Downscaling Monthly Forecasts to Simulate Impacts of Climate Change on Soil Erosion and Wheat Production

X.-C. Zhang,* M. A. Nearing, J. D. Garbrecht, and J. L. Steiner

ABSTRACT

Climate change can affect agricultural production and soil and water conservation. 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 develop a method for downscaling monthly climate forecasts to daily weather series using a climate generator (CLIGEN), and to determine the potential impacts of projected mean and variance changes in precipitation and temperature on soil erosion and wheat (*Triticum Aestivum* L.) yield. Monthly forecasts for the periods of 1950–1999 and 2056–2085 for the Oklahoma region, projected by a general circulation model (HadCM3), were used. Projected mean and variance changes in precipitation and temperatures between the two periods were satisfactorily incorporated into CLIGEN input parameters derived for the El Reno station, Oklahoma, and future transitional probabilities of precipitation occurrence were estimated as a linear function of historical monthly precipitation. Five climate change scenarios were constructed, and the Water Erosion Prediction Project (WEPP) model was run for each combination of five climate scenarios and three tillage systems. A 50% increase in CO_2 resulted in some 26% increase in wheat yield. At that elevated CO_2 level, projected decrease in total precipitation decreased surface runoff, soil loss, and wheat yield. However, predicted changes in precipitation variance increased runoff by 15 to 17%, and increased soil loss by 10 and 19% under conservation and conventional tillage, respectively. Predicted increase in mean temperature reduced wheat yield by 31%, and increased soil loss by 40 and 19% under conservation and conventional tillage, respectively. Under the assumed climate change, predicted average soil loss under conventional tillage was about 2.6 times that under conservation tillage and 29 times that under no-till. With all changes considered, predicted average wheat yield during 2056–2085, compared with the present climate at the present CO_2 level, would decrease by 12%; runoff would increase by $<7\%$; and soil loss would increase by $<8\%$ in all tillage systems. Overall results indicate that adoption of conservation tillage and no-till will be effective in controlling soil erosion under projected climate change used in this study.

Climate change will, to varying degrees, affect agricultural production and soil and water conservation. Great efforts have been undertaken to predict future climate change due to increases in greenhouse gases and to analyze observed climate records for existing trends. Several general circulation models (GCMs) have projected that globally averaged temperature, precipitation, and intensity of rainfall events will increase in the future with increased greenhouse gases (Intergovernmental Panel on Climate Change [IPCC] Working Group I, 2001; U.S. National Assessment Synthesis Team [NAST], 2001). Interestingly, analysis of climatology throughout the contiguous USA has revealed an upward trend in total precipitation and a bias toward more intense rainfall events during the last century (Soil and Water Conservation Society [SWCS], 2003). As was stated in that report, the potential for such 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. The report called for more detailed assessments of the impacts and environmental consequences in various regions, seasons, and agricultural production systems (SWCS, 2003).

Many variables such as precipitation, temperature, CO_2 concentration, and solar radiation affect soil erosion and crop production. The impact of each variable is different and complex. A change in precipitation, for example, affects soil erosion and crop growth differently if that change comes from a change in precipitation frequency (number of wet days) versus a change in precipitation intensity (rainfall amount per day) as shown by Pruski and Nearing (2002a). Furthermore, the interactive effects among climatic variables can be significant. The actual effects of individual variables and their interactions would ultimately depend upon their individual and/or collective impacts on plant growth and biomass production.

Impact of global climate change, including changes in precipitation, temperature, and CO_2 on crop production, has been evaluated by many researchers (e.g., Rosenzweig and Parry, 1994; Mearns et al., 1997; Semenov and Porter, 1995; Mavromatis and Jones, 1998). Mean and variance changes in both precipitation and temperature were considered when generating climate change scenarios in those studies, and their results indicated that changes in climate variability (as measured by variance) could have more profound effects on crop productivity than changes in mean climate under certain circumstances. Similarly, impacts of global climate change on soil erosion and surface runoff were evaluated under variously generated climate change scenarios. To date, the effort has been mainly focused on simulating consequences induced by changes in mean precipitation. 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 (Pruski and Nearing, 2002a, 2002b; Savabi et al., 1993; Favis-Mortlock et al., 1991; Boardman and Favis-Mortlock, 1993). However,

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Abbreviations: CLIGEN, climate generator; GCMs, general circulation models; HadCM3, the third Hadley Centre coupled ocean-atmosphere GCM; IPCC, Intergovernmental Panel on Climate Change; RCMs, regional climate models; SRES, Special Report on Emissions Scenarios; SWCS, Soil Water Conservation Service; WEPP, Water Erosion Prediction Project; WGEN, weather generator.

the impacts of precipitation variance changes on soil erosion and surface runoff have not yet been evaluated.

Using the WEPP model (Flanagan and Nearing, 1995), 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 storm size 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 storm size 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 USA (Savabi et al., 1993) and Great Britain (Favis-Mortlock et al., 1991) showed that average soil erosion increased by 2 to 4% for a 1% increase in precipitation if changes in storm intensity accounted for all the increase.

Stochastic daily weather generators, such as WGEN (Richardson and Wright, 1984) and CLIGEN (Nicks and Gander, 1994), have been used to generate daily weather series of climate change scenarios for impact studies (e.g., Wilks, 1992; Katz, 1996; Mearns et al., 1997; Semenov and Porter, 1995; Mavromatis and Jones, 1998; Pruski and Nearing, 2002a, 2002b; Savabi et al., 1993; Favis-Mortlock et al., 1991). Model parameters of these weather generators can be readily manipulated to simulate changes in mean and variance quantities for sensitivity analyses, or be deliberately modified to mimic changes in mean and variance as predicted by GCMs for impact assessment. As stated in the SWCS report (SWCS, 2003), all GCMs considered predicted that precipitation intensity would increase at a rate greater than the rate of increases in mean. This trend toward precipitation occurring in more intense and more extreme events may be simulated through modifying mean, variance, and skewness of daily precipitation distribution. A change in mean would result in a shift in precipitation distribution, but changes in variance and skewness would change the shape of the distribution, especially in the tail region, which controls the intensity and frequency of extreme events. For soil erosion assessment, adequate simulation of increased frequency of extreme events is extremely important, because most soil erosion occurs during infrequent severe storms (Zhang and Garbrecht, 2002).

Climate change scenarios used in this study were from the recent climate change experiments conducted using a third generation general circulation model at the Hadley Centre, UK (HadCM3). The HadCM3 climate change experiments issued monthly forecasts for the next 100 yr for the entire globe. The selection of the HadCM3 model was subjective, and other GCMs could also be used. It should be mentioned that future climate projections may differ between GCMs, especially in particular regions, and therefore the resultant impacts on hydrology and soil erosion in a particular region would be different when different GCMs are used.

The objectives of this study were to (i) develop a method for downscaling monthly climate forecasts to daily weather series using the CLIGEN model by considering both mean and variance changes in precipitation and temperatures, and to (ii) estimate further the responses of soil erosion, surface runoff, and wheat yield to mean and variance changes in precipitation and/or temperatures projected for the period of 2056–2085 for El Reno, OK using the WEPP model. The El Reno location was selected for this study because the WEPP model had been calibrated on this site.

MATERIALS AND METHODS

Watershed Description and Monitoring

Three experimental watersheds, located at the USDA, ARS, Grazinglands Research Laboratory, 7 km west of El Reno, OK were used for 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 to 4%. Soils are predominantly silt loam with an average of 23% sand and 56% silt in the A horizon. The watersheds were in the annual winter wheat–summer fallow rotation in contrasting management and tillage systems including conventional tillage, conservation tillage, and no-till from 1980 to 1995. Precipitation, surface runoff, and sediment were recorded between 1985 and 1995, and wheat yields and soil moisture contents were intermittently measured during the period.

Water Erosion Prediction Project Model Calibration

The WEPP model is a continuous daily simulation model (Flanagan and Nearing, 1995). It contains erosion, hydrology, climate, daily water balance, plant growth, and residue decomposition components. The hydrology, water balance, and plant growth components were calibrated using measured hydrological and winter wheat data on these watersheds (Zhang, 2004). The calibrated WEPP model simulated annual surface runoff, daily soil moisture content, and wheat biomass production reasonably well. For example, the model efficiency, which is a good measure of model prediction relative to measured data, between WEPP-predicted and measured annual runoff was 0.31 (Zhang, 2004). The model efficiency between predicted and measured aboveground biomass at harvest was 0.50.

In this study, the WEPP erosion component was further calibrated on all three watersheds using measured sediment data. Three erodibility parameters (interrill erodibility, rill erodibility, and rill critical shear stress) were adjusted to match measured and simulated average annual soil losses from the watersheds. The calibrated average annual soil losses agreed well with the measured soil losses for all three tillage systems (Fig. 1). Since soil properties in the three watersheds were similar, one set of the erodibility parameters was derived and used in all simulations. The good agreement indicates that the relative effects of crop management including tillage operations on soil erosion are adequately represented in WEPP.

The WEPP model (version 2001), which was modified to be CO_2–sensitive, was used in this study. The modified WEPP model as described by Favis-Mortlock and Savabi (1996) invokes CO_2–sensitive biomass production and plant transpiration subroutines when CO_2 concentration is above the present level.

Stochastic Climate Generator

The CLIGEN model is a stochastic daily weather generator (Nicks and Gander, 1994). It generates the occurrence of daily

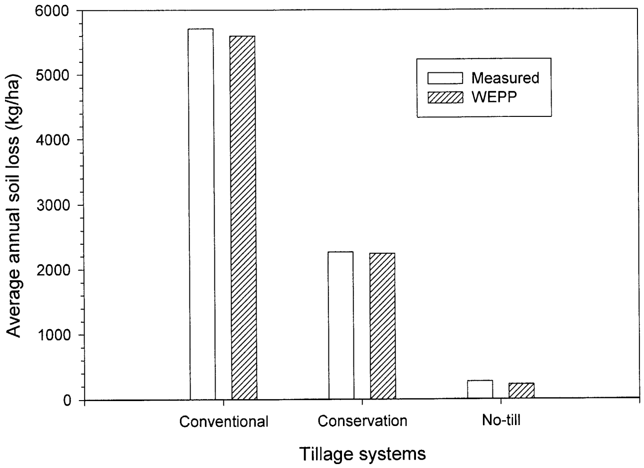

Fig. 1. Measured and WEPP-simulated average annual soil loss in three tillage systems at El Reno for the period of 1980–1995.

precipitation (related to precipitation frequency) using a first-order, two-state Markov chain based on the transitional probability of a wet day following a wet day and a wet day following a dry day. The daily precipitation amounts are generated using a transformed (skewed) normal distribution. The daily maximum and minimum temperatures are generated using normal distributions. Other variables such as storm characteristics, dew temperature, solar radiation, and wind speed and direction are also generated in CLIGEN but not considered in this study. In CLIGEN, daily weather is generated on a monthly basis (i.e., no dependency between months), and each variable is generated independent of other variables. A detailed account of the CLIGEN model can be found at http://horizon.nserl.purdue.edu/Cligen/ (verified 27 Feb. 2004).

Zhang and Garbrecht (2003) and Zhang (2003) evaluated the CLIGEN model for four dispersed Oklahoma locations, ranging in mean annual precipitation from 420 to 1150 mm. They reported that CLIGEN adequately reproduced daily precipitation, wet and dry spells, number of wet days, and daily maximum and minimum temperatures in Oklahoma.

Because each variable is generated independently and each variable's mean and standard deviation are explicitly used in its probability distribution function, incorporation of GCM-projected monthly changes in statistical moments into model parameters becomes straightforward. In contrast, adaptation of other weather generators such as WGEN for generating climate change scenarios through modifying relevant distribution parameters is more complex, and requires additional constraints and assumptions that would result in additional alternatives for a possible climate change scenario (Wilks, 1992; Mearns et al., 1997).

Emissions Scenario and Projected Climate Change

The HadCM3 climate change experiments used the emissions scenarios reported in the Special Report on Emissions Scenarios (SRES) of 2000 by the IPCC (IPCC, 2000). 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-B2a scenario was used for this study. This emissions scenario emphasized more environmentally conscious, and regionalized solutions to economic, social, and environmental sustainability. The assumed emissions of greenhouse gases in this scenario were relatively low compared with other scenarios. For example, it was assumed that atmospheric CO_2 concentrations would increase to 0.05% by volume (about a 50% increase over the present level) by the Year 2070. This increase is much slower than the increase in the IPCC-IS92a scenario, which assumed a 100% increase in CO_2 by 2070. The IS92a scenario was considered benchmark and was widely used in the impact studies in the past.

The HadCM3 model was configured with grid cells that extended 2°30′ by 3°45′ (latitude by longitude). The two grid cells (between 35°N and 37°30′ N lat. and from 101° 25′ W to 93°25′ W long.) selected in this study cover the majority of Oklahoma. The monthly precipitation, mean maximum temperature, and mean minimum temperatures that were projected for these two cells for the periods of 1950–1999 and 2056–2085 were extracted from HadCM3 for this study. Projected data between 1950 and 1999 were used as a control, and data from 2056 to 2085 were assumed to represent the changed climate. Overall means and variances (interannual) 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. Because the study site is located near the middle grid line of the two cells, the calculated quantities of the two cells were averaged based on an equal weighting. The weighted quantities or guided perturbations were then used to modify CLIGEN input parameters to generate either hypothetical or future climate changes for the El Reno location.

Generating Climate Change Scenarios

Dynamic and empirical (statistical) approaches are often used to downscale GCM projections. Dynamic downscaling is achieved by nesting Regional Climate Models (RCMs) within GCM output fields. One frequently used approach for empirical downscaling is to perturb the present climate under the guidance of the GCM-projected relative changes. An empirical approach similar to that of Hewitson (2003) was used here. In this approach the average relative changes were applied to the observational climatology at El Reno. This approach avoided potential errors associated with the direct use of raw GCM outputs and tied the projected relative changes directly back to the historical climatology at the scale of interest.

Five climate change scenarios were generated below using CLIGEN by adapting the HadCM3-projected relative changes in a stepwise manner to isolate the potential impacts of each variable (temperature or precipitation) and each parameter (mean or variance) on soil erosion, surface runoff, and wheat yield. Scenario 1 represents the present climate (baseline); Scenarios 2 to 4 are hypothetical climate patterns; and Scenario 5 reflects the future climate change during 2056–2085. To ensure reliable representation of each climate scenario, 100 yr of daily weather data were generated for each scenario.

The baseline scenario (Scenario 1) was based on daily precipitation, maximum temperature, and minimum temperature measured at the El Reno station between 1950 and 1999. The CLIGEN monthly precipitation and temperature parameters in Table 1 were derived from these measured daily data. The other parameters required to perform the baseline scenario were triangulated for El Reno from the CLIGEN databases using a CLIGEN-support parameterization software program. The baseline scenario was then generated using all the derived parameters, which served as the basis of comparison for other scenarios performed in the study.

Following the establishment of the baseline, Scenario 2 that accounted for the changes in future mean precipitation and transitional probabilities of rainfall occurrence was generated. The projected 2056–2085 means of monthly total precipitation

Table 1. Baseline and modified CLIGEN input parameters (monthly means of daily values) for El Reno.†

Month	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						Baseline climate (1950–1999)						
Mean P (R_d), mm	6.10	5.84	9.14	10.16	14.22	13.21	10.67	10.67	13.72	13.72	9.40	6.86
SD P, mm	8.38	7.87	12.45	12.95	18.03	17.02	14.48	14.22	23.37	18.03	14.73	10.16
$P_{w/w}$	0.34	0.38	0.38	0.40	0.46	0.43	0.39	0.35	0.42	0.41	0.45	0.34
$P_{w/d}$	0.09	0.13	0.15	0.18	0.24	0.21	0.14	0.17	0.16	0.13	0.11	0.12
Mean T_{max}, °C	8.39	11.59	16.23	21.75	25.92	30.43	33.52	33.10	28.79	22.84	15.16	9.90
SD T_{max}, °C	8.26	8.71	8.48	7.81	7.64	7.87	8.12	8.18	8.38	7.88	7.82	7.64
Mean T_{min}, °C	−3.88	−1.41	2.83	8.52	13.79	18.58	21.14	20.30	16.08	9.70	2.74	−1.99
SD T_{min}, °C	5.91	5.73	5.91	5.49	4.43	3.51	2.83	3.03	4.61	5.36	5.41	5.59
						Modified or changed climate (2056–2085)						
Mean P (R_d), mm	5.73	6.43	8.67	9.51	14.42	13.39	8.40	8.31	15.11	12.97	9.66	7.09
SD P, mm	10.62	10.22	13.54	14.34	21.08	15.84	12.03	9.89	31.22	17.55	14.95	8.65
$P_{w/w}$	0.29	0.34	0.37	0.35	0.45	0.43	0.33	0.24	0.39	0.37	0.46	0.34
$P_{w/d}$	0.09	0.15	0.15	0.17	0.25	0.21	0.13	0.19	0.16	0.14	0.10	0.12
Mean T_{max}, °C	12.45	13.96	19.24	24.61	29.90	35.49	39.55	39.36	32.87	27.11	18.59	13.10
SD T_{max}, °C	7.72	10.05	8.32	8.51	6.35	6.20	7.50	6.33	8.24	9.89	9.82	7.61
Mean T_{min}, °C	−0.38	0.49	4.81	10.55	16.53	21.94	25.07	24.74	19.97	13.73	5.38	0.58
SD T_{min}, °C	3.81	5.68	4.69	4.73	3.95	2.76	3.06	2.72	3.98	6.62	7.01	4.27

† P, daily precipitation; R_d, mean daily precipitation of wet days; SD, standard deviation, $P_{w/w}$, probability of a wet day following a wet day; $P_{w/d}$, probability of a wet day following a dry day; T_{max}, maximum temperature, T_{min}, minimum temperature.

for the El Reno location were obtained by multiplying the ratios (Fig. 2A) by the baseline average monthly precipitation amounts. To estimate transitional probabilities of a wet day following a wet day ($P_{w/w}$) and a wet day following a dry day ($P_{w/d}$) for the 2056–2085 period, historical records were divided into dry (1950–1974) and wet (1975–1999) periods, and $P_{w/w}$, $P_{w/d}$, and mean monthly precipitation were calculated for each period and month. Linear interpolation was then used to estimate new $P_{w/w}$ and $P_{w/d}$ for the projected 2056–2085 mean monthly total precipitation (Fig. 2B) for each month. If projected monthly precipitation was outside the interpolation range as was the case for February and July in this study, about 30 wettest or driest months (say Februaries) were selected from the entire station records (1901–1999) such that the resulting range encompassed the projected monthly precipitation. To preserve the projected mean monthly precipitation totals (R_m) following the transitional probability adjustments, the mean daily precipitation per wet day (R_d, Table 1) was adjusted for the changed climate using:

$$R_d = \frac{R_m(1 - P_{w/w} + P_{w/d})}{N_d P_{w/d}}$$

where N_d is the number of days in the month, and $P_{w/w}$ and $P_{w/d}$ are the interpolated probabilities. These new R_d, $P_{w/w}$, and $P_{w/d}$ values were then used to generate Scenario 2.

Changes in precipitation variance were further incorporated (Scenario 3). Note the variances calculated from the HadCM3 monthly outputs are the interannual variances of monthly precipitation, and hence the variance ratios in Fig. 2C reflect the potential changes in variability of monthly precipitation. However, if $P_{w/w}$, $P_{w/d}$, and persistence or autocorrelation in both the baseline climate and changed climate are assumed identical, the variance ratios of monthly precipitation (Fig. 2C) are applicable to the variances of daily precipitation (CLIGEN input parameter) in a multiplicative manner (derivation not shown). That is, new variances of daily precipitation under the change climate were obtained by multiplying the baseline variances of daily precipitation by the variance ratios of Fig. 2C. Since changes in $P_{w/w}$ and $P_{w/d}$ in this study were relative small (Table 1), this assumption was deemed acceptable.

Changes in mean maximum and minimum temperatures were adjusted on top of the precipitation adjustments (Scenario 4). The projected mean maximum and minimum temperature shifts (Fig. 3A) were directly added to the corresponding baseline means (the mean shift was about 3°C for minimum

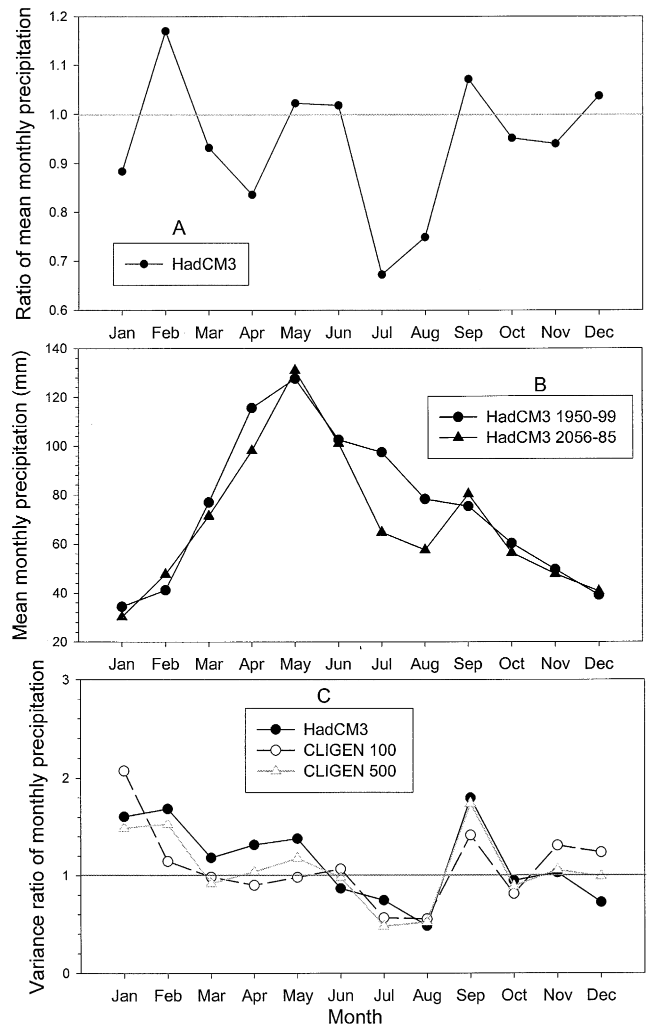

Fig. 2. HadCM3-projected changes of monthly precipitation between 1950–1999 and 2056–2085 for El Reno using B2a emissions scenario forcing (A) ratios of mean monthly precipitation, (B) projected mean monthly precipitation, (C) variance ratios of HadCM3-projected monthly precipitation and those calculated with 100 and 500 yr of CLIGEN-generated monthly precipitation.

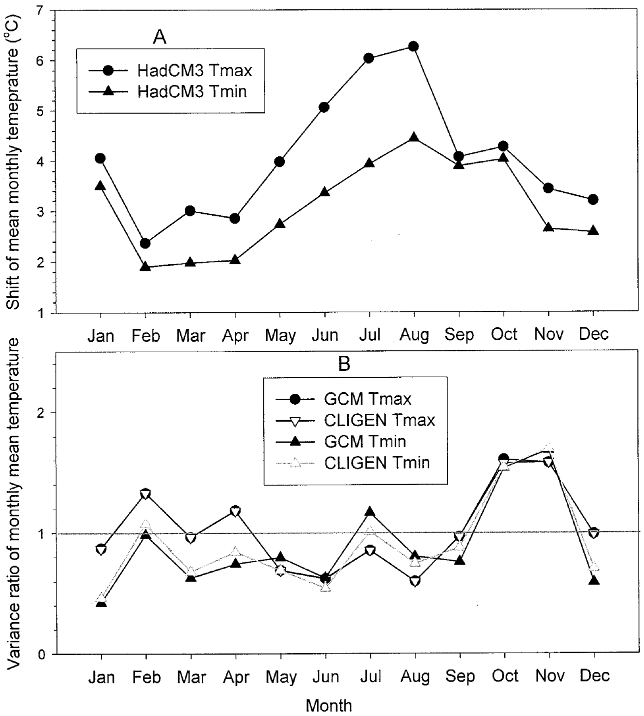

Fig. 3. HadCM3-projected changes of monthly mean maximum temperature (T_{max}) and minimum temperature (T_{min}) between 1950–1999 and 2056–2085 for El Reno using B2a forcing (A) Shifts of mean monthly temperatures, (B) variance ratios of HadCM3-projected and CLIGEN-generated mean monthly temperatures.

temperature and 4°C for maximum temperature). This method was used by other modelers for mean temperature adjustment (e.g., Wilks, 1992; Mearns et al., 1997; Katz, 1996).

Changes in temperature variance were incorporated (Scenario 5). Temperature variances calculated from HadCM3 monthly values are the interannual variances of monthly temperature. The variance ratios (Fig. 3B) are applicable to the variances of daily temperatures (used in CLIGEN) in a multiplicative manner, if autocorrelation coefficients of all orders in the baseline are identical to those in the changed climate (Katz, 1985). That is, new variances were calculated by multiplying the baseline daily variances by the monthly variance ratios. Though mean temperatures were increased considerably, the structure of autocorrelation in the baseline climate would presumably be similar to that of the changed climate at the same geographical location. As a first approximation, multiplicative adjustments were made to the variances of daily maximum and minimum temperatures, and the resulting parameters in Table 1 were used to generate the changed climate, called for by HadCM3 for the period of 2056–2085 at El Reno.

Simulated Management Systems

Four input files (i.e., slope, soil, climate, and crop management) are needed to run the WEPP model. Measured slope profile and soil properties as described earlier 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. For the simulations of Scenarios 1, 2, and 3, winter wheat was planted on 15 October and harvested on 20 June of the following year. However, for the simulations of Scenarios 4 and 5, a planting date of 1 November and a harvest date of 1 June, which are representative of northern Texas where the present temperature regime is similar to the projected temperature at El Reno, were used to accommodate the increased temperature. For tillage operations, one moldboard plow and three disk operations, approximately 1 mo apart in the summer, were used in the conventional tillage treatment. In contrast, three disk operations, which left about 50% of residue on the soil surface for each operation, were used in the conservation tillage treatment. The WEPP model was run for 100 yr for each combination of the three tillage systems and five climate scenarios at both present and elevated CO_2 levels using the same slope, soil, and crop management input files.

RESULTS AND DISCUSSION

Downscaling Evaluation

Annual precipitation observed at and projected for El Reno for the period of 1950–1999, along with the 5-yr moving averages, are shown in Fig. 4. The projected annual precipitation amounts were downscaled averages based on an equal weighting. Five-year moving averages of the projected data were consistently greater than those of the observed data before 1985. However, the trend lines converged and became similar thereafter. The similarity in trends near the end of the 20th century is encouraging and boosts our confidence in the projected climate scenarios for the region. It should be pointed out that the method of averaging the two grid cells is not a true downscaling, and a more sophisticated downscaling scheme may further improve the agreement between the observed and projected annual precipitation. Nevertheless, given the strong east–west precipitation gradient and the flat topography in the region, the method used here seems to provide a reasonable first approximation for the El Reno location.

To evaluate the validity of directly scaling temperature and precipitation variances of daily values with their corresponding variance ratios derived from HadCM3 monthly values (sort of temporal downscaling), monthly precipitation and monthly mean temperature were computed from CLIGEN-generated daily values of Scenario 1 (baseline) and Scenario 5 (reflection of future climate) for each month and year. Variances and their ratios (Scenario 5 over Scenario 1) were then com-

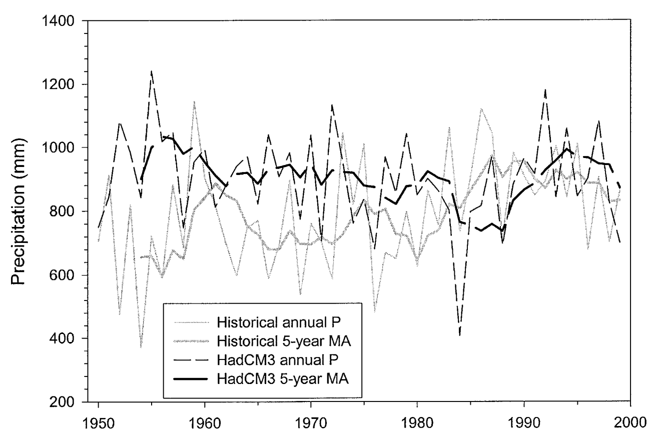

Fig. 4. HadCM3-projected and historical annual precipitation (P) and 5-yr moving average (MA) at El Reno for the period of 1950–1999.

puted with the monthly values. The variance ratios calculated using 100 yr of CLIGEN-generated climate agreed relatively well with those of HadCM3 (Fig. 2C); however, the agreement was improved when 500 yr of CLIGEN-generated climate were used. The overall agreement indicates that the assumption used in this study was acceptable, and that as a first approximation the direct multiplication method provided a viable means of transferring interannual variability of monthly precipitation to variability of daily precipitation. Nonetheless, this method has a tendency of underpredicting monthly variance. This is because an increase in daily variance would generate more events with larger and smaller precipitation amounts, but their effects on monthly variance would be somewhat discounted by the summation of the larger and smaller values in the calculation of monthly total.

Variance ratios of CLIGEN-generated monthly mean maximum and minimum temperatures are plotted in Fig. 3B. The HadCM3 variance ratios of maximum temperature were reproduced well by CLIGEN, but the ratios of minimum temperature were slightly overpredicted for most of the months. The lesser agreement for minimum temperature may have resulted from a range check imposed in CLIGEN. Since daily maximum and minimum temperatures are generated independently, daily minimum temperature is forced to be less than maximum temperature. This range check may have altered the minimum temperature distribution, and the resultant bias seemed to vary with season. The overall results indicate that the assumption that autocorrelation structures in the baseline and changed climate are identical is acceptable, and the direct multiplication method is viable as a first approximation.

Response at the Present Carbon Dioxide Level

Simulated 100-yr means of annual precipitation, runoff, soil loss, and wheat grain yield as well as their percentage changes in each scenario relative to the baseline (Scenario 1) at the present CO_2 level are shown in Table 2. The simulated average annual precipitation during 2056–2085 was 767 mm yr^{-1}, which is 4.7% less than the baseline average of 805 mm yr^{-1} (1950–1999). Compared with the 5.6% decrease in annual precipitation as called for by HadCM3, the adjustments of transitional probabilities and mean daily precipitation amounts as was done in Scenario 2 accommodated the projected precipitation decrease fairly well. The projected decreases occurred in April, July, and August (Fig. 2B). With changes in the precipitation mean and conditional probabilities (Scenario 2), WEPP-simulated surface runoff, soil loss, and wheat yield were slightly reduced as a result of the reduction in total precipitation. On average, a 1% decrease in precipitation resulted in an average decrease of <0.5% in runoff, 0.9% in wheat yield, and 3.8% in soil loss (excluding no-till). The sensitivity of soil loss to changes in precipitation mean was comparable with those reported in the literature (Pruski and Nearing, 2002a; Savabi et al., 1993; and Favis-Mortlock et al., 1991). Since the predicted soil losses in the no-till system were relatively small in all climate scenarios, the percentage changes were not very meaningful and therefore were omitted in Table 2.

With changes in both precipitation mean and variance (Scenario 3), the average annual precipitation increased by 1%, compared with Scenario 2. This may be caused by model approximation (e.g., use of pseudo-random number or approximation of distribution function) and numerical instability resulting from the variance pertur-

Table 2. Simulated average annual precipitation, runoff, soil loss, and wheat yield at the present CO_2 level, and their percent changes relative to the baseline climate.†

Tillage systems	Precipitation Depth	Precipitation Change	Runoff Depth	Runoff Change	Soil loss Rate	Soil loss Change	Wheat yield Rate	Wheat yield Change
	mm	%	mm	%	kg ha^{-1}	%	kg m^{-2}	%
				Scenario 1, Baseline				
Conv.	805	0	86	0	5824	0	0.245	0
Cons.	805	0	76	0	2240	0	0.246	0
NT	805	0	64	0	224	0	0.237	0
				Scenario 2, P(m)				
Conv.	767	−4.7	84	−2.9	4928	−15.4	0.234	−4.5
Cons.	767	−4.7	76	0.0	1792	−20.0	0.235	−4.5
NT	767	−4.7	61	−4.0	224	NA	0.227	−4.2
				Scenario 3, P(m,v)				
Conv.	775	−3.8	97	11.8	5824	0	0.235	−4.1
Cons.	775	−3.8	86	13.3	2016	−10.0	0.236	−4.1
NT	775	−3.8	71	12.0	224	NA	0.230	−3.0
				Scenario 4, P(m,v)T(m)				
Conv.	775	−3.8	94	8.8	6944	19.2	0.170	−30.6
Cons.	775	−3.8	86	13.3	3136	40.0	0.170	−30.9
NT	775	−3.8	74	16.0	224	NA	0.169	−28.7
				Scenario 5, P(m,v)T(m,v)				
Conv.	775	−3.8	91	5.9	6944	19.2	0.169	−31.0
Cons.	775	−3.8	84	10.0	3136	40.0	0.169	−31.3
NT	775	−3.8	74	16.0	224	NA	0.168	−29.1

† P, precipitation; T, temperature; m, mean adjustment; v, variance adjustment; Conv., conventional till; Cons., conservation till; NT, no-till; NA, not appropriate.

bation. A perfect generator would preserve the mean when the variance alone is changed. Though the resulting change in mean annual precipitation is undesirable from the weather generation point of view, it can be readily corrected by readjusting the mean precipitation parameter (R_d in Table 1) as needed. This was not done here because in this particular study the impact of each parameter was individually evaluated and the resultant errors from inadequate parameter estimation could be corrected. Compared with Scenario 2, simulated runoff increased by 13 to 16% in all tillage systems, simulated soil loss by 15% under conventional tillage and 10% under conservation tillage, and simulated wheat yield by about 0.7% in all systems (Table 2). The increases in runoff and soil loss were attributed to the increase in the frequency and intensity of large storms (Table 3). This trend toward precipitation occurring in more intense and more extreme events, stemming from changes in precipitation variance, was the main cause for the increases in the simulated runoff and soil erosion. Zhang and Garbrecht (2002) analyzed soil loss data measured on these watersheds and found that the largest 2% of storms accounted for 60 to 85% of total soil loss in the three tillage systems.

In Scenario 4, where mean maximum and minimum temperatures were elevated, simulated wheat grain yield, compared with Scenario 3, was reduced by approximately 26% for the adjusted planting and harvest dates, suggesting that winter wheat is sensitive to temperature. The mean maximum temperature increased more in the summer (up to 6°C) than in the other seasons (up to 4°C, Figure 3A). A similar trend was shown by the mean minimum temperature, which increased up to 4.5°C in July thru October and up to 3.5°C in the remaining months. The average increase in mean daily temperature during the growing season (October thru June of following year) was 3.2°C (3.6°C for the maximum and 2.8°C for the minimum), which translates to about 8% reduction in wheat yield for a 1°C increase in growing-season mean temperature. It should be noted that if the planting and harvesting dates were not adjusted for the warmer temperature, a 9% yield reduction per 1°C increase would result. These yield impacts are similar to results obtained by Mearns et al. (1997), who evaluated temperature sensitivity of wheat grain yield using the WGEN and CERES-wheat models at two Kansas locations. They reported that for a 1°C increase in mean annual temperature simulated wheat yield was reduced by 10 to 12% at the present CO_2 level. Lobell and Asner (2003) analyzed historical corn and soybean yields throughout the USA and reported that a 1°C increase in mean temperature in the growing-season (summer) reduced corn and soybean yields in the Midwest USA by some 17%. Owing to reduced wheat biomass and a shortened growing-season, the temperature increase intensified soil erosion, showing a 19% increase over Scenario 3 under conventional tillage and 50% increase under conservation tillage.

Table 3. Statistics of CLIGEN-generated daily precipitation for days with >1 mm d^{-1} for Scenarios 1 to 3.†

To be updated	Scenario 1, baseline	Scenario 2, P(m)	Scenario 3, P(m,v)
N_d, ≥ 1 mm yr^{-1}	62.3	55.9	55.9
N_d, ≥ 43 mm yr^{-1}	3.07	2.98	3.17
N_d, ≥ 77 mm yr^{-1}	0.59	0.52	0.62
95 percentile, mm	42.6	44.1	45.1
99 percentile, mm	76.6	74.8	79.6
All time maximum P, mm	175.7	220.2	289.4
Observed maximum P, mm	179.8		

† N_d, number of wet days; *P*, daily precipitation; m, mean adjustment; v, variance adjustment.

In Scenario 5, changes in temperature variance were further incorporated. Changes in temperature variance (Fig. 3B), compared with Scenario 4, had no impact on simulated soil loss, but resulted in slight reductions in simulated runoff (<3%) and wheat yield (<0.5%) for all three systems. The increase in temperature variance would increase the occurrence of extreme temperatures (highs and lows), which would hinder photosynthesis and therefore biomass production. The overall results indicate that changes in mean temperatures have a much greater impact on soil erosion and wheat yield than do changes in temperature variability.

Response at the Elevated Carbon Dioxide Level

The WEPP-simulated outputs at the elevated CO_2 level and their relative changes with respect to the baseline climate at the present CO_2 level (Scenario 1 of Table 2) are shown in Table 4. Under the baseline climate, the 50% increase in CO_2 increased wheat yield by some 26%, decreased runoff by 2.5%, and reduced soil loss by 12% for all systems except for no-till in which the predicted soil loss was zero. These relative sensitivities to the CO_2 rise were similar across all five climate scenarios.

Changes in mean precipitation (Scenario 2), compared with Scenario 1 of Table 4, resulted in decreases in surface runoff, soil loss, and wheat yield due to the 5% reduction in precipitation. The relative reduction in runoff and soil loss was, in general, similar to the reduction under the present CO_2 level. However, the average reduction in wheat yield in all three systems was slightly greater for the elevated CO_2 condition (6.7%) than for the present CO_2 level (4.4%), indicating an interactive effect of CO_2 concentration and precipitation on wheat productivity.

Compared with Scenario 2, changes in precipitation variance (Scenario 3), increased surface runoff by 15 to 17% in all systems, intensified soil loss by 19% under conventional tillage and 10% under conservation tillage, and increased wheat yield by 1%. Further changes in mean temperature (Scenario 4), compared with Scenario 3, reduced runoff by an average of 3% due to high evaporative loss, increased soil loss by 19% under conventional tillage and by 40% under conservation tillage, and reduced wheat yield by about 31%. Note the percentage increase in soil loss was greater under conservation tillage than under conventional tillage, but the predicted average soil loss under conservation tillage was less than half of the soil loss under conventional tillage in Scenario 4. Further comparison with Scenario 1 revealed that the Scenario 4 changes (i.e., mean and

Table 4. Simulated average annual precipitation, runoff, soil loss, and wheat yield at the elevated CO_2 level (50% increase), and their percent changes relative to the baseline climate at the present CO_2 level (Scenario 1 of Table 2).†

Tillage systems	Precipitation		Runoff		Soil loss		Wheat yield	
	Depth	Change	Depth	Change	Rate	Change	Rate	Change
	mm	%	mm	%	kg ha^{-1}	%	kg m^{-2}	%
				Scenario 1, Baseline				
Conv.	805	0	86	0	5152	−11.5	0.311	26.9
Cons.	805	0	74	−3.3	2016	−10.0	0.312	26.8
NT	805	0	61	−4.0	0	NA	0.295	24.5
				Scenario 2, P(m)				
Conv.	767	−4.7	81	−5.9	4256	−26.9	0.294	20.0
Cons.	767	−4.7	71	−6.7	1568	−30.0	0.295	19.9
NT	767	−4.7	58	−8.0	0	NA	0.280	18.1
				Scenario 3, P(m,v)				
Conv.	775	−3.8	94	8.8	5376	−7.7	0.297	21.2
Cons.	775	−3.8	84	10.0	1792	−20.0	0.297	20.7
NT	775	−3.8	69	8.0	224	NA	0.283	19.4
				Scenario 4, P(m,v)T(m)				
Conv.	775	−3.8	89	2.9	6496	11.5	0.217	−11.4
Cons.	775	−3.8	81	6.7	2688	20.0	0.217	−11.8
NT	775	−3.8	69	8.0	224	NA	0.214	−9.7
				Scenario 5, P(m,v)T(m,v)				
Conv.	775	−3.8	89	2.9	6496	11.5	0.217	−11.4
Cons.	775	−3.8	81	6.7	2464	10.0	0.217	−11.8
NT	775	−3.8	69	8.0	224	NA	0.214	−9.7

† P, precipitation; T, temperature; m, mean adjustment; v, variance adjustment; Conv., conventional till; Cons., conservation till; NT, no-till; NA, not appropriate.

variance in precipitation and mean in temperatures) increased runoff by 3 to 12%, increased soil loss by 23% under conventional tillage and 30% under conservation tillage, and reduced wheat yield by 37%. As opposed to the 30% yield reduction at the present CO_2 level, the greater yield reduction at the higher CO_2 level indicates a negative interaction between temperature increase and CO_2 rise.

Compared with Scenario 4, changes in temperature variance in Scenario 5 had no impacts on simulated runoff, soil loss, and wheat yield in all three tillage systems except for conservation tillage in which soil loss was reduced by 10%. More importantly, simulated average surface runoff in Scenario 5, compared with Scenario 1 of Table 2 (at the present CO_2 level), increased by 3 to 8% in all systems; average soil loss increased by 12% to 6496 kg ha^{-1} under conventional tillage and by 10% to 2464 kg ha^{-1} under conservation tillage; and wheat grain yield decreased by 11%. These relative changes reflect future responses as predicted by WEPP to climate change during 2056–2085.

Seasonal Distribution of Soil Loss

Measured and simulated mean monthly soil losses for the three tillage systems are shown in Fig. 5. Measured soil loss was for the period of 1980–1995. Two erosion-prone periods were exhibited by the measured data: one was before the full development of wheat canopy in early spring and the other was when the fields were in fallow (September through November, Fig. 5A). Simulated soil loss sharply increased in the late summer, especially in September, but decreased in the winter in the conventional tillage systems (Fig. 5B). Three key reasons were responsible for the spike in the predicted

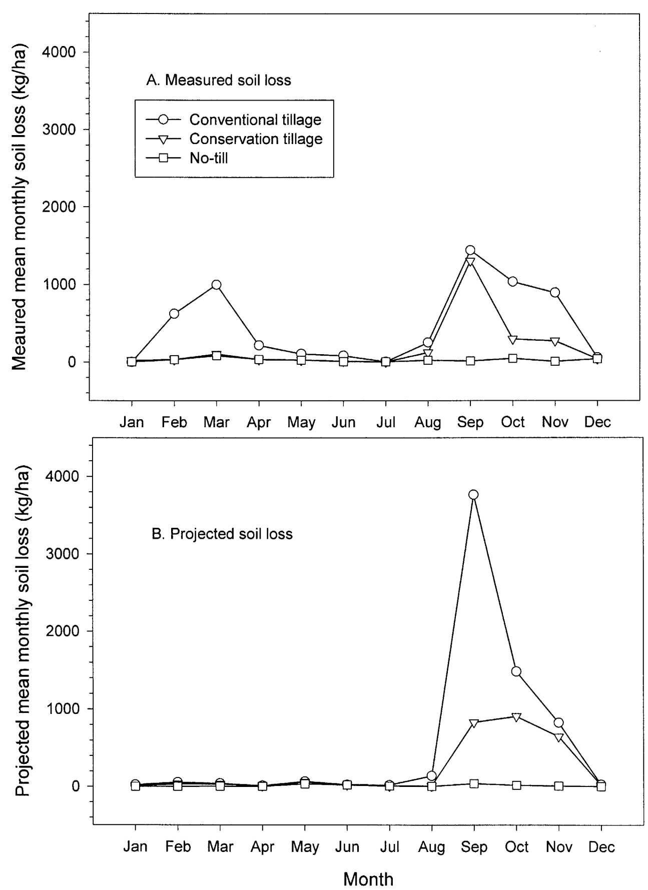

Fig. 5. Mean monthly soil loss in three tillage systems (A) measured between 1980 and 1995, (B) projected for Scenario 5 at the increased CO_2 level.

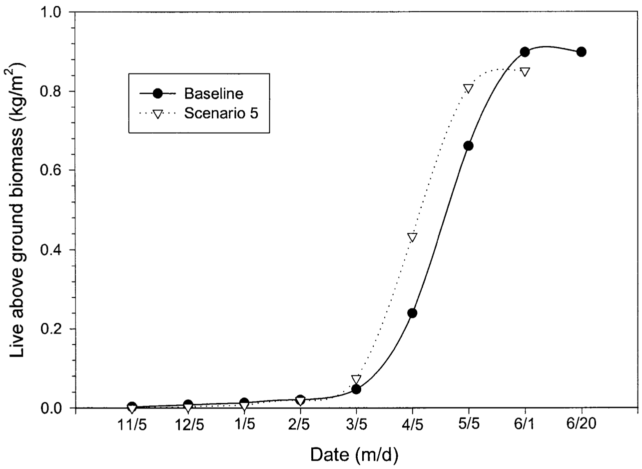

Fig. 6. WEPP-simulated average wheat growth curves under no-till for the baseline climate at the present CO_2 level and for Scenario 5 at the increased CO_2 level with adjusted planting date.

summer erosion rates. First, soils were loosened by tillage operations for seedbed preparation and winter wheat planting. Second, the soil surfaces were unprotected by crop residue under the conventional tillage. Third, albeit mean precipitation in September remained largely unchanged (Fig. 2B), the variances of monthly and daily precipitation were substantially increased (Fig. 2C). As discussed earlier, an increase in precipitation variance would lead to increases in more intense and more extreme events, which would result in more severe soil loss. The disappearance of the winter peak was because of the early growth of winter wheat (Fig. 6). Though winter wheat was planted 2 wk later in Scenario 5, significant early growth in March and April were simulated. Results also indicate that the no-till systems were effective in controlling soil erosion in the changed climate scenarios. This implies that implementation of no-till systems would be sufficient to combat soil erosion in central Oklahoma under the climate changes assumed in this study.

CONCLUSIONS

A practical downscaling method has been developed to construct climate change scenarios using GCM monthly outputs and the CLIGEN model. Changes in means and variances of monthly precipitation and temperatures derived from the GCM outputs were directly incorporated into the CLIGEN input parameters. Future transitional probabilities of precipitation occurrence were estimated as a linear function of historical monthly precipitation. The method can be used to generate future daily weather as called for by GCM monthly forecasts such as Scenario 5 in this study, or to generate hypothetical climate scenarios (e.g., Scenarios 2–4) to evaluate each climatic variable's impact on soil erosion and crop productivity (or other aspects of interest) under climate change. This method may also be used to downscale seasonal climate forecasts to daily weather data for use in crop forecasts.

Relative soil loss, runoff, and wheat yield changes estimated with WEPP for the present and elevated CO_2 levels were similar across all climate scenarios. At the elevated CO_2 level, the decrease in mean precipitation reduced runoff and wheat yield by an average of 4 and 7% respectively, and reduced soil loss by 15% under conventional tillage and by 20% under conservation tillage. Changes in precipitation variance increased runoff and soil loss by 15 and 19%, respectively, under conventional tillage, and increased runoff and soil loss by 17 and 10% under conservation tillage. Increase in mean temperature dramatically lowered predicted wheat yield by 31% and increased predicted soil loss by 19% under conventional tillage and by 40% under conservation tillage. Each degree increase in the growing-season temperature (°C) resulted in a 10% reduction in wheat yield at the elevated CO_2 level. It should be stressed that soil loss under no-till remained low in all five climate scenarios.

With all changes considered (including correction for the 1% overprediction in precipitation resulting from variance perturbation), predicted average wheat yield during 2056–2085, compared with the present climate at the present CO_2 level, would decrease by 12%; runoff would increase by $<7\%$; and soil loss would increase by $<8\%$ in all tillage systems. As for the seasonal patterns, average soil loss during 2056–2085 increased dramatically in September under conventional tillage, due to increased frequency in more intense storms and unprotected land surfaces in the month. Overall results indicate that adoption of conservation tillage and no-till systems in the region will be sufficient to combat soil loss under the climate changes assumed in this study.

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