.R., Arnold, J.G., Nicks, A.D., 1993. Impact of global climate change on hydrology and soil erosion: a modeling approach. In: Eckstein, Y., Zaporozec, A. (Eds.), Proceedings of Industrial and Agricultural Impact of Environmental and Climatic Change on Global and Regional Hydrology. Water Environment Federation, Alexandria, Virginia, pp. 3–18.

Semenov, M.A., Porter, J.R., 1995. Climatic variability and the modeling of crop yields. Agricultural and Forest Meteorology 73, 265–283.

SWCS, 2003. Conservation implications of climate change: soil erosion and runoff from cropland. A Report from the Soil and Water Conservation Society. Soil and Water Conservation Society, Ankeny, Iowa. (www.swcs.org/docs/climate%20change-final.pdf).

U.S. NAST (National Assessment Synthesis Team), 2001. Climate change impacts on the United States: the potential consequences of climate variability and change. Foundation Report. U.S. Global Change Research Program. Cambridge University Press, Cambridge, UK.

Wood, R.A., Keen, A.B., Mitchell, J.F.B., Gregory, J.M., 1999. Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model. Nature 399, 572–575.

Zhang, X.C., 2004. Calibration, refinement, and application of WEPP model for simulating climatic impact on wheat production. Transactions of the American Society of Agricultural Engineers 47 (4), 1075–1085.

Zhang, X.C., Nearing, M.A., Garbrecht, J.D., Steiner, J.L., 2004. Downscaling monthly forecasts to simulate impacts of climate change on soil erosion and wheat production. Soil Science Society of America Journal 68, 1376–1385.