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Assessing the site-specific impacts of climate change on hydrology, soil erosion and crop yields in the Loess Plateau of China

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Abstract Climate changes may have great impacts on the fragile agro-ecosystems of the Loess Plateau of China, which is one of the most severely eroded regions in the world. We assessed the site-specific impacts of climate change during 2010–2039 on hydrology, soil loss and crop yields in Changwu tableland region in the Loess Plateau of China. Projections of four climate models (CCSR/NIES, CGCM2, CSIRO-Mk2 and HadCM3) under three emission scenarios (A2, B2 and GGa) were used. A simple spatiotemporal statistical method was used to downscale GCMs monthly grid outputs to station daily weather series. The WEPP (Water and Erosion Prediction Project) model was employed to simulate the responses of agro-ecosystems. Compared with the present climate, GCMs projected a −2.6 to 17.4% change for precipitation, 0.6 to 2.6°C and 0.6 to 1.7°C rises for maximum and minimum temperature, respectively. Under conventional tillage, WEPP predicted a change of 10 to 130% for runoff, −5 to 195% for soil loss, −17 to 25% for wheat yield, −2 to 39% for maize yield, −14 to 18% for plant transpiration, −8 to 13% for soil evaporation, and −6 to 9% for soil water reserve at two slopes during 2010–2039. However, compared with conventional tillage under the present climate, conservation tillage would change runoff by −34 to 71%, and decrease soil loss by 26 to 77% during 2010–2039, with other output variables being affected slightly. Overall, climate change would have significant impacts on agro-ecosystems, and adoption of

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conservation tillage has great potential to reduce the adverse effects of future climate changes on runoff and soil loss in this region.

1 Introduction

According to the Fourth Assessment Report (AR4) of IPCC (Intergovernmental Panel of Climate Change), global mean surface temperature, precipitation and extreme events such as heavy precipitation and droughts have changed significantly, and the changes are very likely to continue (IPCC 2007). Those changes will very likely increase runoff, soil erosion and related environmental and ecological damage (SWCS 2003). Though some general conclusions about climate change and their impacts have been drawn, especially at macro-scales, the potential damages of climate change in particular regions or farms need to be assessed under specific site conditions. Such information is useful for making decisions on how to adapt management practices to mitigate the adverse impacts of climate change.

Different approaches have been developed to assess the impacts of climate change on hydrology, soil erosion and crop yields, such as temporal or spatial analogues (Crowley 1990; Lough et al. 1983; Rosenberg et al. 1993) and modeling (Favis-Mortlock and Boardman 1995; Li et al. 2009b; Zhang 2003). As agricultural systems models are getting more accurate, the modeling approach is gaining popularity for impact assessment of climate change. The Water Erosion Prediction Project (WEPP) model is a physically based, continuous simulation computer program, which predicts soil loss and sediment deposition. It includes erosion, climate, hydrology, daily water balance, plant growth and residue decomposition, and irrigation components (Flangan and Nearing 1995). As a process-based model, WEPP is widely used to study the impacts of climate change on soil erosion and crop production. Its plant growth and water balance components have been modified to account for the CO_2 effects on evapotranspiration and biomass production under climate change (e.g. Favis-Mortlock and Savabi 1996; O'Neal et al. 2005; Pruski and Nearing 2002a; Zhang et al. 2004).

For quantitative impact assessments, General Circulation Models (GCMs) are the major sources of climate change data. However, two major obstacles existed when GCMs outputs are applied to assess climatic change impacts, i.e. the spatial and temporal scale mismatches between coarse resolution projections of GCM and fine resolution data requirements of ecological models (Hansen and Indeje 2004; Zhang and Liu 2005). Regional climate modeling and statistical downscaling are two approaches commonly used to produce higher resolution climate change data at sub-GCM grid scales (IPCC 2001a). The regional climate modeling (RCM) can generate higher resolution data, but RCM output is computationally costly (Solman and Nunez 1999) and often unavailable in many regions. Statistical downscaling (SD) approaches are easy to implement and can be calibrated to local conditions. To improve temporal resolution, commonly used are stochastic weather generators (Bates et al. 1994; Zhang et al. 2004) such as CLIGEN (CLImate GENerator) (Nicks and Gander 1994), and LARS-WG (Semenov and Barrow 1997). A common approach is to adjust the 'present-day' climate parameters according to GCM-projected relative climate changes, and then to generate 'future climate' using perturbed parameter values (Li et al. 2009a; Zhang 2007). However, methods of parameter perturbation and selection of weather generators will influence generated weather data, and therefore caution should be exercised when choosing a method or generator.

Most studies have examined soil erosion under climate change without taking into account farmers' adaptation measures, which are very important because the impacts of management practices could be greater than the impacts of potential changes in precipitation or air temperature (O'Neal et al. 2005). For example, decreased crop yields may lead farmers to change planting dates to take advantage of increased warmth or to avoid high temperatures during crop flowering stage, and exacerbated soil loss may lead farmers to grow a cover crop or to carry out conservation tillage. Such kinds of changes in management would mitigate the adverse effects of climate change on erosion. However, this kind of research is lacking (Holman 2006) and more studies are needed.

The Loess Plateau is one of the most eroded regions in the world because of highly erodible soils, steep slopes, heavy storms, and low vegetation cover stemming from intensive cultivation and improper land uses. Limited crop available water and severe soil erosion are major factors constraining agricultural production in this area (Shi and Shao 2000; Zhang et al. 2008). Under climate change, climate variability will directly influence the trend of soil loss and agricultural production in the region; therefore, the impacts of future climate change on soil and water resources and agricultural production need to be assessed in detail. Zhang and Liu (2005) simulated the surface runoff, soil erosion and crop productivity on the Changwu tableland of the Loess Plateau by downscaling HadCM3 using an implicit downscaling method. The study without an explicit spatial downscaling tends to reflect more of a first-order regional sensitivity of natural resources to climate change. For the site-specific impact assessments, especially for variables that are heavily influenced by local conditions such as soil loss and crop yield, an explicit downscaling method should be used (Wilby et al. 1999; Zhang 2007).

The objectives of this study were to assess potential changes in hydrology, soil erosion and crop yields under projected climate during 2010–2039 and explore countermeasures that could be used to control soil erosion in Changwu under climate change.

2 Materials and methods

2.1 Site description

The Changwu experiment station is located at 107.8°E and 35.2°N, in the Changwu county of Shaanxi Province on the Loess Plateau (Fig. 1). The station situates in the temperate semi-arid zone, the mean annual precipitation is 582 mm with 52.8% falling between July and September, and the average annual temperature is 9.2°C. The elevation is about 1,206 m above sea level. The prevailing landform is loess tableland with the loess more than 100-m thick. The soil is predominantly silt loam with silt content greater than 50%. Rainfed agriculture is the dominant production system and the common regional cropping system is a three-year rotation of winter wheat–winter wheat–spring maize. The long-term average annual soil loss in the tableland-gully geomorphologic region was 5,000–10,000 t km^{-2}. Most of soil loss occurred in summer months and from gullies and sloped lands with little from flat tablelands (Tang 2004).

Fig. 1 The study site of the Changwu experimental station

2.2 Calibration of CLIGEN and WEPP

A preliminary test at the location showed that there were biases in daily weather data generated by the CLIGEN (v5.111), and some adjustments were carried out to calibrate CLIGEN. For example, the generated precipitation duration was multiplied by 3, wind speed by 2.18, and relative peak intensity of rainfall divided by 3.14.

Measured soil, climate, crop management information, surface runoff, and sediment yield from 1988 to 1992 were used to calibrate soil erodibility parameters of the WEPP model (v2004.7), which was modified to incorporate the effect of elevated CO_2 on plant growth and evapotranspiration (Favis-Mortlock and Guerra 1999; O'Neal et al. 2005; Pruski and Nearing 2002b; Zhang et al. 2004). Two field runoff plots and two cropping systems were selected. One runoff plot (20.1 m long by 5 m wide with a 5° slope) was under conventionally tilled continuous bare fallow. Another plot (20.3 m long by 5 m wide with a 10° slope) was under conventionally tilled continuous soybean with residue removed after harvest. Soybean seed yield was calibrated to the average yield of the region. Soil erodibility was calibrated by minimizing the differences between measured and predicted average soil losses under the condition that measured average annual runoff matched WEPP-predicted runoff. The measured and calibrated average annual soil loss was 7.2 and 7.6 Mg ha^{-1}, respectively, for continuous soybean, and 9.4 and 9.2 Mg ha^{-1} for continuous fallow.

For the site-specific assessment in Changwu, a common regional 3-year rotation of wheat–wheat–maize was selected. In the simulation under the baseline climate condition, winter wheat was planted on September 23 and harvested on June 27 of the following year; and maize was planted on April 15 and harvested on September 22. However, under the future climates, the growth period was adjusted to adapt to the changed climate, wheat was planted 3 days later and harvested 3 days earlier; and maize was planted 3 days earlier and harvested 3 days earlier to accommodate the increased temperature.

Two tillage and residue management systems were simulated. For the common traditional system, 90% of crop residue was removed and field was moldboard plowed 1 week after harvest. For a conservation system with delayed tillage operation, residue was left in place after harvest and the field was moldboard plowed one week before planting of the next crop. The two plots that were used in the model calibration were used in the simulation.

2.3 Climate models and emission scenarios

As there are uncertainties in climate change projections, multiple GCMs and emission scenarios were used to represent a wide range of possibilities of climate change. Climate change projected by four GCMs (CCSR/NIES, CGCM2, CSIRO-Mk2 and HadCM3) under three emission scenarios (A2, B2 and GGa) from the Third Assessment Report of IPCC (IPCC 2001c) were used in this study. The GCMs-projected data are monthly values at coarse spatial scales (Table 1), which need to be downscaled to daily weather data at the target station using a statistical method. The monthly precipitation, mean maximum temperature, and mean minimum temperature for 1957–2005 and 2010–2039 were extracted from the four GCMs projections.

Scenario A2 describes a very heterogeneous world, which results in a continuous increasing population together with a relative slow economic growth and technological change. Scenario B2 emphasized local solutions to economic, social, and environmental sustainability, with the whole world oriented toward environmental protection and social equity. Scenario GGa applies the historical increase of greenhouse gases during 1860–1990 and 1% increase under the present climate conditions from 1991 to 2099 as described in the IS92a emissions scenario, which was widely used and considered a benchmark in past impact studies. Based on the characteristics of the above scenarios, the A2 scenario has the most increases in greenhouse gases, while B2 has the least increases with moderate increases for GGa. The three emission scenarios were selected to project the climate change under the middle-high, middle-low, historical emission rates of greenhouse gases. Based on the above emissions scenarios, CO_2 concentration by the year 2025 would increase to 592 ppmv (parts

Table 1 Grid box size and simulated data duration of the four GCMs

Name		CCSR/NIES	CGCM2	CSIRO-Mk2	HadCM3
Grid size		5.625° × 5.625°	3.75° × 3.75°	5.625° × 3.25°	3.75° × 2.5°
Data duration	A2,B2	1890~2100	1900~2100	1961~2100	1950~2099
	GGa	1900~2099	1900~2099	1900~2100	1900~2099

per million by volume) for A2, 416 ppmv for B2, and 445 ppmv for GGa (IPCC 1992, 2001b).

2.4 Spatial downscaling of GCMs outputs

Two methods were combined to transform the GCMs grid outputs to the target station. Firstly, GCM grid data were spatially smoothened using inverse distance weighted averaging of the four neighboring grid boxes (Fig. 2), and then a transfer function was used to calibrate the GCMs grid data to the target station.

2.4.1 Inverse distance weighting interpolation

Taking the center as the grid point for each grid box (Fig. 2), the following formula was used to compute the weights w_i:

$$w_i = (d_i + \varepsilon)^{-1} \Big/ \sum_{i=1}^{4} (d_i + \varepsilon)^{-1}$$

where ε is a small number to prevent division by zero, d_i is the angular distance between source and destination (target station) and is estimated as:

$$d_i = cos^{-1}\left[sin\,(d_{lat})\,sin\,(s_{lat}) + cos\,(d_{lat})\,cos\,(s_{lat})\,cos\left(d_{long} - s_{long}\right)\right]$$

where d_{lat} and d_{long} is the latitude and longitude of a grid box center, respectively; s_{lat} and s_{long} is the latitude and longitude of the target station, respectively.

After obtaining the $w_{i,}$ the data for the target station can be calculated as following:

$$data_{smoothed} = \sum_{i=1}^{4} w_i \cdot data_i$$

where $data_{smoothed}$ is a smoothed GCM time series of monthly data for the target station, $data_i$ is the data in a GCM grid box.

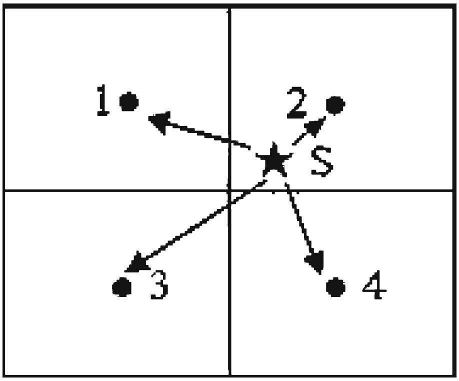

Fig. 2 The illustrative scheme of inverse distance weighted interpolation

2.4.2 *Transfer function*

A simple transfer function developed by Zhang (2005) was used in this study. This method emphasizes reproducing probability distributions of local observations rather than finding strong correlations between local variables (predictands) and GCM output variables (predictors). This simple method directly calibrates GCM monthly hindcast to the probability distribution of observed data while disregarding the 1:1 correspondence between the two. It has been proved to be a valid method for site-specific assessment of climate impacts (Zhang 2007; Zhang and Liu 2005). The specific procedures are as follows:

The GCM grid monthly precipitation during 1957–2005 was used as a control, and the historical monthly precipitation during 1957–2005 as a baseline. First, ranked historical monthly precipitation (Y) was plotted with ranked GCM grid precipitation (X) to obtain a simple univariate linear and a nonlinear function (transfer functions) for each month. Second, the transfer functions were used to downscale 2010–2039 monthly precipitation from the GCM grid scales to the Changwu station. The nonlinear function was used to transform the GCM monthly precipitation values that were within the range in which the nonlinear function was fitted, while the linear function was used for the values outside the range. Third, the spatially downscaled monthly precipitation values were used to calculate monthly mean and variance of the future climate for the target station for further temporal downscaling. Likewise, the GCM grid monthly maximum and minimum temperatures were spatially downscaled in the same manner. Mean temperature shifts as well as variance ratios between the downscaled monthly GCM projections of 2010–2039 and the station monthly measurements of 1957–2005 were calculated for each month and further used in temporal downscaling.

2.5 Temporal downscaling of GCMs monthly data

Measured daily weather data for 1957–2005 at Changwu were used to estimate the baseline CLIGEN input statistical parameters, which were modified using downscaled climate change perturbations estimated in Section 2.4 to generate daily weather series of the changed climates for the Changwu station. For precipitation, the adjusted parameters included transitional probabilities of wet day following wet day ($P_{w/w}$) and wet day following dry day ($P_{w/d}$), mean and variance of daily precipitation of wet days. Future $P_{w/w}$ and $P_{w/d}$ of each month were estimated from linear relationships developed using historical transitional probability and monthly precipitation at the Changwu station. The mean daily precipitation per wet day was computed using the future transitional probabilities, downscaled monthly mean, and number of days in the month. Daily precipitation variance was estimated from the spatially downscaled monthly precipitation variance, monthly mean precipitation, and precipitation occurrence probability using the equation of Wilks (1992). For temperature, spatially downscaled mean maximum and minimum temperature shifts were directly added to the corresponding baseline means, daily baseline temperature variances were multiplied by the calculated variance ratios. Zhang (2005) provided a detailed description of the temporal downscaling method. Parameter adjustment was made separately for each climate change scenario. All adjusted parameter values were input to CLIGEN, and 100 years of daily weather data were generated for each climate change scenario.

3 Results and discussions

3.1 Projected climate change

Compared with 1957–2005, the four GCMs under three emission scenarios projected a −2.6 to 17.4% change for precipitation (Table 2). Variance ratios of projected monthly precipitation between 2010–2039 and 1957–2005 were 0.984–1.389. Both inter-model and inter-emission scenario variability was great. However, compared with 1957–2005, a t- and F-test showed that the mean annual precipitation during 2010–2039 would very likely to increase with a probability of 98.6%, and monthly variance ratios with a probability of 99.9%. The increase in variance would lead to increases in frequency of large storms, and further to more soil erosion (Zhang and Liu 2005). Projected climate changes were different for different GCMs under the same emission scenario, which may be mainly attributed to model uncertainty due to, for example, differences in representations of physical processes and their nonlinear interactions in the climate–ocean–land–soil–plant systems (Mort and Andrei 2000). Therefore, any impact study based on results from one GCM should be interpreted with caution (Minville et al. 2008).

GCMs projected a 0.6 to 2.6°C increase for maximum temperature (T_{max}) and 0.6 to 1.7°C rise for minimum temperature (T_{min}) (Table 2). Variance ratios of 2010–2039 to 1995–2005 were 0.748–1.155 for T_{max} and 0.736–1.387 for T_{min}. It is obvious that both maximum and minimum temperature would increase during 2010–

Table 2 Averaged annual climate perturbations of four GCMs under three emission scenarios

GCMs	Emission scenarios	Precipitation			T_{max}		T_{min}	
		Depth (mm)	Change (%)	R.V.[a]	Shift (°C)	R.V.	Shift (°C)	R.V.
CCSR	A2	571.8	−1.6	1.022	2.1	0.884	1.5	0.797
	B2	570.0	−1.9	1.023	2.3	1.137	1.7	1.146
	GGa	632.1	8.8	1.230	2.1	1.066	1.6	0.768
CGCM2	A2	565.9	−2.6	1.223	1.7	0.781	1.1	0.798
	B2	568.4	−2.2	0.984	1.9	0.748	1.1	0.831
	GGa	605.1	4.1	1.181	2.6	1.017	1.6	1.042
CSIRO	A2	612.9	5.5	1.224	1.1	1.128	0.6	1.027
	B2	615.9	6.0	1.158	1.6	0.915	1.1	0.908
	GGa	682.2	17.4	1.389	2.6	1.061	1.7	0.736
HadCM3	A2	621.0	6.9	1.345	0.9	1.155	1.1	1.387
	B2	638.5	9.9	1.189	0.6	1.140	1.1	1.254
	GGa	597.9	2.9	1.200	1.6	1.110	1.2	1.345
Probability[b] (%)		98.6	–	99.98	99.99	61	100	52

[a] *R.V.* variance ratios of monthly precipitation or temperature of 2010–2039 over 1957–2005

[b] Probability of a t-test or F-test being greater than the baseline values

2039 compared with the present; however, a F-test showed that the temperature variance ratios would increase with low certainty (the probability is 60% for maximum temperature and 52% for minimum temperature). Temperature changes have little direct influence on erosion; however, erosion would be indirectly affected by alteration to the growth pattern of crops resulting from increased temperature (Favis-Mortlock and Boardman 1995). It should be noted that most studies projected that minimum temperature would increase more than maximum temperature (e.g. Ding et al. 2006; Mearns et al. 2003; Thornton et al. 1997; Zhang and Liu 2005); however, most scenarios of this study produced the opposite results, which were possibly caused by the downscaling method. Nonlinear transfer functions should provide better results than linear functions; however, linear functions were used for the data outside of the range in which the nonlinear functions were fitted, which might alter the change trend to some extent. This indicated some deficiencies of transfer functions for downscaling temperatures, which were higher than historical records, as reported by Zhang (2005).

3.2 Response under conventional tillage

3.2.1 Runoff, soil loss and crop yields

Under the conventional tillage, runoff on both slopes increased from 13 to 130% during 2010–2039 compared with 1957–2005 (Table 3). Soil loss changed from −5 to 195%. Twenty one of 24 scenarios (4 GCMs × 3 Emission scenarios × 2 slopes) predicted that soil loss would increase, and a t-test showed that mean soil loss would increase with a 99.98% probability. Changes of runoff and soil loss did not always correlate well with changes in precipitation amounts. The lack of the correlation in some case was very likely caused by changes in variance (Table 2) or number of large storms. For instance, precipitation decreased while both runoff and soil erosion increased under the A2 and B2 scenarios of CCSR and CGCM2.

WEPP projected a −17 to 25% change for wheat yields and a −2 to 39% change for maize yields. A t-test showed that maize yields would increase with more certainty than wheat. The probability for a yield increase was more than 99.9% for maize and about 52% for wheat. Changes of crop yields mainly followed precipitation and temperature changes. For example, lower crop yields were produced in scenarios with decreased precipitation and/or increased temperature, because water is the limiting factor for agricultural production in the region (Liu and Zhang 2007; Shan 1994). Ambient CO_2 concentration affects crop yields directly. Higher CO_2 often lead to greater crop yields. For example, crop yields of A2 scenarios were often greater than those of B2 with similar changes in precipitation and temperature (Table 2). Most scenarios predicted maize yields would increase more than wheat, which is possibly because (a) temperature increase had less adverse effect for maize than wheat and (b) maize as a C4 crop were more sensitive to CO_2 increases (Zhang and Liu 2005). Changes of crop yields affected runoff and soil loss indirectly through altering surface cover. Increased crop growth would provide better ground protection and therefore reduce runoff and soil loss. For example, under each emission scenario, CSIRO predicted greater crop yields than the other GCMs, and it predicted less runoff and soil loss too.

Table 3 Predicted mean annual precipitation, runoff, soil loss, grain yield as well as their percent changes relative to the corresponding slope in the baseline scenario under *conventional* tillage during 2010–2039

Scenarios (CO_2, ppmv)			Base	A2 (592)				B2 (416)				GGa (445)				Increase probability (%)
GCMs			(350)	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	
Runoff	5°	Depth (mm)	34	54	49	41	74	48	56	44	42	39	79	51	58	99.98
		Change (%)	0	58	43	20	115	40	63	29	24	13	130	49	70	–
	10°	Depth (mm)	40	61	57	47	81	55	63	50	49	44	88	57	65	99.98
		Change (%)	0	54	42	19	104	37	58	26	23	10	121	43	64	–
Soil loss	5°	Rate (t ha^{-1})	3	5	5	3	7	5	6	4	4	3	9	4	6	99.8
		Change (%)	0	67	56	0	126	53	82	14	17	2	195	31	100	–
	10°	Rate (t ha^{-1})	8	14	13	8	17	12	14	9	10	8	22	11	15	99.8
		Change (%)	0	68	52	−5	106	47	74	10	18	−1	165	28	88	–
Wheat	5°	Yields (t ha^{-1})	3	3	3	3.8	3.1	2.6	2.6	3.3	2.9	3.2	2.7	3.7	2.5	52
		Change (%)	0	−1	0	24	3	−14	−13	7	−3	6	−11	22	−17	–
	10°	Yields (t ha^{-1})	3	2.9	3	3.7	3	2.5	2.6	3.2	2.9	3.1	2.6	3.6	2.5	51
		Change (%)	0	−2	0	25	3	−14	−13	8	−3	6	−12	22	−17	–
Maize	5°	Yields (t ha^{-1})	7.1	9.2	8.7	9.6	8.8	7	7.5	7.8	8.4	8.9	7.5	9.8	7.7	99.97
		Change (%)	0	29	22	35	24	−2	5	9	18	25	5	38	8	–
	10°	Yields (t ha^{-1})	7	9	8.5	9.4	8.6	6.9	7.3	7.6	8.3	8.8	7.2	9.7	7.5	99.96
		Change (%)	0	28	21	34	23	−2	4	8	18	25	3	39	7	–

3.2.2 Soil water balance

The projected changes of key water balance components (such as soil water, plant transpiration, soil evaporation, and deep percolation) are presented in Table 4. Compared with the present climate, WEPP projected a −6 to 9% change for mean soil water, and increases in 16 of 24 scenarios (4 GCMs × 3 Emission Scenarios × 2 slopes) for soil water. A t-test showed that mean soil water would increase in 2010–2039 with a probability of >86%, with the GGa of CSIRO being the most and A2 of CCSR the least. Overall, soil water changes were closely correlated with precipitation change (Tables 2 and 4), because rainwater is the sole water source in the region. Mean plant transpiration changed from −8 to 13%, and increased in 10 of 24 scenarios. A t-test result showed that the trend was not clear with a probability of about 50%. These changes were caused by the integrated effect of climate change and crop growth change. For example, the scenarios with increased precipitation and better crop growth showed greater plant transpiration. Mean soil evaporation would change from −14 to 18% during 2010–2039 compared with the present condition, and increase in 14 of 24 scenarios. A t-test showed that the probability for an increase was about 80%. These changes corresponded with the changes of precipitation and temperature. Generally, soil evaporation increased as precipitation and temperature increased, and decreased as soil water content decreased. Percolation changed little, only showing a slight increase in the B2 of CCSR and GGa of CSIRO.

3.3 Response under conservation tillage

Compared with the conventional tillage during 1957–2005, WEPP predicted a −34 to 71% change for runoff and a 26 to 77% decrease for soil erosion (Table 5) under conservation tillage during 2010–2039. Though 10 of 24 scenarios (4 GCMs × 3 Emission Scenarios × 2 slopes) showed increases in runoff under conservation tillage due to increased precipitation amounts and variability, the magnitudes under the conservation tillage were much smaller than those under the conventional tillage during 2010–2039 (Table 3) due to enhanced infiltration under conservation. All GCMs predicted decreases in soil loss in all scenarios. These results showed that crop residue cover left in place until next sowing can decrease runoff and soil erosion effectively, and the adoption of unconventional crop residue management would benefit the region. Crop yields under the conservation tillage are similar to that under the conventional tillage, with wheat yields being slightly higher and maize yields being slightly lower.

As the change trends of runoff and soil loss at two slopes were similar, the 5° slope was taken as an example to analyze the difference between GCMs and emission scenarios. Compared with the conventional tillage under the baseline climate, percent runoff changes averaged across all GCMs were 9% for A2, −8% for B2, and 11% for GGa, and those averaged across emission scenarios were −12% for CCSR, 27% for CGCM2, −12% for CSIRO, and 13% for HadCM3. The average soil loss reduction across models was 54% for A2, 60% for B2, and 53% for GGa, and those across scenarios was −63% for CCSR, −40% for CGCM2, −63% for CSIRO, and −57% for HadCM3. B2 scenario would possibly cause less adverse impacts on environments than A2 and GGa scenarios. Climate change projected by CGCM2 and HadCM3 would cause more severe soil and water loss than CCSR and CSIRO. The

Table 4 Predicted mean annual plant transpiration, soil evaporation, percolation to below 1.8 m, averaged daily soil moisture in 1.8-m soil profile as well as their percent changes relative to the corresponding slope in the baseline scenario under *conventional* tillage during 2010–2039

Scenarios (CO_2, ppmv)			Base	A2 (592)				B2 (416)				GGa (445)				Increase
GCMs			(350)	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	probability (%)
Soil water	5°	Depth (mm)	299	282	286	304	299	292	296	308	328	320	308	324	301	86
		Change (%)	0	−6	−4	2	0	−2	−1	3	9	7	3	8	0	–
	10°	Depth (mm)	296	279	283	301	295	289	292	305	324	317	304	321	297	100
		Change (%)	0	−6	−5	2	0	−2	−1	3	9	7	3	9	1	–
Plant transpiration	5°	Depth (mm)	365	358	347	387	365	341	338	374	381	385	342	411	351	50
		Change (%)	0	−2	−5	6	0	−7	−8	3	4	5	−6	13	−4	–
	10°	Depth (mm)	361	352	342	382	359	337	332	370	376	381	336	407	347	46
		Change (%)	0	−2	−5	6	−1	−7	−8	3	4	6	−7	13	−4	–
Soil evaporation	5°	Depth (mm)	186	162	171	187	184	183	178	200	217	210	187	220	190	80
		Change (%)	0	−13	−8	1	−1	−2	−5	8	16	13	0	18	2	–
	10°	Depth (mm)	184	159	168	185	181	180	175	198	214	208	183	217	187	76
		Change (%)	0	−14	−9	0	−2	−2	−5	8	16	13	−1	18	2	–
Percolation	5°	Depth (mm)	0.6	0.6	0.6	0.6	0.6	1.4	0.6	0.6	0.9	0.6	0.6	1.2	0.7	100
	10°	Depth (mm)	0.6	0.6	0.6	0.6	0.6	1.3	0.6	0.6	0.7	0.6	0.6	0.9	0.6	100

Table 5 Predicted mean annual precipitation, runoff, soil loss, grain yield under *conservation* tillage during 2010–2039 as well as their percent changes relative to the corresponding slope in the baseline scenario under conventional tillage during 1957–2005

Scenarios (CO_2, ppmv)			Base (350)	A2 (592)				B2 (416)				GGa (445)			
GCMs				CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3
Runoff	5°	Depth (mm)	34	36	33	29	51	32	39	29	26	23	58	32	39
		Change (%)	0	5	−4	−15	49	−8	15	−14	−23	−34	71	−6	13
	10°	Depth (mm)	40	41	38	34	57	36	45	33	30	26	65	36	43
		Change (%)	0	4	−5	−15	43	−9	12	−16	−24	−34	63	−9	9
Soil loss	5°	Rate (t ha^{-1})*	3	1	2	1	2	1	2	1	1	1	2	1	2
		Change (%)	0	−62	−51	−63	−40	−57	−43	−63	−77	−71	−26	−62	−53
	10°	Rate (t ha^{-1})	8	3	4	3	5	4	5	3	2	3	6	3	4
		Change (%)	0	−61	−50	−61	−35	−53	−44	−61	−72	−68	−31	−59	−51
Wheat	5°	Yields (t ha^{-1})	3.0	3.0	3.0	3.6	3.3	2.9	3.0	3.4	3.3	3.3	2.7	3.7	3.0
		Change (%)	0	−1	−1	20	8	−3	0	12	10	7	−11	21	−1
	10°	Yields (t ha^{-1})	3.0	2.9	3.0	3.6	3.2	2.9	3.0	3.4	3.3	3.2	2.6	3.6	3.0
		Change (%)	0	−1	0	20	8	−2	1	14	12	8	−11	22	0
Maize	5°	Yields (t ha^{-1})	7.1	8.7	8.0	8.5	8.4	6.6	7.2	7.1	8.0	8.3	7.4	9.4	7.4
		Change (%)	0	23	12	20	19	−7	1	0	12	16	5	33	4
	10°	Yields (t ha^{-1})	7.0	8.5	7.8	8.3	8.3	6.5	7.0	7.0	7.9	8.2	7.3	9.3	7.3
		Change (%)	0	22	12	19	18	−7	0	−1	13	17	4	33	4

Table 6 Predicted mean annual plant transpiration, soil evaporation, percolation to below 1.8 m, averaged daily soil moisture in 1.8-m soil profile under *conservation* tillage during 2010–2039 as well as their percent changes relative to the corresponding slope in the baseline scenario under conventional tillage during 1957–2005

Scenarios (CO_2, ppmv)			Base-350	A2 (592)				B2 (416)				GGa (445)			
GCMs				CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3
Soil water	5°	Depth (mm)	299	277	279	290	298	270	276	281	298	289	288	298	280
		Change (%)	0	−8	−7	−3	0	−10	−8	−6	0	−4	−4	−1	−6
	10°	Depth (mm)	296	275	277	288	296	269	274	280	297	287	286	296	279
		Change (%)	0	−7	−7	−3	0	−9	−7	−6	0	−3	−3	0	−6
Plant transpiration	5°	Depth (mm)	365	353	340	374	366	348	348	378	393	389	357	422	367
		Change (%)	0	−3	−7	3	0	−5	−5	4	8	7	−2	16	1
	10°	Depth (mm)	361	349	336	369	361	344	343	374	390	386	352	418	362
		Change (%)	0	−3	−7	2	0	−5	−5	4	8	7	−3	16	1
Soil evaporation	5°	Depth (mm)	186	185	194	212	206	193	184	212	222	223	193	230	196
		Change (%)	0	−1	4	14	10	3	−1	14	19	20	3	23	5
	10°	Depth (mm)	184	184	193	211	204	191	183	211	221	222	191	229	194
		Change (%)	0	0	5	15	11	4	−1	15	20	21	4	24	6
Percolation	5°	Depth (mm)	0.6	0.6	0.6	0.6	1.1	1.9	0.6	0.6	0.7	0.7	0.6	0.9	0.7
	10°	Depth (mm)	0.6	0.6	0.6	0.6	0.9	1.8	0.6	0.6	0.6	0.6	0.6	0.9	0.7

above results showed the variability of inter-GCMs for the impact assessments of climate change was fairly large and stressed the need to use multiple models output for assessment.

Annual mean soil water, plant transpiration, soil evaporation and percolation under conservation tillage during 2010–2039 have similar change trends as under conventional tillage during 1957–2005, and only small differences in magnitudes existed (Table 6). Compared with conventional tillage, soil water content decreased slightly; plant transpiration decreased for some scenarios but increased for others; soil evaporation increased considerably; and percolation changed little under conservation tillage in 2010–2039. Many experiments indicated that crop residue cover can decrease soil evaporation and increase soil water content (Wang et al. 2006; Zhang et al. 2007); however, the simulated results of WEPP gave the contradictory results, which was also reported in the study of Zhang and Liu (2005). These results indicated that WEPP might overpredict the soil evaporation under residue cover.

Conservation tillage where wheat residue was left in place until planting of the next crop had a profound effect on surface runoff and soil loss, compared with conventional tillage during 2010–2039. Relative to the runoff and soil loss amounts under conventional tillage during 1957–2005, percent runoff and soil loss during 2010–1039 were greatly reduced in conservation tillage than in conventional tillage (Fig. 3a, b), indicating that adoption of conservation tillage in future would reduce runoff and soil loss to below the current levels under conventional tillage without a conservation measure. The percent differences in winter wheat yields between the two tillage systems were relatively small with no consistent trends among the three scenarios (Fig. 3c), stemming from variations in projected precipitation amounts and variance, temperature increases, and model-simulated runoff amounts between the three scenarios. However, simulated summer maize yields tended to be consistently greater under conventional tillage than under conservation tillage (Fig. 3d). This is because greater soil evaporation was simulated under conservation tillage (Fig. 3f), which led to lower soil water balance (Fig. 3e) and consequently lower maize grain yield. The overprediction of soil evaporation under conservation resulted from an error in surface residue interception and evaporation, which has been fixed in a later version of the WEPP model.

3.4 Comparison with results from previous studies

Each percent change in future precipitation under the conventional tillage would result in a 1 to 36% increase in surface runoff, −1 to 48% change in soil loss, −7 to 5% change in wheat yield, −1 to 18% change in maize yield, −4 to 1% change in soil water, −4 to 1% change in plant transpiration, and −9 to 2% change in soil evaporation (Table 7). The sensitivities of runoff and soil loss to precipitation increase are greater than those in some previous studies (e.g. Chiew et al. 1995; Favis-Mortlock and Savabi 1996; Lee et al. 1996; Pruski and Nearing 2002a), which indicated that a 1% increase in precipitation would result in a 1 to 4% increase in surface runoff and a 0.5 to 4% increase in soil loss. However, the results obtained here are within the range reported in literatures. For example, O'Neal et al. (2005) found a 10 to 20% increase in annual precipitation to be associated with up to an approximate +300% change in runoff and soil loss in Midwest United States considering the variation in management and planting dates in addition to climate.

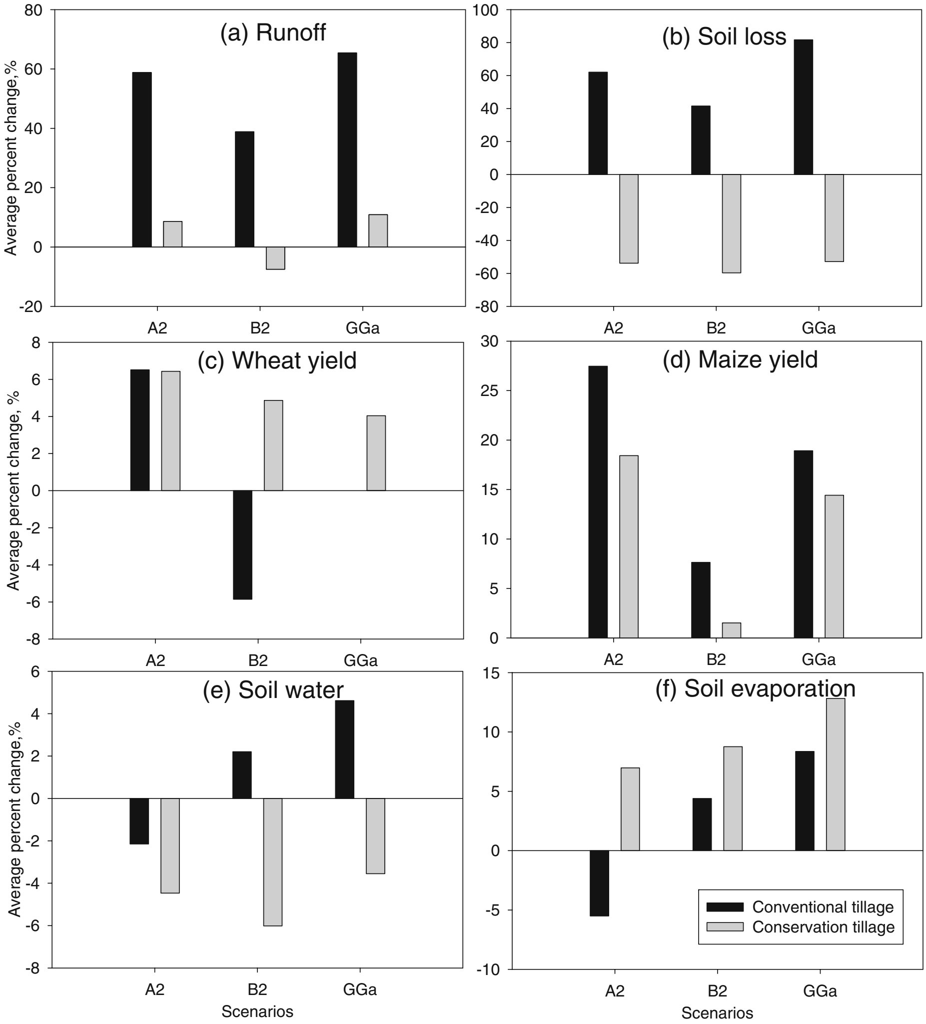

Fig. 3 Percent change averaged across the GCMs by the scenarios for selected variables under conventional and conservation tillage during 2010–2039, compared with those under conventional tillage during 1957–2005

Zhang (2007) found that a 4 to 18% increase in annual precipitation would result in a 49 to 112% increase in runoff and a 31 to 167% increase in soil loss using the same explicit method to spatially downscale GCMs grid outputs as here.

The differences might be caused by management practices or methods used for developing climate scenarios, especially by the downscaling methods. Zhang (2007) concluded that responses to climate change, simulated with the explicit method, seemed more dynamic and sensitive, compared with those simulated with implicit methods. Therefore, the sensitive response of runoff and soil loss to climate change obtained in this study is consistent with the downscaling methods used as well as those reported in literature.

Table 7 Percent changes of selected variables for 1% change in precipitation under the conventional tillage, as calculated between 2010–2039 and 1957–2005 climates

		A2 (592)				B2 (416)				GGa (445)			
		CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3	CCSR	CGCM2	CSIRO	HadCM3
Runoff	5°	36	17	4	17	21	29	5	2	1	32	3	24
	10°	34	16	3	15	19	26	4	2	1	30	2	22
Soil loss	5°	42	22	0	18	28	37	2	2	0	48	2	34
	10°	43	20	−1	15	25	34	2	2	0	40	2	30
Wheat yield	5°	−1	0	4	0	−7	−6	1	0	1	−3	1	−6
	10°	−1	0	5	0	−7	−6	1	0	1	−3	1	−6
Maize yield	5°	18	8	6	3	−1	2	2	2	3	1	2	3
	10°	18	8	6	3	−1	2	1	2	3	1	2	2
Soil water	5°	−4	−2	0	0	−1	0	1	1	1	1	0	0
	10°	−4	−2	0	0	−1	0	1	1	1	1	1	0
Plant transpiration	5°	−1	−2	1	0	−4	−4	1	0	1	−1	1	−1
	10°	−1	−2	1	0	−4	−4	1	0	1	−2	1	−1
Soil evaporation	5°	−8	−3	0	0	−1	−2	1	2	1	0	1	1
	10°	−9	−3	0	0	−1	−2	1	2	1	0	1	1

Positive number means an increase while negative number a decrease in selected variables between the two periods

4 Conclusions

Compared with 1957–2005, four GCMs under three emission scenarios projected a −2.6 to 17.4% change for precipitation, a 0.6 to 2.6°C and 0.6 to 1.7°C rises for maximum and minimum temperature, respectively. Compared with the conventional tillage during 1957–2005, during 2010–2039 WEPP predicted a 10 to 130% increase for runoff, a −5 to 195% change for soil loss, a −17 to 25% change for wheat yield, a −2 to 39% change for maize yield, a −14 to 18% change for plant transpiration, a −8 to 13% change for soil evaporation and a −6 to 9% change for soil water on the two slopes (note that the relative changes on two slopes are similar). Though changes of some hydro-meteorological variables are complex, a t-test showed that mean precipitation amounts, maximum and minimum temperature, runoff, soil loss, maize yields, soil evaporation, soil water and percolation would very likely increase with probabilities of greater than 80%; however, variance of maximum and minimum temperature, wheat yields and plant transpiration would increase with less certainty (the probabilities are about 50%). Compared to the conventional tillage during 1957–2005, under conservation tillage during 2010–2039, runoff would change −34 to 71%, soil loss decrease 26 to 77%, and the other variables such as crop yields, plant transpiration and soil water balance were affected slightly. Overall, climate change would have significant impacts on surface hydrology, soil loss and crop growth, and in particularly it would increase runoff and soil loss in the region. A change in tillage and residue management systems is necessary to reduce soil erosion and surface runoff in future climate change in the area. Adoption of conservation tillage such as delayed tillage, which leaves residue on soil surface by postponing tillage until the planting of the next crop, is a feasible and effective way to reduce runoff and soil loss in the region under climate change.

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