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Can conservation trump impacts of climate change on soil erosion? An assessment from winter wheat cropland in the Southern Great Plains of the United States

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ABSTRACT

With the need to increase crop production to meet the needs of a growing population, protecting the productivity of our soil resource is essential. However, conservationists are concerned that conservation practices that were effective in the past may no longer be effective in the future under projected climate change. In winter wheat cropland in the Southern Great Plains of the U.S., increased precipitation intensity and increased aridity associated with warmer temperatures may pose increased risks of soil erosion from vulnerable soils and landscapes. This investigation was undertaken to determine which conservation practices would be necessary and sufficient to hold annual soil erosion by water under a high greenhouse gas emission scenario at or below the present soil erosion levels. Advances in and benefits of agricultural soil and water conservation over the last century in the United States are briefly reviewed, and challenges and climate uncertainties confronting resource conservation in this century are addressed. The Water Erosion Prediction Project (WEPP) computer model was used to estimate future soil erosion by water from winter wheat cropland in Central Oklahoma and for 10 projected climates and 7 alternative conservation practices. A comparison with soil erosion values under current climate conditions and conventional tillage operations showed that, on average, a switch from conventional to conservation tillage would be sufficient to offset the average increase in soil erosion by water under most projected climates. More effective conservation practices, such as conservation tillage with a summer cover crop would be required to control soil erosion associated with the most severe climate projections. It was concluded that a broad range of conservation tools are available to agriculture to offset projected future increases in soil erosion by water even under assumed worst case climate change scenarios in Central Oklahoma. The problem is not one of a lack of effective conservation tools, but one of adoption and implementation. Increasing the implementation of today's conservation programs to address current soil erosion problems associated with the large year-to-year climate variability in the Southern Great Plains would greatly contribute towards mitigation of projected future increases in soil erosion due to climate change.

1. Introduction

Controlling accelerated soil erosion by water in agricultural environments has been a problem since man began plowing the ground. Climate change adds an additional dimension to already existing soil erosion problems. A vast body of knowledge and experience on soil erosion, conservation practices, and conservation tools has been built over the past century. Conservationists can rely on this knowledge and available tools to search for effective soil erosion controls under a changing climate. A brief historical background on soil erosion work and successes is given below to provide an overview of the existing foundation and framework within which this interdisciplinary investigation on soil erosion

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and climate change is conducted. In the following, the word "soil erosion" implies sheet and rill erosion by water. Soil erosion by wind is outside the scope of this study.

Conservation of soil resources in the United States made significant strides during the 20th century. Led by Hugh Hammond Bennett and conservationists of the time, the Soil Erosion Service was established within the US Department of Agriculture (USDA) in 1933 (Bennett, 1939), which later became the Soil Conservation Service and more recently the Natural Resources Conservation Service (NRCS). This agency promoted the use of soil conservation practices such as construction of terraces, grasses waterways, contour tillage, and gully control structures (Ayres, 1936; Bennett, 1939) to control soil erosion, reduce sediment loss, and maintain soil productivity. The cultivation-revolution since the early 1980s brought about by the use of minimum tillage and no-till production systems, along with government programs, such as the Conservation Reserve Program that took highly erodible land out of crop production, led to additional significant improvements in soil conservation (US Department of Agriculture, 2013).

In 1982, the USDA conducted the first National Resource Inventory (NRI), which uses a statistical sampling technique to document land use, conservation practices, and erosion rates on non-federal lands across the United States. The survey has been repeated on an intermittent basis since that time. The NRI uses the Universal Soil Loss Equation (Wischmeier and Smith, 1978) to estimate soil loss rates at its sampling sites. The numbers reported indicate that soil erosion by water, on non-federal, cultivated croplands decreased by approximately 30% between 1982 and 2010 (based on data taken from US Department of Agriculture, 2013). These numbers only address sheet and rill erosion caused by water, and do not reflect soil erosion caused by water in ephemeral or permanent gullies, or by wind.

While conservation advances were made over the last century in the United States, the climate has also changed. Climate change impacts soil erosion rates by various pathways, of which primary ones include the drivers of rainfall, temperature, and atmospheric CO_2 concentrations, which impact biomass production and runoff, which in turn impact erosion rates (Fig. 1) (Walthall et al., 2012; Izaurralde et al., 2011; Nearing et al., 2004). Temperature may have either a positive or negative impact on biomass production, depending on the plant and its response to the temperature changes (Walthall et al., 2012). Atmospheric CO_2 concentrations and rainfall amounts and intensities are generally expected to have a positive correlation to plant biomass production, though the impact of rainfall can be negative in cases when intense storm events during the early growing season remove seedlings or when rainfall causes excessive soil moisture conditions that may either influence the timing of planting or plant growth under waterlogged soil conditions (Bassu et al., 2014; Walthall et al., 2012). Implicit in this generalized representation of the impacts of climate on erosion by water is that producers' response to climate change also will impact soil erosion rates (Delgado et al., 2013; O'Neal et al., 2005). Under climate change farmers will alter planting and harvest dates, as well as cultivars or crops produced because of changes in temperatures, soil moistures, and rainfall patterns (Walthall et al., 2012; Southworth et al., 2002; Pfeifer and Habeck, 2002).

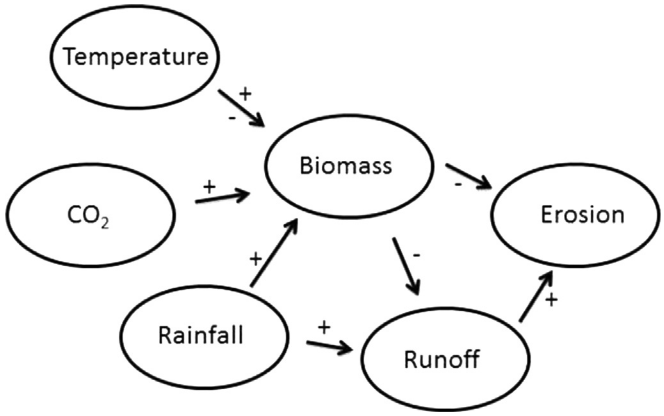

Fig. 1. Primary pathways by which climate change may impact rainfall-driven soil erosion, with most common correlation trends specified as plus or minus.

Sustainable, high-yield crop production is critical to maintaining food security, especially during a time of climate change. Long-term sustainability of high crop yields requires soil management practices that promote soil function, soil quality, and soil health. Soil erosion adversely affects soil productivity by gradually depleting the soil of nutrients, fine soil particles, and water holding capacity. Degradation of soil aggregate stability also increases the risks of crusting and increased runoff. Soil conservation practices have proven effective in reducing soil erosion and maintaining soil productivity. However, climate change introduces a new dimension to the soil erosion problem. Soil erosion and conservation practices that were effective in the past may no longer be effective in the future. This question is examined for conditions in central Oklahoma.

Average temperature has increased over most of the contiguous United States in the last century and is expected to continue to do so this century and beyond (Melillo et al., 2014; Karl et al., 2009). Annual precipitation is also changing. Trends in winter and spring precipitation are projected to rise for the northern United States and decline in the Southwest (Peterson et al., 2013; AMS, 2013, 2012). In the Southern Great Plains, rising air temperature and changes in timing and magnitude of rainfall events have already been observed (Peterson et al., 2013; Higgins and Kousky, 2013; Groisman et al., 2012).

Rainfall amounts and daily rainfall intensities generally increased in the United States between years 1910 and 1996 (Karl and Knight, 1998). More than half of observed increases in total annual precipitation for the United States measured during that time were caused by increases in the frequency of heavy events, which were considered to be those in the upper 10 percentile of daily amount values. Also, the proportions of precipitation falling in heavy (> 95th percentile), very heavy (> 99th percentile), and extreme (> 99.9th percentile) daily precipitation events increased during the years 1910 through 1999 by 1.7, 2.5, and 3.3% per decade, respectively, on average across the United States (Soil and Water Conservation Society, 2003). This is a pattern that appears to be occurring in many parts of the world (Groisman et al., 2005; Meehl et al., 2007). Changes in the water cycle propagate through the watershed system and affect processes such as runoff, foliar and ground cover production, soil erosion, sediment transport, and land productivity. Changes in rainfall timing, amount, intensity, and frequency, and minimum and maximum air temperature will inevitably impact the agricultural landscape (O'Neal et al., 2005; Karl and Knight, 1998). More intense and more frequent extreme rainfall events increase soil erosion, accelerate the degradation of soil quality, and diminish crop yields. Potentially large increases in soil erosion on cropland due to climate change are becoming a serious concern for farmers, land owners, and conservationist (Nearing et al., 2005; Zhang and Nearing, 2005; Soil and Water Conservation Society, 2003). Existing conservation practices may prove inadequate to manage soil erosion in light of projected climate change impacts (Melillo et al., 2014).

Assessing the effectiveness of current conservation practices under changed climatic conditions that are assumed to prevail in the future is a complex task that involves many climate and agronomic drivers, physiographic variables, interdependencies, and feed-back mechanisms (Delgado et al., 2011; Nearing et al., 2004, 2005). Much research is being conducted to assess potential impacts of climate change scenarios on soil erosion and to establish the potential need for additional and/or more effective conservation practices to provide adequate protection. However, these efforts are hampered by sizable uncertainties in the projected future climate for which conservation practices are sought.

In this study, a typical system of climate, hydrologic, and soil erosion models is briefly reviewed and the source of uncertainties in model results is laid out. This is followed by an example of potential impacts of climate change and conservation practices on soil erosion by water from winter wheat crops in Central Oklahoma. Irrigation of winter wheat, such as encountered in the Texas and Oklahoma panhandles, was not considered because, first, soil erosion by irrigation runoff is minimal when irrigation is applied according to recommendations; and, second, irrigation of winter wheat is not a common practice in central Oklahoma where, during most years, there is sufficient rainfall to successfully grow a winter wheat crop. The impact of climate model uncertainties on simulated soil erosion is presented, and the effectiveness of several conservation options to offset the increase in projected soil erosion and associated uncertainty is investigated for a typical winter wheat field in Central Oklahoma. The goal of this study is to determine if and which traditional conservation practices would be necessary and sufficient to hold projected annual soil erosion by water, including uncertainties, at no more than today's soil erosion levels.

1.1. *System of climate change and conservation assessment models*

1.1.1. *Climate change models*

Climate change models project future climate conditions. Several model selections must to be made before proceeding with the climate projections. Selections include a Green House Gas (GHG) emission scenario, a General Circulation Model (GCM), and a downscaling method (Fig. 2, upper right).

The GHG emission scenario called Representative Concentration Pathway RCP8.5 was chosen for this study. It has a GHG emission path that produces the greatest GHG gas concentrations and leads to the greatest warming of the planet. By inference, this scenario is associated with the greatest change in climate and impacts on the hydrologic cycle and soil erosion. Thus, soil conservation practices that are shown to perform well under RCP8.5 are expected to perform well under scenarios of lower GHG emissions and lesser climate change. These conservation practices are said to be robust under climate uncertainty; that is, they are desirable under virtually any climate scenario (Wilby and Dessai, 2010).

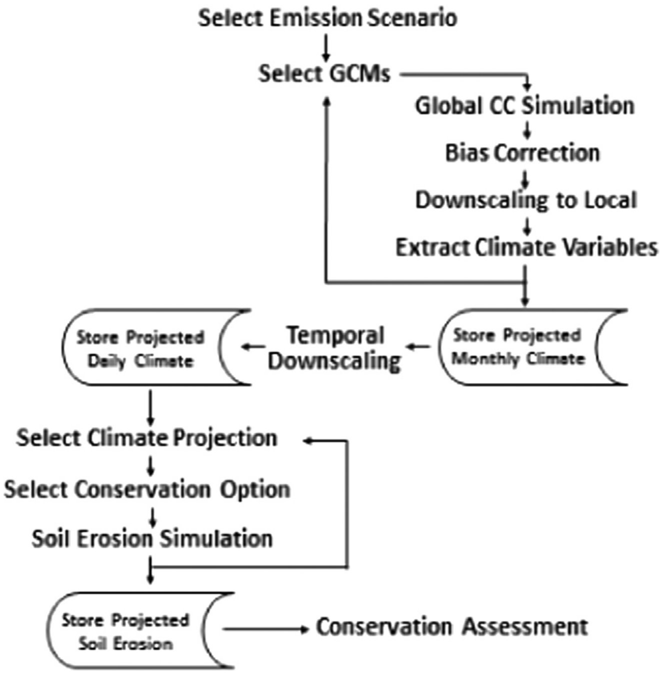

Fig. 2. Schematic of the system of climate change and conservation assessment models.

Many GCMs are available to project the future climate for a given climate scenario. Different GCMs project different climates which, in turn, lead to different soil erosion estimates. A representative sample of ten GCMs was selected for this study to define the potential climate evolution over the next half century. The ten GCMs include a Canadian, three US, one European, one Australian, one English, two Japanese, and one German model (acronyms are not listed because of the limited information they convey). Primary climate change variables considered were monthly precipitation and min/max air temperature (Fig. 2, upper right).

The climate projections computed by the GCMs were bias corrected and spatially downscaled to a grid of approximately 12 by 12 km resolution as described by Maurer et al. (2007). For agricultural and soil conservation applications, a supplemental downscaling step was necessary to express the projected monthly climate in terms of daily weather data at a particular location within the downscaled GCM grid-box. Synthetic weather generator SYNTOR (Garbrecht et al., 2014) was used to perform this supplemental downscaling (Fig. 2, middle). SYNTOR is a stochastic weather generator patterned after WGEN (Richardson and Wright, 1984) that also accounts for user-provided seasonal climate forecasts or other monthly climate modulations. Precipitation is generated independently of the other variables by using a Markow chain-exponential model. The other three variables are generated by using a multivariate model with the means and standard deviations of the variables conditioned on the wet or dry day status of the day as determined by the precipitation model (Richardson, 1981). With appropriately adjusted weather generation variables, SYNTOR can generate long records of synthetic daily weather data representative of current and projected future climate conditions.

The bias corrected and spatially downscaled GCM monthly precipitation and air temperature projections (Fig. 2, upper right) are readily available for the contiguous United States from the archive of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset (Maurer et al., 2007). This archive is referred to as the CMIP5 archive and the climate projections used in this study were downloaded from this archive (CMIP5 archive accessible at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/).

1.1.2. *Watershed description*

Three unit experimental watersheds near El Reno, Oklahoma were used in the WEPP model calibration. Each watershed is 80-m wide and 200-m long with a drainage area of 1.6 ha. The longitudinal slope of the watershed is approximately 3–5%. Soils are primarily silt loam with an average of 23% sand and 56% silt in the tillage layer. An annual winter wheat–summer fallow cropping system with three contrasting tillage systems of no-till, conservation (disks) and conventional (moldboard) tillage systems was studied on each watershed between 1980 and 1996. Measured rainfall data, soil properties (particle size, bulk density, field capacity, and wilting point), surface runoff and soil loss were used to calibrate the hydrological and erosion components of the WEPP model (Zhang, 2004). The measured soil loss showed that the peak erosion occurred in summer months when the ground was bare and rainfall intensity was high. The unit watershed was used to simulate the erosion responses to climate changes under the selected tillage and cropping systems.

1.1.3. Tillage and crop systems

A regional cropping system of continuous annual winter wheat–summer fallow was simulated under climate change for seven tillage alternatives: conventional tillage with and without terraces, conservation tillage with and without terraces, double-crop system, no-till, and conversion of cropland to rangeland. Conventional tillage comprises one moldboard plow and 3 disks at a 30-day interval in summer. Conservation tillage comprises 3 disks in summer at a 45-day interval. No till only uses a drill planter. A no-till double- crop system (annual winter wheat-summer soybean) and a rangeland pasture are also simulated. The first tillage was made 2 weeks following wheat harvest. Wheat was planted on 20th October and harvested on 15th June under the baseline climate, while it was planted on 20th October and harvested on 20th May under climate change to accommodate enhanced growth and early maturation of the wheat due to increased temperature and increase CO_2 levels.

1.1.4. Soil erosion model

Application of the soil erosion model involved selection of conservation practices, and simulation of relevant watershed processes required for the estimation of soil erosion under future climate conditions (Fig. 2, lower half).

Soil erosion was simulated using the Water Erosion Prediction Project (WEPP) model Version 2004.7 (Laflen et al., 1997; Flanagan and Nearing, 1995). Carbon dioxide (CO_2) component was added to capture the effects of increased CO_2 on plant growth. The WEPP model is driven by the SYNTOR generated synthetic daily weather of the current or projected climate. Major hillside rainfall-runoff processes simulated by WEPP include infiltration, evapotranspiration, vegetation growth, tillage and residue decomposition, effects of increased carbon dioxide, surface runoff, soil erosion, sediment transport and deposition, and sediment yield. The WEPP model was calibrated using measured hydrological and biological data at the Water Resources and Erosion Experimental (WRE) watersheds of the USDA, Agricultural Research Service, Grazinglands Research Laboratory, El Reno, Oklahoma (Zhang, 2004). The WEPP model was applied for each projected climate and each conservation practice. Baseline soil erosion was simulated under current climate conditions and conventional tillage operations. Soil erosion was simulated for all other combinations of projected climate and conservation practices (Fig. 2, lower half). Those combinations that resulted in soil erosion values at or below the baseline soil erosion were categorized as being effective at offsetting the expected increase in soil erosion under climate change conditions.

1.2. Uncertainty in projected climate and soil erosion

For this study, uncertainty is defined as imperfect knowledge, especially with regard to the probability of future climate outcomes (Runde, 1998). For example, the specific pathway that GHG emissions may take in the future represents an uncertain event. Likewise, climate models are not perfect and alternative models lead to differences in projected future climate characteristics, thereby introducing uncertainty as to which of the projected climates will be realized. These uncertainties in future climate propagate down the chain of models to ultimately result in uncertainties in simulated soil erosion. Sources of relevant climate model uncertainties are summarized below. Uncertainties associated with the WEPP model are outside the scope of this study. They are assumed to be independent of the climate and conservation scenarios.

1.2.1. Emission scenario uncertainty

Scenarios, in the context of this study, describe alternative possible, plausible, but not necessarily equally probable paths of future GHG concentrations. The likelihood that any one scenario will occur is generally not known (Tebaldi and Knutti, 2007). The problem of emission scenario uncertainty was bypassed in this study by selecting the scenario that produces more intense and more frequent storms that would result in the greatest increase in soil erosion (worst case scenario).

1.2.2. Climate model uncertainty

Different GCM models, subjected to the same emission scenario or external heating (i.e. an imbalance between incoming and outgoing solar radiation), simulate different responses in the climate, which is a form of model uncertainty. Model uncertainty is a result of different physical and numerical model formulations of global warming processes (Hawkins and Sutton, 2009). A multi-model approach is often used to provide an ensemble of responses. In this study, ten GCMs were selected resulting in ten different estimates of soil erosion distributions due to model uncertainty.

1.2.3. Climate-model internal variability

The variability of the climate system that arises in the absence of external heating is known as internal uncertainty (Deser at al., 2012). In this study, the lead time of the climate projection was 50 years and model internal variability played a subordinate role to scenario and model selection uncertainty (Hawkins and Sutton, 2009).

1.2.4. Downscaling uncertainty

The resolution of GCM grid-box climate projections is too large to assess climate impacts on agricultural systems (Wilby et al., 1998; Tabor and Williams, 2010). In general, one cannot distinguish which downscaling model performs best, and the subjective selection among competing models leads to downscaling uncertainty.

For climate change impact assessment using agricultural models an additional downscaling to local and daily scales was necessary. Stochastic weather generator SYNTOR (Garbrecht et al., 2014) was used in this study to downscale the monthly GCM climate predictions to daily weather outcomes at the location of interest within the GCM grid-cell.

1.2.5. Storm intensification uncertainty

Frequency and intensity of heavy downpours have been increasing in recent decades across most of the continental United States (Melillo et al., 2014; Higgins and Kousky, 2013; Groisman et al., 2004). Climate projections suggest that this trend towards heavier precipitation will continue (Kunkel et al., 2013a, 2013b). In this study, the percent increase in amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) in the Southern Great Plains from 1958 to 2012 (approximately 16% according to Melillo et al., 2014) were assumed to persist through the middle of this century and very heavy precipitation events of the projected climate were adjusted accordingly.

2. Results

2.1. Baseline weather and climate

Baseline climate was defined as the weather observed at the WRE experimental watersheds of the USDA ARS Grazinglands Research Laboratory, El Reno, Oklahoma, and over the 1977-2012 time period. SYNTOR was calibrated with baseline weather data.

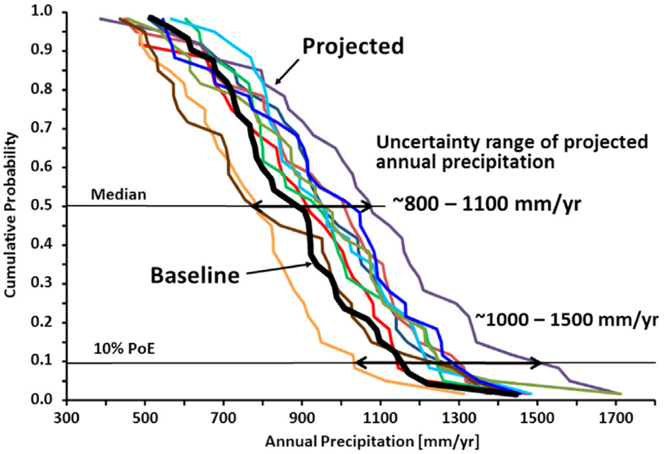

Fig. 3. Distribution of baseline and projected annual precipitation. Projections are for high emission climate change scenario RCP8.5. The thick line represents the 1977–2012 baseline precipitation distribution, and the thin lines represent the 2041–2070 precipitation distributions for the 10 projected climates. The uncertainty range of annual precipitation at the median and at the 10% Probability-of-Exceedance (PoE) are given on the right side of the figure.

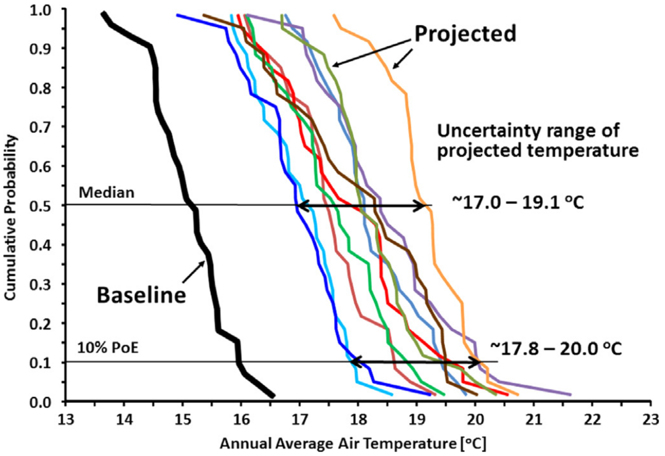

Fig. 4. Distribution of baseline and projected annual average air temperature. Projections are for high emission climate change scenario RCP8.5. The thick line represents the distribution of the 1977–2012 baseline annual average air temperature, and the thin lines represent the 2041–2070 projected annual average air temperature distributions for the 10 projected climates. The uncertainty range of annual average air temperature at the median and at the 10% Probability-of-Exceedance (PoE) are given on the right side of the figure.

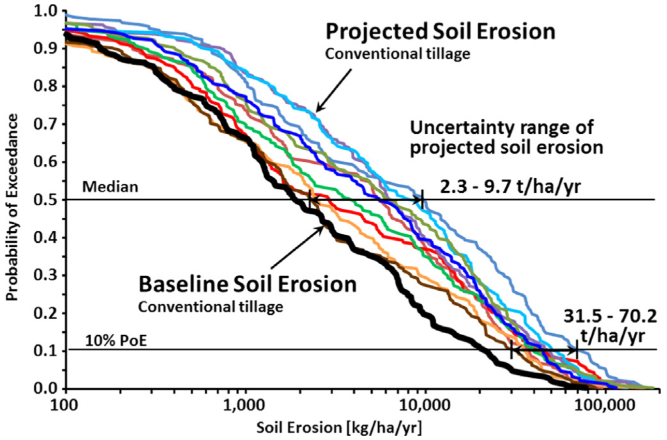

Fig. 5. Distribution of baseline and projected annual soil erosion. Projections are for high emission climate change scenario RCP8.5. The thick line represents the distribution of the generated 1977–2012 baseline soil erosion, and the thin lines represent the distribution of the simulated 2041–2070 projected soil erosion for the 10 projected climates. The uncertainty range of annual soil erosion at the median and at the 10% Probability-of-Exceedance (PoE) are given on the right side of the figure.

The calibrated SYNTOR was used to generate 200 years of synthetic daily precipitation and min/max temperature for subsequent simulation of soil erosion under baseline climate conditions. The distribution of annual precipitation and annual average air temperature for the baseline climate are displayed by the thick line in Figs. 3 and 4, respectively.

2.1.1. GCM projected climates

Ten different climate projections were generated by the ten selected GCMs. SYNTOR was first calibrated for each of the climate projections, and with the calibrated generation parameters 200 years of synthetic daily precipitation and min/max air temperature representative of the respective projected climate were generated. This produced ten different weather time series each representing potential future precipitation and air temperature outcomes for the 2041–2070 time period. The distribution of annual precipitation and annual average air temperature for the ten projected climates are displayed by the thin lines in Figs. 3 and 4, respectively.

2.1.2. Soil Erosion Projections

Baseline soil erosion from winter wheat cropland under conventional tillage operations was simulated by WEPP for the 200 years of generated baseline weather (Fig. 5, thick line). The average simulated annual soil erosion for baseline weather and conventional tillage operations was 7.1 t/ha/yr, and at the 10% Probability-of-Exceedance (PoE) level it was 21.1 t/ha/yr.

Projected soil erosion was simulated for winter wheat under conventional tillage operations and for the 200 years of generated weather for each of the ten projected climates (Table 1 and Fig. 5, thin lines). The average of projected soil erosion corresponding to the ten projected climates was 15.3 t/ha/yr, and at the 10% PoE it was 44.3 t/ha/yr. This soil erosion simulation was repeated for each of the seven conservation practices. Relevant statistical characteristics of the simulated soil erosion for the ten projected climates and seven conservation practices are shown in Table 1 and plotted in Fig. 6.

2.2. Discussion of results

The average simulated annual soil erosion for winter wheat under conventional tillage operations and under the 1977–2012 baseline climate conditions was 7.1 t/ha/yr. At the 10% Probability-of-Exceedance (PoE) level, it was 21.1 t/ha/yr. The high mean soil erosion in this baseline scenario emphasizes the importance of conservation practices to sustain soil resources under recent observed climate.

Future average annual soil erosion (2041–2070) simulated with the ten different projected climates ranged from 9.8 to 23.6 t/ha/yr with an average of 15.3 t/ha/yr (Table 1, first data record), which is about double that produced under baseline climate conditions, indicating an even greater need for conservation.

The projected soil loss is consistent with those reported by Zhang (2012) and Zhang et al. (2011), who simulated soil erosions for annual winter wheat in central Oklahoma using the WEPP model for the time period of 2010–2039 (next 30 years). These authors used three emission scenarios and four GCMs and a different spatiotemporal downscaling method. Their results showed that the projected mean precipitation would decrease during 2010–2039 by about 6%. However, the overall soil loss averaged over all tillage systems would increase by about 40% due to a

Table 1
Average, minimum, and maximum value of the mean and 10% Probability-of-Exceedance (PoE) values of the soil erosion distribution corresponding to each of the ten climate projections for 2041–2070 and for each of the seven conservation alternatives.

Tillage alternative	Annual soil erosion in t/ha/yr for 2041–2070 projected climate					
	Means			10% PoE		
	Average	Min	Max	Average	Min	Max
Conventional	15.3	9.8	23.6	44.3	31.5	70.2
Conventional with terraces	8.5	5.7	12.4	22.3	15.5	32.6
Conservation	7.2	4.9	11.3	20.4	15.5	32.0
Conservation with terraces	4.8	3.4	6.8	11.9	8.6	17.5
Double cropping W. wheat-soybean	3.4	2.3	5.0	8.7	4.6	16.4
No till	0.6	0.4	0.9	1.4	1.0	1.7
Pasture/rangeland	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0

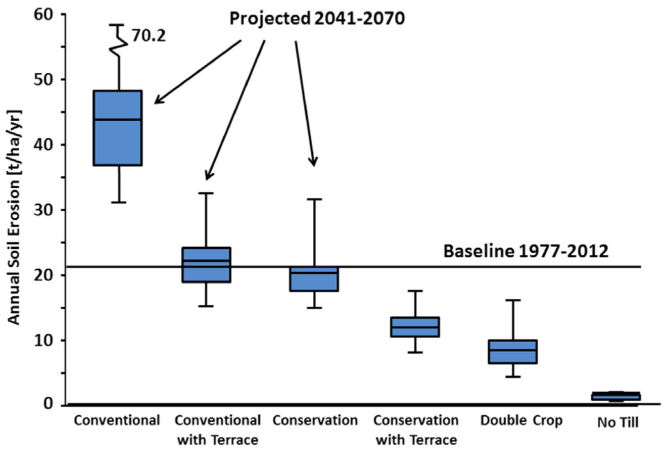

Fig. 6. Basic statistical characteristics of the simulated soil erosion for the ten GCM projected climates and six conservation practices (pasture/rangeland is omitted because it had nearly zero soil erosion). Projections are for high emission climate change scenario RCP8.5. The whiskers of each conservation practice box represent the uncertainty range of projected soil erosion at the 10% Probability-of-Exceedance level. The horizontal line is the baseline soil erosion of 21.1 t/ha/yr at the 10% Probability-of-Excendance level.

sizable increase in heavy rainfall storms. The greater soil erosion obtained in this study is mostly due to simulating soil erosion under projected climates that are further in the future (2041–2070) and thereby exhibit a greater climatic change, as well as focusing on a high emission scenario.

Repeating the soil erosion simulations for conventional tillage with terraces, resulted in a future soil erosion of, on average, 8.5 t/ha/yr (Table 1, second data record). For conservation tillage the future soil erosion was, on average, 7.2 t/ha/yr (Table 1, third data record). When considering the average of the soil erosion produced by the ten different projected climates, both conventional tillage with terraces and conservation tillage without terraces would reduce future soil erosion close to the target baseline soil erosion of 7.1 t/ha/yr. The other four conservation practices (conservation with terraces, double cropping, no till, and conversion to pasture) produced future soil erosion values that were substantially lower than the target baseline soil erosion. As such, they were categorized as effective conservation alternatives that reduced the soil erosion below the baseline target soil erosion (Table 1). These results are in line with findings reported by Zhang (2012) and Zhang et al. (2011) for the time period of 2010–2039.

In the preceding, effectiveness of conservation practices was assessed in terms of average soil erosion. However, typically the largest 2% of storms accounted for 60–85% of total soil erosion in all the wheat production systems in the study region (Zhang and Garbrecht, 2002). Thus, focusing on large infrequent storm events provides a more appropriate basis for assessing the effectiveness of conservation practices because the bulk of the annual soil erosion is the result of these storms. In this case, if one were to use soil erosion values at the 10% PoE level in the conservation assessment (Table 1, right columns), one would reach similar conclusions as when using average soil erosion values. Thus, either conventional tillage with terraces (22.3 t/ha/yr) or conservation tillage (20.4 t/ha/yr) would be sufficient to reduce future soil erosion close to or below the target baseline soil erosion value of 21.1 t/ha/yr at the 10% PoE level.

The above considerations do not account for the uncertainty introduced by the spread of potential future climates resulting from the use of ten different GCMs. More effective conservation alternatives have to be considered to reach the target baseline soil erosion for the full range of projected future climate conditions. Referring to Table 1, the maximum average annual soil erosion for conventional tillage was 70.2 t/ha/yr at the 10% PoE level. This is about 3 times higher than the target baseline soil erosion of 21.1 t/ha/yr at the 10% PoE level. Thus, conservation tillage alone would not reduce projected soil erosion enough to overcome the soil erosion uncertainty range and reduce all projected future soil erosion to or below the target baseline soil erosion. Conservation tillage with terraces (17.5 t/ha/yr) or a summer cover crop (16.4 t/ha/yr) would be necessary to achieve soil erosion reductions to or below the target baseline value of 21.1 t/ha/yr.

No till and land conversion to pasture land produced the lowest soil erosion under all projected climate conditions. No till produced a maximum average soil erosion of less than 1 t/ha/yr, and a maximum soil erosion of 1.7 t/ha/yr at the 10% PoE level. These values are over an order of magnitude less than the corresponding target baseline soil erosion.

The sizeable reductions in soil erosion achieved by established and proven conservation practices attests to the wide range of available conservation tools and their effectiveness to hold soil erosion and soil erosion within tolerable levels. The progress in protecting our soil resource that was made recent decades is an important achievement for the long-term sustainability of the agricultural production system and for future food security. Improvements brought about by implementing conservation practices do not persist if the conservation practices are removed. In order to maintain the progress we have made in protecting the soil resource through conservation conditions, policies and incentives that fostered the positive changes over recent decades must be maintained and enhanced. With current trends in our changing climate, which point to the potential for those improvements to be reversed, this is not the time to become complacent about soil conservation.

2.3. Summary and conclusions

Concerns have been expressed by the conservation community that climate change may increase soil erosion from cropland and that conservation practices that were effective in the past may no longer be adequate under future climate conditions. This question was examined for winter wheat cropland in central Oklahoma under the assumption of persistent high greenhouse gas emission scenario. The climate under this emission scenario was projected half a century into the future (2041–2070) by ten different Global Circulation Models. The resulting ten projected climates were used, one at a time, by a rainfall-runoff-erosion model to simulate soil erosion from winter wheat crops under various conservation practices. Seven alternative conservation practices were evaluated for their effectiveness to keep soil erosion at or below today's level. Findings and conclusions of this study are specific to winter wheat crops and physiographic conditions prevailing at the USDA ARS research watersheds at Fort Reno, Oklahoma, yet they are believed to be valid for the winter wheat production region in Central Oklahoma.

1. Projected climate change will lead to an increase in soil erosion from winter wheat cropland. Under conventional tillage practices, the average projected soil erosion (15.3 t/ha/yr) was approximately double the rate of that under today’s climate (7.1 t/ha/yr). This increase in projected soil erosion was largely attributed to the increase in intensity of heavy storm events.
2. A switch from conventional to conservation tillage practices would be sufficient to offset the average increase in soil erosion under most projected climates.
3. Conservation tillage with terraces or conservation tillage with summer cover crop (soybeans) would be required to control soil erosion under extreme conditions associated with the most severe climate projections.
4. Implementation of no-till and land use conversion to grassland would produce soil erosion values under most projected climates that are a fraction of today's soil erosion.

The baseline scenario in this study, conventional tillage of monoculture winter wheat, indicates that existing conservation practices are absolutely essential to sustain the agricultural soil resource. The climate change scenarios indicate that even greater conservation will be required in the future. Fortunately, these findings show that agriculture in Central Oklahoma has a broad range of conservation tools with which it could offset projected future increases in soil erosion under assumed worst case climate change scenarios. Thus, the issue is not a lack of effective conservation tools, but one of adoption and implementation. The time-scale of climate change by far exceeds the time-scale of producers planning horizon and the uncertainty of the pathway climate will take in the future limits the urgency to change from the wide spread use of conventional tillage for winter-wheat crops in Central Oklahoma. Implementation of soil conservation practices are more likely to be driven by current climatic events. Specifically, the large year-to-year precipitation variability typical in the Southern Great Plains provide a great incentive to adopt soil conservation practices that ensure a sustainable utilization of agricultural soil resources and high crop yields. Increasing the implementation rate of today's conservation programs for today’s problems would greatly contribute towards mitigation of projected increases in soil erosion and soil erosion due to climate change. And yes, conservation can trump impacts of climate change on long term mean soil erosion from winter wheat cropland in the central Oklahoma region.

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