Sensitivity of soil loss to climate change in the Inland Northwest USA

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Geography

in the

College of Graduate Studies

University of Idaho

by

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April 2015

Authorization to Submit Thesis

This thesis of Paige Farrell, submitted for the degree of Master of Science with a Major in Geography and titled "Sensitivity of soil loss to climate change in the Inland Northwest USA," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Climate variability and anthropogenic climate change present challenges in achieving sustainable agriculture. One of the challenges in maintaining a healthy agroecological system is abundant topsoil and limited soil erosion. In the Inland Northwestern United States temperatures are expected to increase by 1.5-4˚C and cool season precipitation is expected to increase 5-10% by the mid-21st century. The sensitivity of soil loss to projected changes in climate was simulated using the Water Erosion Prediction Project (WEPP) model. Sensitivity experiments were performed by running WEPP simulations for a variety of hillslopes and both conventional and no-till cropping practices by altering temperature, precipitation and precipitation extremes from a baseline climate representative of Moscow, Idaho using a continuous winter wheat rotation. Warming experiments enhanced erosion loss through indirect processes such as changes in precipitation phase and soil erodibility. In contrast, precipitation impacted soil loss directly. Projected changes in soil loss were also estimated by forcing WEPP with downscaled climate projections from 20 global climate models (GCM) from the fifth Coupled Model Intercomparison Project for both late 20th century and mid-21st century climate forcings. Increased soil loss rates were simulated by all GCMs for mid-21st century runs compared to late 20th century conditions. These model results suggest increases in soil loss rates under future climate change that will present additional challenges to agricultural sustainability and prompt adaptation practices to conserve soil.

Acknowledgements

This project had the help and guidance of many people. I would like to thank my advisor, John Abatzoglou for sharing his knowledge and capabilities throughout the project. I would like to also thank my committee members, Erin Brooks and Karen Humes, who have been present and encouraging every step of the way.   I am also indebted to my office mates, Alex Peterson for his eagerness to help me and teach me when my expertise fell short as well as Lauren Parker for her continuous support and guidance.

This research was supported by Regional Approaches to Climate Change (REACHH) Pacific Northwest Agriculture (PNA) under award #2011-68002-30191 from USDA National Institute of Food and Agriculture.

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Chapter 1:

Introduction

Understanding the impact of changing environmental conditions on agroecological systems is critical for allowing existing agricultural regions to maintain productivity and global food sustainability. Direct and indirect impacts resulting from anthropogenic climate change are perhaps the most widespread threats to existing agroecological systems due to increases in temperature and precipitation intensity (O'Neal 2005; IPCC 2013). Although climate change may increase carbon enrichment and growing season length, allowing crops to take advantage, changes in both temperature and precipitations can have negative impacts on crop yields. High-intensity precipitation events including extreme sub-daily events in addition to daily- and multi-day durational events that are theorized to increase non-linearly in frequency and at a more rapid rate than overall global mean precipitation (Pall 2007), upending various hydrologic and physical processes and the agroecological systems that depend on them, decreasing yields. Likewise, higher temperatures can have direct negative impacts on crops and yields through water and heat stress. Indirectly, however, these effects of climate change can present themselves in many ways, including soil erosion, which is one of the most significant threats to agricultural regions.

Climate change may impact soil erosion processes in a number of ways. First, an accelerated global hydrologic cycle with anthropogenic climate change posited to increase global mean precipitation. The most intense one percent of precipitation events are theorized to increase more rapidly than overall global mean precipitation (O'Gorman and Schneider, 2009). Soil erosion due to hydrologic processes can occur in multiple ways, but two of the most common processes include infiltration excess overland flow and saturation excess overland flow. Infiltration excess overland flow occurs when water is introduced to a soil system faster than the soil can absorb it, whereas saturation excess overland flow occurs as a result of inadequate subsurface water storage (Smith 2005). In general in the Palouse region, infiltration flow is most common in the fall months and saturations excess overland flow is most common during the spring. Increases in precipitation, and in particular extreme precipitation can have a direct impact on soil erosion over the next century (Pruski 2002). Secondly, warming can result in indirect impact on soil loss through changes in live biomass, microbial activity, evapotranspiration rates, and changes in precipitation phase (O'Neal 2005). Additionally, two types of erodibility, interill and rill, can be impacted by temperature through changes in biomass, roots, and canopy coverage. Rill erosion occurs when small channels form as a results of surface runoff and will rill erosion occurs less frequently than interill erosion, the magnitude of erosion can be higher. Interill erosion occurs at a lesser magnitude, but a higher frequency on the 'sheets' of land between the small rill channels (Toy 2002). While both interill and rill erosion occur coincidently, interill erosion is the results of raindrop impact whereas rill erosion is due to water flowing over the soil surface.

A potentially positive effect of climate change on wheat yields is an increase in CO_2. Two distinct results of increased CO2 include accelerated plant growth due to increased CO2 in the atmosphere and increased soil fertility with increases in soil carbon as a result of decomposing plants and other biomass (Carson 2014). These effects can potentially lead to increased crop production. While increased atmospheric carbon concentrations can be advantageous for agroecological systems through increased soil carbon content and thereby more fertile environments for plant growth, changes in energy and moisture resulting from climate change may compound or offset such changes as it portends to. Zhang (2005) found that climate change increased soil loss because of increased precipitation extremes and variability across the loess plateau of China. Increased precipitation may result in reduced wheat yields due to soil erosion (Nearing et al. 2004). Additionally, temperature increases of 2°C have been found to decrease winter wheat yields through heat stress on vegetation and shorten the growing period by as much as 20 days in Central Europe (Thaler 2012). Therefore, direct and indirect impacts of changes in climate on agricultural yield may confound the otherwise beneficial impacts of carbon fertilization with rising levels of atmospheric carbon dioxide.

Winter wheat spans approximately 3.27 million acres in the Pacific Northwest and supplies over 15% of the winter wheat yields in the United States (USDA, NASS, 2014). Additionally, wheat production in the inland northwest amounts to annual exports of more than $300 million (Schillinger 2008). All of which contribute to the region's rural economy. This is significant when considering the impact of climate change in the region as it has been found that as a result of climate change, winter wheat production could decrease by 4% in the Inland Northwest (Stockle 2010).

The dryland grain producing regions of the Inland Northwest is composed primarily of silt loam, loess soils (Brejda, 2000). The Palouse silt loam has been found to exhibit high erodibility and low shear stress (McCool et al. 2013). These soils, in conjunction with the climate of the Inland Northwest where a vast majority of annual precipitation falls from Nov-May, are ideal conditions for growing winter wheat. Soil erosion in the region generally results from multi-day precipitation events during the cool season (Nov-May) when precipitation falls as rain coincident with snowmelt (McCool 2013), but can also occur coincident to lesser precipitation rates in late winter and early spring when soils thaw resulting in low cohesion in the soils and higher runoff rates (McCool 2013). Increased precipitation can have positive impacts on crop growth, but over an extended period, increases in mean precipitation and extreme precipitation may cause higher runoff rates and more erosion that could inhibit productivity in subsequent years. Additionally, the conversion from snow to rain due to increased temperatures may enhance soil erosion, negatively impacting the sustainability of wheat yields across the region.

The agricultural management of this crop plays a role in how erosive the soil is; generally, management focuses on conventional tillage and no-tillage. Conventional tillage breaks down the structure of the soils by digging or overturning and leaves the soil susceptible to the high precipitation that occurs in winter. No-tillage leaves surface residue which protects the soil from raindrop impact and shields the mineral soil from shear forces of running water. The number of farms that practice conventional tillage has decreased since 1975, using a moderate amount of tillage referred to as 'conservation tillage' (Kok et al. 2009). In the Pacific Northwest, conventional tillage has been found to cause greater soil loss over time due to continued perturbations of the soil (Mochado 2007; Prahsun 2012). By contrast, no-till has been shown to be a more productive means in maintaining a crop for longer periods of time (Jin et al. 2007) through the preservation of soil quality and hindrance of erosion in observed no-tillage farming systems over the last 30 years (Kok et al. 2009). No-till practices, however, often incur higher costs of operating and maintaining a farm as well as higher rates of certain diseases (Scheinost et al. 2001). Understanding the seasonality of both precipitation and soil erosion across the Inland Northwest and the agricultural management decisions available provides a framework for analyzing the sensitivity of soil loss to climate change.

In the Pacific Northwest, it is estimated that an annual mean difference in temperature between observed 1950-1999 values and predicted 2041-2070 values could be approximately 3.2°C. With regards to precipitation, the mean percent change could amount to +3.2%. Moreover, winter precipitation is expected to increase by mean amount of 7.2%, albeit with a larger range of variability that includes no significant change (Dalton et al. 2013). This heightened winter precipitation will be a substantial factor when it comes to soil loss. Extreme precipitation events are also expected to increase in the Pacific Northwest (Salathe 2014), and these changes may negatively impact the Inland Northwest’s rural economy through decreased wheat yields due to greater soil erosion. For example, yields can decrease due to increased temperatures causing depleted available water.

Studies carried out in the Palouse region have found that much of the erosion in the region is due to thawing soils and high intensity precipitation (Boylan 2014). Additionally, Li (2011) found increases of 130% and 195% in runoff and erosion, respectively, under climate change in areas of the Loess Plateau of China using conventional tillage on winter wheat. Changes in soil loss are hypothesized to be dependent on the magnitude of climate change as well as specific mechanisms for soil loss at any given location and a specific cropping practice. As much as 85% of soil erosion in the Inland Northwest occurs during the winter months, partially as a result of snowmelt and the thawing of soils (McCool 2006), it is likely that changes in precipitation phase with warming will have geographically specific impacts in areas near the rain-snow transition during winter.

Chapter 2:

Data and Methods

a. Study Area

We focus on soil erosion near the eastern extent of the semi-arid dryland winter wheat growing of the Columbia Plateau in the northwestern US region near Moscow, Idaho located at 46.73 °N, -117 °W at an elevation of 786 m (Figure 2.1). Moscow is located in an area known as the Palouse, which is known to be one of the richest wheat growing areas in the United States in terms of productivity.

Moscow receives more precipitation than most other wheat growing areas of the Inland Northwest with approximately 60 cm of rainfall and approximately 120 cm of snowfall per 1981-2010 (Figure 2.2) climate normals (NCDC). Moscow receives approximately 39% of its November-March precipitation as snow. Collectively these conditions provide a more conducive environment for favorable dryland winter wheat yields than other areas of the semi-arid northwestern US. Annual average maximum and minimum temperature averages are estimated at 14.5°C and 2.5°C, respectively. Climatologically, the largest precipitation events occur in late October and November in Moscow, hence the impacts are likely superposed on the largest rainfall rates, rather than strictly mean precipitation. Measurable precipitation is recorded on approximately 60% of days between Nov-April, however, over 25% of the heaviest 1 percent of days with precipitation occurs in November.

The soils of the region are mostly formed in loess and made of silt loam (Brejda 2000). This means that they have no less than 20% sand content and no less than 70% silt content. The higher the sand content the more erodible the soil (Ritter 1978) and while the water holding capacity of these soils is relatively high, they are still prone to erosion if the soil is frequently disrupted. These soils, in conjunction with the vast majority of annual precipitation occurring from Nov-May, are ideal conditions for growing winter wheat. Erosion in the region occurs at a higher baseline level across increasing slope grades and there is a higher rate of erosion under conventional tillage practices than on farms that utilize the no tillage management practice, all of which can be seen in Figure 2.2. Conventional tillage controls on a moderate hillslopes exhibited 0.075 kg/m^2 and no tillage control on the same hillslope exhibited 0.007 kg/m^2.

b. *Erosion Model*

We use the Water Erosion Prediction Project (WEPP), which is the 'process based, distributed parameter, continuous-simulation model for erosion prediction' (Flanagan et. al 1995). WEPP accounts for various parameters including soil type, cropping practice, slope profile, land use and vegetation for hillslopes and watersheds and uses. WEPP accepts actual daily meteorological data including temperature and precipitation and then uses the CLIGEN stochastic weather generator to temporally disaggregate sub daily data including precipitation intensity as well as derive other necessary variables such as dew point, wind and solar radiation. WEPP output includes numerous parameters, most notably soil loss rates. We considered ancillary data to better understand the relationship between soil loss and driving forces including: (i) runoff from snowmelt and rain, (ii) live biomass, (iii) precipitation falling as rain, (iv) precipitation falling as snow, (v) soil erodibility. For example, water balance outputs provide the analysis with rain and melt amounts that represent how phase changes in precipitation from snow to rain will change as a result of increased temperatures and therefore how soil loss is impacted seasonally and annually. The water balance outputs also provide insight as to how frozen soil will change seasonally with climate change and allow us to analyze the impact of a loss of soil cohesion with climate change. Additionally, the impact climate has on the rill and interill erodibility of the soils in the region was considered. The interill and rill erodibility in WEPP are calculated using slightly different erodibility adjustment factors. Both of the erodibility factors take into account the dead and live root masses as well as the sealing and crusting of the soil. However, rill erodibility takes into account the buried biomass in the hillslope being modeled, whereas interill erodibility takes into account live biomass. These variable were considered in the final analysis.

We considered five different hillslopes that spanned the topography of the study area to run WEPP over: flat (2%), moderately flat (5%), moderate (8%), moderately steep (12%) and steep (35%). In the 10 km radius of Moscow, 74% of the land is cultivated and of that 15% is classified as flat, 27% as moderately flat, 30% as moderate, 21% as moderately steep, and 7% as steep. Palouse silt loam was used in all experiments. Southwick soils, which have an argillic layer that makes them more prone to saturated excess runoff than the Palouse soils (Boylan, 2014), are found in the region and would add to the soil profiles of this experiment. Finally, two simulations of annual, continuous cropping systems were applied that included annual no tillage winter wheat and annual conventional tillage winter wheat. While growers in the annual cropping zone typically follow a three year winter wheat, spring grain, and spring pulse crop rotation, a continuous winter wheat rotation was selected in this analysis to provide a consistent annual crop management signal to assist in assessing trends across years.

c. Climate data:

Daily maximum, minimum temperature and precipitation near Moscow, Idaho from 1979-2013 was acquired from the gridded surface meteorological dataset of Abatzoglou (2013). Additionally, downscaled daily data from twenty global climate models (GCMs) participating in CMIP5 for the same location were used. Daily GCM output was downscaled using the Multivariate Adaptive Constructive Analogs method (Abatzoglou and Brown, 2012) to ensure compatibility with observed historical data. Historical model runs (1950-2005) and mid-21st century climate (2041-2070) using the RCP8.5 experiment were used. The Representative Concentration Pathway 8.5 represents the future climate prediction if anthropogenic forcing of climate change continues on its current path. This scenario was used because it is the current trajectory of climate change if minimal adaptation and mitigation were to occur before mid-century.

d. Analysis:

We first ran a set of sensitivity experiments to assess how changes in temperature or precipitation impact soil erosion. The sensitivity analysis was carried out over each hillslope and both conventional and no-till management using perturbations of precipitation and temperature perturbations from observed data (1979-2013) that generally encompassed projected changes by GCMs. Annual precipitation was modified between -15 to 15% using 5% increments, while temperature was modified using warming between 0 and 4°C using a 1°C increment. Perturbations to temperature and precipitation were applied uniformly to the observed data (e.g., increasing every day's temperature by 1°C, increasing precipitation amount on every day with precipitation by 5%) to the full 35-year observed record. An extreme precipitation sensitivity experiment modified the top 1% of precipitation days from -15% to +15% using 5% increments, and applying opposing changes to all other precipitation days such that the net change in precipitation was zero. Sensitivity studies were conducted separately for temperature and precipitation, and through combined effects. These sensitivity studies serve as a precursor to the analysis involving the downscaled climate data in order to understand what the specific driving forces are behind climate change driven soil erosion.

Secondly, we examined changes in WEPP output across the 20 downscaled climate projections. This analysis combined with the sensitivity study serves as the comprehensive study as to how climate change will impact the Inland Northwest. To analyze how the GCMs and the sensitivity experiments compared, the first step was to calculate the change in temperature and precipitation for each model. Once the ability to compare temperatures and precipitation was established, the annual changes in soil erosion of each model was simulated using WEPP and from that the multi-model means served to compare the experiments to the RCP8.5 'business as usual' scenarios for the mid-21st century projections.

We focus on describing the results for sensitivity experiments on moderate hillslopes under conventional tillage practices given that this is largely representative of the bulk of the agricultural land in the region susceptible to erosion. However, figures and tables provide supplemental information on how changes are manifest for different slope and management practices as well as in a section devoted to emphasizing differences across these conditions.

Chapter 3:

Results

a. Sensitivity Experiments

Increases in baseline annual soil loss for Moscow, ID were simulated for flat, moderately flat, moderate, moderately steep and steep hillslopes and under conventional tillage and no tillage. Warming experiments result in a unanimous increase in soil loss rates across all hillslope and tillage permutations (Figure 3.1). We focus on specific results under conventional tillage and a moderate hillslope hereafter, but provide a discussion of differences across these variables at the end of the section. For the conventional till-moderate slope runs, the increase in soil loss was nonlinear with warming. A 28% and 80% increase in annual average soil loss was simulated for a 1°C and 2°C warming, respectively, whereas a more muted increase in annual soil loss of 69% and 49% was simulated with warming of 3°C and 4°C, respectively. An additional experiment was performed using an extreme increase in temperature of 6°C resulting in a net increase in soil erosion of 59% (Table 3.3).

Changes in the seasonal timing of soil loss provide a complementary view of annual summaries (Figure 3.2). Warming resulted in large increases in erodibility in October and November for conventional till-moderate slope experiments. Whereas the increase in soil loss scaled with the amount of warming in October, a nonlinear response was found in November with peak loss for a +3°C warming. Soil loss rates were largest for warming experiments of 2°C and 1°C for December and January, respectively. Conversely, decreased erosion rates were modeled in February for all warming experiments as a result of less snowmelt.

Warming impacts soil erosion in indirect and complex ways. While we identified overall changes in soil loss at the annual and monthly timescales, our results also suggest a 33% increase in the number of erosion events and a 30% increase in the maximum erosional loss rate per event for conventional till-moderate slope experiments versus control experiments. We highlight three climatic contributing factors through which warming may impact erosion loss rates (Figure 3.3).

First, snow water equivalent (SWE) during the winter months decreased substantially with warming indicative of the decrease in snowfall amounts and higher relative snowmelt rates. The amount of combined precipitation falling as rain combined with snowmelt is also seen in Figure 3.3. The combination of rain and snowmelt increased by approximately ~30% in December and January when an increase in 2˚C was compared to the baseline. Whereas these changes result in an increase in the rainfall runoff during early to mid-winter due to the phase change of precipitation and increased erosion potential, reduced snowpack and possibly the magnitude of rain-on-snow events during late winter mitigate erosion rates in February and March.

The amount of soil erosion is directly related the erodibility of the soil. Soil erodibility increases with tillage and decreases with surface residue and buried root matter or carbon. Soil erodibility decreases with time since tillage due to soil consolidation. The WEPP model distinguishes between interill erodibility (i.e. erosion due to raindrop impact) and rill erodibility (i.e. erosion due to water flowing over the soil surface). Interill erodibility is most sensitive to surface residue cover and rill erodibility is most sensitive to buried organic/root mass. The amount of surface residue and buried residue is directly related to the amount of live crop biomass produced each year (i.e. more residue and root mass remains in the soils having larger crop biomass production). Overall the soil erodibility therefore will be inversely related to crop biomass production. WEPP predicts changes in crop biomass production based on soil water availability as a reflection of the climate at a specific location. This feedback between climate, crop production, and soil erodibility was an important process affecting future soil erosion simulations.

The large increases in soil erosion predicted by WEPP in October can be largely explained by the effect of climate on crop biomass production on soil erodibility. The warmer future climates result in decreased crop biomass production and decreased overall buried biomass (Figure 3.4), resulting in increased rill erodibility in the fall for warming scenarios (Figure 3.5). Therefore with increasing temperature, buried biomass decreased, causing the rill erodibility of the soil to increase. This change in rill erodibility causes the increase in soil loss during October. The nonlinearity of the winter changes in erosion as a result of temperature change resides in the fact that the tendency for the erodibility of the soils to increases as temperatures increases. Between December 15-March 1, the soils in the 2°C experiment exhibited~12% higher daily erodibility as compared to the 4°C experiment driving the erosion during winter to be elevated under the +2°C experiment over the +4°C experiment and indicating that overall soil loss is highly dependent on daily events.

Thirdly, warming results in an advancement in the development of biomass in the spring given the phenological-climate linkages. Live biomass increases nearly 100% per degree Celsius warming from February to April (Figure 3.6). As crop biomass of winter wheat develops more rapidly during late winter and spring this mitigates soil erosion potential by providing coverage under warming scenarios. Note, however that peak crop biomass declines with warming due to the additional moisture deficit during the end of the growing season (Figure 3.4).

By contrast, precipitation experiments generally exhibited direct and linear impacts on soil erosion. Under conventional tillage practices and moderate slopes, soil erosion increases linearly at a rate 5% per 1% increase in precipitation (Figure 3.7, Table 3.4), with the changes in erosion being most prominent in October and November with more subtle and non-linear changes in mid-to-late winter (Figure 3.8). Similarly, the precipitation extremes (Figure 3.9 and Table 3.4) experiments yielded substantial increases in erosion rates in the absence of any change in annual total precipitation. Increases in annual erosion loss were similar to those in the precipitation experiments. Unlike for precipitation experiments, precipitation extremes experiments resulted in changes isolated to October and November coincident with the concentration of precipitation extremes during late fall and when soil erodibility is highest. The modeled influence of changes in precipitation and precipitation extremes on soil erosion is congruent with other studies (Boylan 2014, O’ Neal 2005, Routscheck 2014).

Changes in soil loss using combined temperature and precipitation experiments are presented in Table 3.5. Soil loss rates are not simply additive when both temperature and precipitation changes are considered. For example, in the combination study, an increase in precipitation of 5% and an increase of 2°C in temperature results in a 0.09 kg/m^2 of soil loss annual change from the baseline or a 118% increase. Under the individual studies, an increase of 2°C results in a 0.06 kg/m^2 (80%) increase in erosion annually and an increase of 5% in precipitation results in a 0.017 kg/m^2 (23%) increase in erosion annually. Simply adding the two isolated experiments results in a 17% higher erosion rate than in the combination study. There are also subtle changes that occur when the combination study is examined more closely. For example, with no changes in precipitation, soil loss peaks with a warming of 2°C, whereas for a 15% increase in precipitation, soil loss peaks with a warming of 4°C.

Hillslope variations:

When considering the variations in hillslopes in the sensitivity experiments, erosion processes react in variable ways depending on the climatic variable acting on them. When temperature is considered, flat, moderately flat, and moderate hillslopes react nonlinearly with each degree increase in warming. In contrast, moderately steep and steep hillslopes exhibited linear soil loss in response to increases in temperature   when strictly precipitation mean changes and extreme precipitation changes were considered, all slopes and tillage practices exhibited linear annual soil losses as slopes increase. The most prevalent hillslopes in the region exhibited a variable response to temperature under conventional tillage and more linear response under no-tillage with erosion increasing by 30%-40% between 1°C and 2°C, and linearly by 15% per degree Celsius thereafter.

Management Practices:

As has been seen through various studies, conventional tillage practices cause a greater soil loss than no tillage due to the fact that the soil is disturbed and the strength of the soil decreases, allowing for greater detachment (Zhang 2011). Likewise, cropping management practices are a large consideration in these experiments. No tillage exhibited an overall nominal increase in soil erosion when compared to conventional tillage across all hillslopes and sensitivity experiments. Moreover, conventional tillage differs from no tillage, most notably in the temperature experiments, in that conventional tillage experiences variable soil losses when temperatures increase above 2°C. No till practices result in a more linear erosion loss response to climatic factors due to the fact that no till methods preserve crop residue allowing for protecting the soil better moisture content than conventional till methods and therefore a higher level of soil stability.

b. Climate Modeling Experiments

While sensitivity experiments can provide one approach for estimating changes in soil loss ranges under climate change, they are unable to capture the range of dynamics inherent with climate change. It should be noted that the historical GCMs exhibited slightly varied levels of soil loss rates as compared to the historical baseline runs used for the sensitivity experiments; however, the difference between the two is slight and the two sets of data are from different sources which could account for the discrepancy. A more involved approach using downscaled GCMs is presented for comparison. Figure 3.11 shows that most of the models span the range of our joint temperature and precipitation experiments falling between a +1.5°C to +4.5°C increase in annual mean temperature and a 5% decrease to 15% increase in annual precipitation. Projected changes in soil loss showed large inter-model spread across hillslopes and management practices. However, all models resulted in increased soil erosion relative to control simulations. The multi-model mean soil loss on a moderate hillslope was 137% and 131% increase (Figure 3.14, Table 3.6) under conventional tillage and no tillage practices, respectively. Under conventional tillage practices flat and moderately flat hillslopes had the highest increases in erosion, whereas moderate and moderately steep hillslopes had the highest increases under a no till scenario.

The multi-model distribution can be seen in Figure 3.12. The outliers seen in this figure are the some of the same outliers seen in the previous figures, the most drastic of which being the HADGEM2-ES with up to 375% and 550% increases in erosion under no tillage and conventional tillage, respectively. The multi-model means in erosion under no tillage lie between a 100% increase and a 150% increase and between 75% and 175% under conventional tillage. It should also be noted that that the magnitude of the actual soil loss amounts (Figure 3.13) exhibited relatively different changes in soil loss when no tillage and conventional tillage practices are considered.

A comparison between our sensitivity study results and the soil loss simulated by the GCMs is provided in Figure 3.13 for conventional till on moderate slopes. In general the models that experienced higher warming rates and increases in annual mean precipitation incurred bigger increases in soil loss, consistent with our sensitivity results. Differences between GCM simulated soil loss rates and soil loss rates inferred from our joint temperature-precipitation sensitivity analysis for each model were substantial (Figure 3.15). However, some models such as CSIRO-Mk3-6-0, showed a decrease in precipitation of -2% and an increase in temperature of 3.6°C, but had a large increase in soil loss of 249%. By comparison, the joint sensitivity analysis suggested only a 9% increase in soil loss for a similar rate of annual warming and precipitation decline. The HadGEM2-ES model simulated a 4-6 fold increase in soil loss. This model simulates an annual mean warming of around 4.5°C, but only a minor increase in annual mean precipitation. This drastic increase in the HadGEM2-ES is due to not only increases in the intensity of precipitation extremes (top 1% of precipitation events increases by 15%) and 10-20% increase in monthly precipitation from October-December, but also a large increase in summer aridity which reduce crop yields and increase soil erodibility in the autumn. Conversely, soil loss increase for NorESM1-M was nearly identical to corresponding changes in soil loss of 120% for a +3C warming and +5% precipitation increase in the joint sensitivity analysis. Overall, GCM resulted tended to predict slightly larger increases (+17%) in soil loss rates than for their respective sensitivity analysis results. These results are not surprising given that the joint sensitivity experiments do not account for changes in distribution of precipitation intensity.

Chapter 4:

Discussion and Conclusions

Increases in soil erosion were modeled for the Palouse region of the Inland Northwest based sensitivities experiments that utilized proximate changes in climate, as well as for simulations that directly utilized downscaled GCM output. Whereas climate projections simulate significant and robust increases in temperature for the region with anthropogenic forcing, projected changes in precipitation are small compared to internal climate variability and include both increases and decreases (Mote and Salathe, 2010). The large increase in soil loss rates with warming in the study area is an important feature of the sensitivity experiments. Despite the higher uncertainty regarding changes in precipitation, our results suggest increases in soil loss with warming across the region.

The influence of temperature change on soil erosion has been less well resolved compared to the influence of precipitation change. However, we show both direct and indirect mechanisms through which warming alters soil erosion loss seasonally. Warming in areas that receive substantial precipitation amounts with temperatures near freezing can substantially alter the percent of precipitation that falls as snow (Klos et al., 2014), leading to increased runoff and erosion rates (Nearing 2004). This mechanism will vary geographically with climate, as regions that do not receive snow will be void of this influence. The nonlinear response that occurs with a number of the temperature sensitivity experiments was found to be a result of variable erodibility of the soils with increased temperature. The extent to which temperature impacts soil erodibility in the Palouse is potentially complex as erodibility varies through processes such as freezing and thawing of soils on an event by event scale, which can have large impacts on daily, monthly, and annually modeled soil erosion (Greer 2006, Wang 2013).

Sensitivity analyses provide insight into the relative influence of different factors. Projected climate change includes changes in temperature and precipitation, including factors beyond just mean change that may confound the ability to understand the underlying sensitivities in a system being studied. While precipitation and precipitation extreme sensitivity experiments yielded relatively predictable results, the sensitivity of soil loss to warming rates is less well understood. Direct and indirect mechanisms including changes in precipitation phase as well as seasonal changes in biomass and erodibility highlight important aspects that have not received much previous attention. By understanding these indirect processes, future studies can focus on the details of how climate impacts erosion.

Similar results have found that mid-21st century will see increases in soil erosion coincident with potential decreases in wheat yields in the Loess Plateau of China due to climatic changes (Li 2011). Li (2012) primarily highlighted detrimental impacts on soil erosion as a result of increases in storm intensities and changes in precipitation. The Inland Northwest receives most of its extreme precipitation events in the late autumn and early winter, some of which currently include snowfall. It is not clear whether the influence of warming on soil loss rates is unique for the geographic setting of the Inland Northwest, but additional sensitivity analysis that covers other wheat growing areas of the globe would provide insight.

While this research includes a vast range of analysis on climate sensitivities and predictions of regional climate change, there are some aspects of how certain aspects of the WEPP model and conceptual caveats to this research. It should be acknowledged that while continuous winter wheat was used in this research, it is not commonplace in the region, but served to look at erosion reacts relative to various climate scenarios. A comparable study that used a more typical crop rotation and a Southwick soils found similar trends in soil loss; however, different cropping rotations and a Southwick silt loam soil type led to higher erosion rates (Boylan 2014) than was found in this research using continuous winter wheat and Palouse silt loams. Some future research that would complement this study includes analyzing the significance of and driving forces behind erosion events and their contribution to overall changes that were simulated. Additionally, much research has been conducted on the ways in which CLIGEN impacts the outcomes that WEPP finding that CLIGEN is generally a good predictor of weather and storm intensity generation (Zhang 2003); however, understanding and analyzing how CLIGEN influenced the sensitivity studies would provide a broader analysis for this research.

The results of these modeling exercises may serve to inform adaptation and mitigation measures for soil management. It is well known that erosion rates are higher on steeper hillslopes and under conventional tillage practices. Likewise, model results show the largest absolute changes in soil loss on steeper hillslopes with climate change. Whereas it might not be feasible to mitigate soil loss over all agricultural lands in the region, targeted measures to reduce soil loss from areas most vulnerable might be an effective approach. For example, projected soil loss of 3.06 kg/m^2 for steep slopes using conventional tillage that comprises 7% of the area contribute up 67% of the overall projected soil loss for the agricultural land considered. Implementation of either no tillage practices, or conservation tillage that has been shown to have similar responses to erosion as no tillage and is used on many of the farms in the Palouse region, may reduce the overall projected changes in soil loss in the region by 93%.

Hillslope	Percent of Cultivated land Classified as a given hillslope
Flat	15
Moderately Flat	27
Moderate	30
Moderately Steep	21
Steep	7

Table 3.1: The percent area of farmland that falls under each of the hillslope simulations in a 10 kilometer radius of Moscow, ID. This was derived using GIS and National Land Cover Data (NLCD 2011) to determine the cultivated areas surrounding Moscow.

Hillslope	Soil Loss - Conventional Till (kg/m^2)	Soil Loss Change- Conventional Till (%)	Soil Loss- No Tillage (kg/m^2)	Soil Loss Change - No Tillage (%)
Flat				
Control	0.024		0.005	
1C	0.036	50	0.008	60
2C	0.048	100	0.01	100
3C	0.046	92	0.01	100
4C	0.044	83	0.011	120
6C	0.045	87	0.014	180
Moderately Flat				
Control	0.037		0.006	
1C	0.054	46	0.009	50
2C	0.071	92	0.011	83
3C	0.068	84	0.012	100
4C	0.061	65	0.013	117
6C	0.058	57	0.016	167
Moderate				
Control	0.075		0.007	
1C	0.096	28	0.01	43
2C	0.135	80	0.013	86
3C	0.127	69	0.014	100
4C	0.112	49	0.015	114
6C	0.119	58	0.018	157
Moderately Steep				
Control	0.218		0.01	
1C	0.289	3	0.015	50
2C	0.375	33	0.018	80
3C	0.379	35	0.02	100
4C	0.36	28	0.022	120
6C	0.385	76	0.025	150
Steep				
Control	1.15		0.042	
1C	1.231	7	0.065	55
2C	1.3	13	0.076	81
3C	1.511	31	0.093	121
4C	1.597	38	0.094	124
6C	1.899	65	0.111	164

Table 3.2: Thirty year annual average soil losses under conventional tillage practices and no tillage practices over all hillslope variations under as modeled with an increase in temperature.

Hillslope	Soil Loss - Conventional Till (kg/m^2)	Soil Loss Change- Conventional Till (%)	Soil Loss- No Tillage (kg/m^2)	Soil Loss Change - No Tillage (%)
Flat				
-15%	0.011	-54	0.002	-60
-10%	0.014	-42	0.003	-40
-5%	0.02	-17	0.004	-20
0 (control)	0.024	0	0.005	0
+5%	0.032	33	0.007	40
+10%	0.044	83	0.009	80
+15%	0.052	117	0.011	120
Moderately Flat				
-15%	0.015	-60	0.003	-50
-10%	0.018	-51	0.003	-50
-5%	0.03	-19	0.004	-33
0 (control)	0.037	0	0.006	0
+5%	0.049	32	0.008	33
+10%	0.061	65	0.01	67
+15%	0.076	105	0.013	117
Moderate				
-15%	0.034	-54	0.003	-57
-10%	0.038	-49	0.004	-43
-5%	0.06	-20	0.005	-28
0 (control)	0.075	0	0.007	0
+5%	0.092	23	0.009	28
+10%	0.125	67	0.011	57
+15%	0.137	83	0.014	100
Moderately Steep				
-15%	0.128	-41	0.005	-50
-10%	0.138	-37	0.006	-40
-5%	0.171	-22	0.008	-20
0 (control)	0.218	0	0.01	0
+5%	0.279	28	0.013	30
+10%	0.354	62	0.016	60
+15%	0.429	97	0.02	100
Steep				
-15%	0.62	-46	0.02	-52
-10%	0.831	-27	0.027	-36
-5%	0.953	-17	0.035	-17
0 (control)	1.15	0	0.042	0
+5%	1.306	14	0.056	33
+10%	1.632	42	0.07	67
+15%	1.893	65	0.087	107

Table 3.3: Thirty year annual average soil losses under conventional tillage practices and no tillage practices over all hillslope variations under as modeled with changes in precipitation.

Hillslope	Soil Loss - Conventional Till (kg/m^2)	Soil Loss Change- Conventional Till (%)	Soil Loss- No Tillage (kg/m^2)	Soil Loss Change -No Tillage (%)
Flat				
-15%	0.012	-50	0.003	-40
-10%	0.016	-33	0.004	-20
-5%	0.02	-17	0.004	-20
0 (control)	0.024	0	0.005	0
+5%	0.032	33	0.006	20
+10%	0.039	63	0.007	40
+15%	0.046	92	0.008	60
Moderately Flat				
-15%	0.017	-54	0.004	-33
-10%	0.022	-41	0.005	-17
-5%	0.029	-22	0.005	-17
0 (control)	0.037	0	0.006	0
+5%	0.048	30	0.007	17
+10%	0.057	54	0.008	33
+15%	0.069	86	0.009	50
Moderate				
-15%	0.046	-39	0.005	-29
-10%	0.057	-24	0.005	-29
-5%	0.064	-15	0.006	-14
0 (control)	0.075	0	0.007	0
+5%	0.087	16	0.008	14
+10%	0.102	36	0.009	28
+15%	0.116	55	0.01	43
Moderately Steep				
-15%	0.167	-24	0.007	-30
-10%	0.172	-21	0.007	-30
-5%	0.19	-13	0.009	-10
0 (control)	0.218	0	0.01	0
+5%	0.245	12	0.011	10
+10%	0.287	32	0.013	30
+15%	0.311	43	0.015	50
Steep				
-15%	0.988	-15	0.028	-33
-10%	1.018	-12	0.031	-26
-5%	1.089	-6	0.036	-14
0 (control)	1.155	0	0.042	0
+5%	1.219	6	0.048	14
+10%	1.296	12	0.053	26
+15%	1.302	13	0.057	36

Table 3.4: Thirty year annual average soil losses under conventional tillage practices and no tillage practices over all hillslope variations under as modeled with changes in extreme precipitation.

Hill Slope	Soil Loss -Conventional Till (kg/m²)				Soil Loss Change-Conventional Till (%)				Soil Loss- No Tillage (kg/m²)				Soil Loss Change -No Tillage (%)			
	1C	*2C*	*3C*	*4C*	*1C*	*2C*	*3C*	*4C*	*1C*	*2C*	*3C*	*4C*	*1C*	*2C*	*3C*	*4C*
Flat																
-15%	0.019	0.021	0.021	0.017	-21	-56	-48	-29	0.003	0.004	0.004	0.005	-40	-20	-20	0
-10%	0.022	0.026	0.03	0.024	-8	8	25	0	0.004	0.006	0.006	0.006	-20	20	20	20
-5%	0.028	0.035	0.034	0.031	-17	46	42	29	0.006	0.008	0.008	0.008	20	60	60	60
0	0.036	0.048	0.046	0.044	50	100	92	83	0.008	0.01	0.01	0.011	60	100	100	120
+5%	0.05	0.061	0.063	0.058	108	154	163	142	0.01	0.012	0.013	0.014	100	140	160	180
+10%	0.064	0.074	0.076	0.076	167	208	217	217	0.012	0.015	0.016	0.018	140	200	220	260
+15%	0.071	0.088	0.096	0.096	196	267	300	300	0.014	0.018	0.02	0.022	180	260	300	340
Moderately Flat																
-15%	0.026	0.028	.029	0.026	-30	-24	-22	-30	0.004	0.004	0.005	0.005	-33	-33	-17	-17
-10%	0.03	0.039	0.043	0.032	-19	5	16	-14	0.005	0.006	0.007	0.007	-17	0	17	17
-5%	0.041	0.052	0.05	0.044	11	41	35	19	0.007	0.009	0.009	0.01	17	50	50	67
0	0.054	0.071	0.068	0.061	46	92	84	65	0.009	0.011	0.012	0.013	50	83	100	117
+5%	0.075	0.094	0.093	0.086	103	154	151	132	0.011	0.014	0.015	0.017	83	133	150	183
+10%	0.092	0.111	0.114	0.111	149	200	208	200	0.013	0.017	0.018	0.021	117	183	200	250
+15%	0.108	0.13	0.143	0.145	192	251	286	292	0.015	0.02	0.023	0.025	150	233	283	317
Moderate																
-15%	0.048	0.051	0.048	0.044	-36	-32	-36	-41	0.004	0.005	0.006	0.006	-43	-28	-14	-14
-10%	0.053	0.073	0.073	0.057	-29	-3	-2.7	-24	0.006	0.007	0.008	0.008	-14	0	14	14
-5%	0.076	0.101	0.104	0.082	1	35	39	9	0.008	0.01	0.011	0.011	14	43	57	57
0	0.096	0.135	0.127	0.112	28	80	69	49	0.01	0.013	0.014	0.015	43	86	100	114
+5%	0.12	0.164	0.165	0.156	60	119	120	108	0.013	0.016	0.017	0.019	86	128	143	171
+10%	0.151	0.197	0.207	0.206	101	163	176	175	0.015	0.018	0.021	0.023	114	157	200	228
+15%	0.185	0.239	0.261	0.269	147	219	248	259	0.018	0.023	0.025	0.029	157	228	257	314
Moderately Steep																
-15%	0.145	0.16	0.179	0.149	-33	-27	-18	-32	0.007	0.008	0.009	0.01	-30	-20	-10	0
-10%	0.177	0.224	0.24	0.21	-19	3	10	-4	0.009	0.011	0.012	0.012	-10	10	20	20
-5%	0.218	0.279	0.31	0.276	0	28	42	26	0.012	0.015	0.016	0.016	20	50	60	60
0	0.289	0.375	0.379	0.361	33	72	74	66	0.015	0.018	0.02	0.022	50	80	100	120
+5%	0.336	0.444	0.473	0.469	54	104	117	115	0.018	0.022	0.026	0.027	80	120	160	170
+10%	0.408	0.572	0.579	0.594	162	162	166	173	0.023	0.027	0.031	0.033	130	170	210	230
+15%	0.499	0.629	0.68	0.746	129	188	212	242	0.027	0.033	0.037	0.041	170	230	270	310
Steep																
-15%	0.629	0.686	0.804	0.849	-45	-40	-30	-26	0.029	0.038	0.042	0.044	-31	-10	0	5
-10%	0.808	0.887	0.967	1.057	-30	-23	-16	-8	0.04	0.046	0.055	0.06	-5	10	31	43
-5%	1.065	1.134	1.207	1.274	-7	-1	5	11	0.05	0.06	0.074	0.073	19	43	76	74
0	1.231	1.3	1.511	1.597	7	13	31	38	0.065	0.076	0.093	0.094	55	81	121	124
+5%	1.506	1.57	1.824	2.009	31	36	59	75	0.081	0.096	0.112	0.117	93	128	167	179
+10%	1.748	1.917	2.097	2.454	52	67	82	86	0.099	0.118	0.133	0.141	135	181	217	236
+15%	1.939	2.334	2.508	2.903	69	103	118	151	0.116	0.141	0.159	0.167	176	236	278	297

Table 3.5: Thirty year annual average soil losses under conventional tillage practices and no tillage practices over all hill slope variations with both temperature and precipitation changes considered.

Hillslope	Future Soil Loss – Conv. Till (kg/m^2)	Historical Soil Loss- Conv. Tillage (kg/m^2)	Soil Loss Change- Conv. Till (%)	Future Soil Loss- No Tillage (kg/m^2)	Historical Soil Loss- No Tillage (kg/m^2)	Soil Loss Change - No Tillage (%)
Flat						
bcc-csm1-1	0.078	0.043	81	0.019	0.012	58
bcc-csm1-1-m	0.103	0.038	171	0.019	0.01	90
BNU-ESM	0.118	0.061	93	0.029	0.011	163
CanESM2	0.158	0.05	216	0.033	0.012	175
CCSM4	0.122	0.053	130	0.024	0.011	118
CNRM-CM5	0.116	0.036	222	0.02	0.009	122
CSIRO-Mk3-6-0	0.118	0.042	181	0.023	0.01	130
GFDL-ESM2G	0.148	0.059	150	0.03	0.012	150
GFDL-ESM2M	0.088	0.04	120	0.022	0.01	120
HadGEM2-CC	0.112	0.081	38	0.033	0.018	83
HadGEM2-ES	0.186	0.037	402	0.043	0.009	377
inmcm4	0.068	0.048	41	0.018	0.012	50
IPSL-CM5A-LR	0.138	0.06	130	0.028	0.012	133
IPSL-CM5A-MR	0.176	0.054	225	0.024	0.01	140
IPSL-CM5B-LR	0.103	0.036	186	0.026	0.007	271
MIROC5	0.139	0.04	247	0.03	0.01	200
MIROC-ESM	0.081	0.042	92	0.021	0.009	133
MIROC-ESM-CHEM	0.073	0.058	25	0.022	0.011	100
MRI-CGCM3	0.059	0.046	28	0.015	0.012	25
NorESM1-M	0.126	0.057	126	0.026	0.014	85
Multi-Model Mean	0.115	0.049	135	0.025	0.011	128
Moderately Flat						
bcc-csm1-1	0.112	0.06	86	0.022	0.013	69
bcc-csm1-1-m	0.166	0.064	159	0.022	0.011	100
BNU-ESM	0.189	0.104	81	0.032	0.012	166
CanESM2	0.249	0.073	241	0.037	0.014	164
CCSM4	0.185	0.068	172	0.027	0.012	125
CNRM-CM5	0.185	0.051	262	0.022	0.01	120
CSIRO-Mk3-6-0	0.209	0.063	231	0.025	0.012	108
GFDL-ESM2G	0.222	0.09	146	0.033	0.014	135
GFDL-ESM2M	0.143	0.06	138	0.024	0.011	140
HadGEM2-CC	0.178	0.123	44	0.035	0.02	75
HadGEM2-ES	0.309	0.049	530	0.045	0.01	350
inmcm4	0.089	0.063	41	0.019	0.013	46
IPSL-CM5A-LR	0.214	0.107	100	0.031	0.014	121
IPSL-CM5A-MR	0.239	0.077	210	0.027	0.011	145
IPSL-CM5B-LR	0.163	0.059	176	0.028	0.008	250
MIROC5	0.212	0.054	292	0.033	0.011	200
MIROC-ESM	0.139	0.067	107	0.024	0.01	140
MIROC-ESM-CHEM	0.116	0.093	24	0.025	0.012	108
MRI-CGCM3	0.086	0.073	17	0.018	0.013	38
NorESM1-M	0.199	0.085	134	0.028	0.016	75
Multi-Model Mean	0.18	0.074	143	0.027	0.012	125
Moderate						
bcc-csm1-1	0.205	0.119	72	0.024	0.014	71
bcc-csm1-1-m	0.33	0.137	140	0.023	0.012	91
BNU-ESM	0.371	0.205	80	0.034	0.014	142
CanESM2	0.465	0.13	257	0.039	0.015	160
CCSM4	0.341	0.133	156	0.028	0.013	115
CNRM-CM5	0.321	0.112	186	0.024	0.011	118
CSIRO-Mk3-6-0	0.419	0.12	249	0.026	0.013	100
GFDL-ESM2G	0.395	0.187	111	0.035	0.015	133
GFDL-ESM2M	0.26	0.118	120	0.026	0.012	116
HadGEM2-CC	0.346	0.223	55	0.038	0.021	80
HadGEM2-ES	0.559	0.116	381	0.048	0.011	336
inmcm4	0.169	0.114	48	0.02	0.014	42
IPSL-CM5A-LR	0.382	0.217	76	0.034	0.014	142
IPSL-CM5A-MR	0.4	0.153	161	0.03	0.012	150
IPSL-CM5B-LR	0.309	0.119	159	0.03	0.008	275

MIROC5	0.38	0.104	265	0.036	0.012	200
MIROC-ESM	0.271	0.154	75	0.026	0.012	116
MIROC-ESM-CHEM	0.218	0.194	12	0.028	0.013	115
MRI-CGCM3	0.145	0.127	14	0.019	0.013	46
NorESM1-M	0.354	0.16	121	0.031	0.017	82
Multi-Model Mean	0.332	0.147	125	0.029	0.013	125
Moderately Steep						
bcc-csm1-1	0.582	0.361	61	0.033	0.018	83
bcc-csm1-1-m	0.877	0.442	98	0.031	0.016	93
BNU-ESM	1.042	0.557	87	0.045	0.019	136
CanESM2	1.263	0.349	261	0.054	0.019	184
CCSM4	0.891	0.371	140	0.037	0.016	131
CNRM-CM5	0.853	0.341	144	0.036	0.015	140
CSIRO-Mk3-6-0	1.117	0.328	240	0.039	0.017	129
GFDL-ESM2G	1.081	0.289	274	0.051	0.015	240
GFDL-ESM2M	0.697	0.327	113	0.035	0.016	118
HadGEM2-CC	1.011	0.606	66	0.05	0.027	85
HadGEM2-ES	1.446	0.43	236	0.065	0.015	333
inmcm4	0.462	0.345	33	0.026	0.018	44
IPSL-CM5A-LR	0.959	0.625	53	0.05	0.02	150
IPSL-CM5A-MR	1.024	0.448	128	0.043	0.016	168
IPSL-CM5B-LR	0.906	0.362	150	0.042	0.012	250
MIROC5	1.035	0.356	190	0.052	0.016	225
MIROC-ESM	0.728	0.455	60	0.041	0.016	156
MIROC-ESM-CHEM	0.665	0.621	7	0.04	0.018	122
MRI-CGCM3	0.443	0.361	22	0.026	0.02	30
NorESM1-M	0.948	0.4437	117	0.044	0.023	91
Multi-Model Mean	0.901	0.421	114	0.042	0.017	138
Steep						
bcc-csm1-1	2.368	1.484	59	0.138	0.083	66
bcc-csm1-1-m	2.839	1.605	76	0.141	0.098	43
BNU-ESM	3.667	2.115	73	0.203	0.092	120
CanESM2	3.917	1.367	186	0.225	0.097	131
CCSM4	2.726	1.389	96	0.165	0.102	61
CNRM-CM5	2.765	1.775	55	0.155	0.074	109
CSIRO-Mk3-6-0	3.675	1.192	208	0.214	0.076	181
GFDL-ESM2G	3.351	1.902	76	0.23	0.095	142
GFDL-ESM2M	2.546	1.309	94	0.174	0.079	120
HadGEM2-CC	3.288	2.231	47	0.232	0.141	64
HadGEM2-ES	4.51	1.525	195	0.279	0.103	170
inmcm4	1.704	1.408	21	0.122	0.088	38
IPSL-CM5A-LR	3.468	2.285	45	0.186	0.123	51
IPSL-CM5A-MR	3.27	1.632	100	0.162	0.088	84
IPSL-CM5B-LR	3.072	1.438	113	0.184	0.065	183
MIROC5	3.81	1.537	151	0.205	0.08	156
MIROC-ESM	2.65	1.753	51	0.176	0.08	120

MIROC-ESM-CHEM	2.573	2.026	26	0.168	0.101	66
MRI-CGCM3	1.728	1.285	34	0.095	0.102	7
NorESM1-M	3.329	1.591	109	0.2	0.105	90
Multi-Model Mean	3.062	1.642	86	0.183	0.093	95

Table 3.6: Thirty year annual average soil losses under conventional tillage practices and no tillage practices as a result of all 20 GCMs under the RCP8.5 scenario.

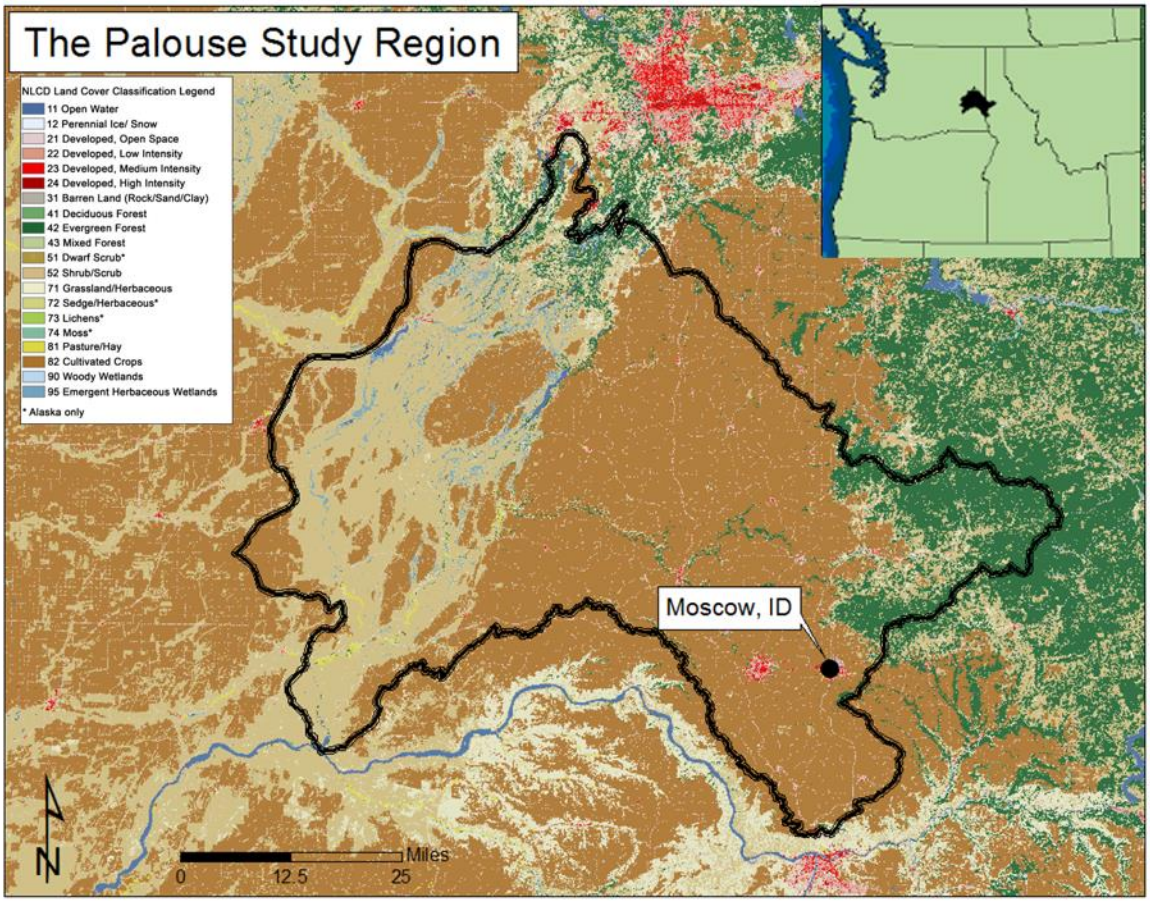

Figure 2.1: The Palouse region of the Inland Northwest with the study area, Moscow, ID represented. Land cover is also shown (NLCD 2011).

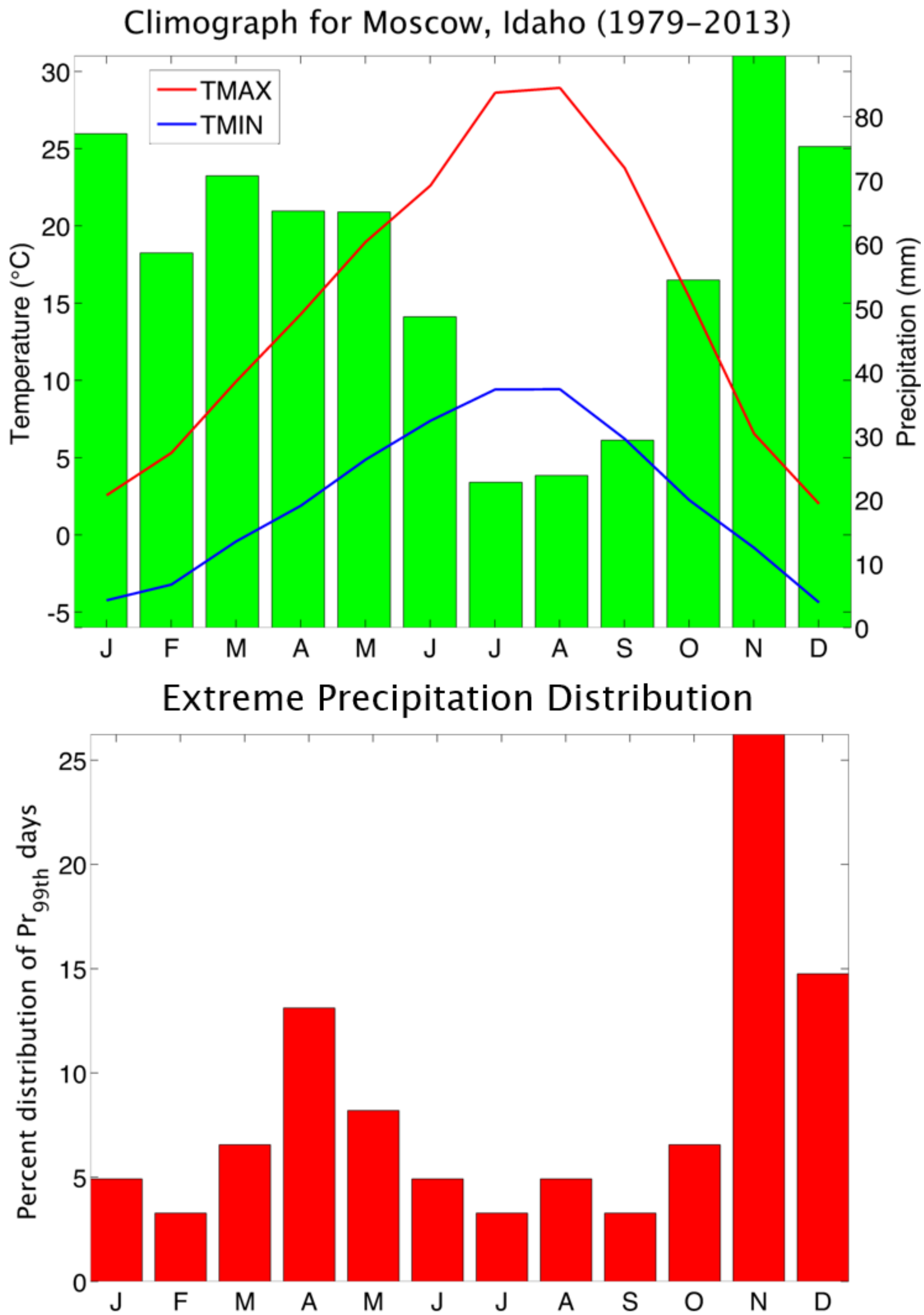

Figure 2.2: Climograph (top) of monthly historical temperature and precipitation and the distribution of the top 99% of extreme events (bottom).

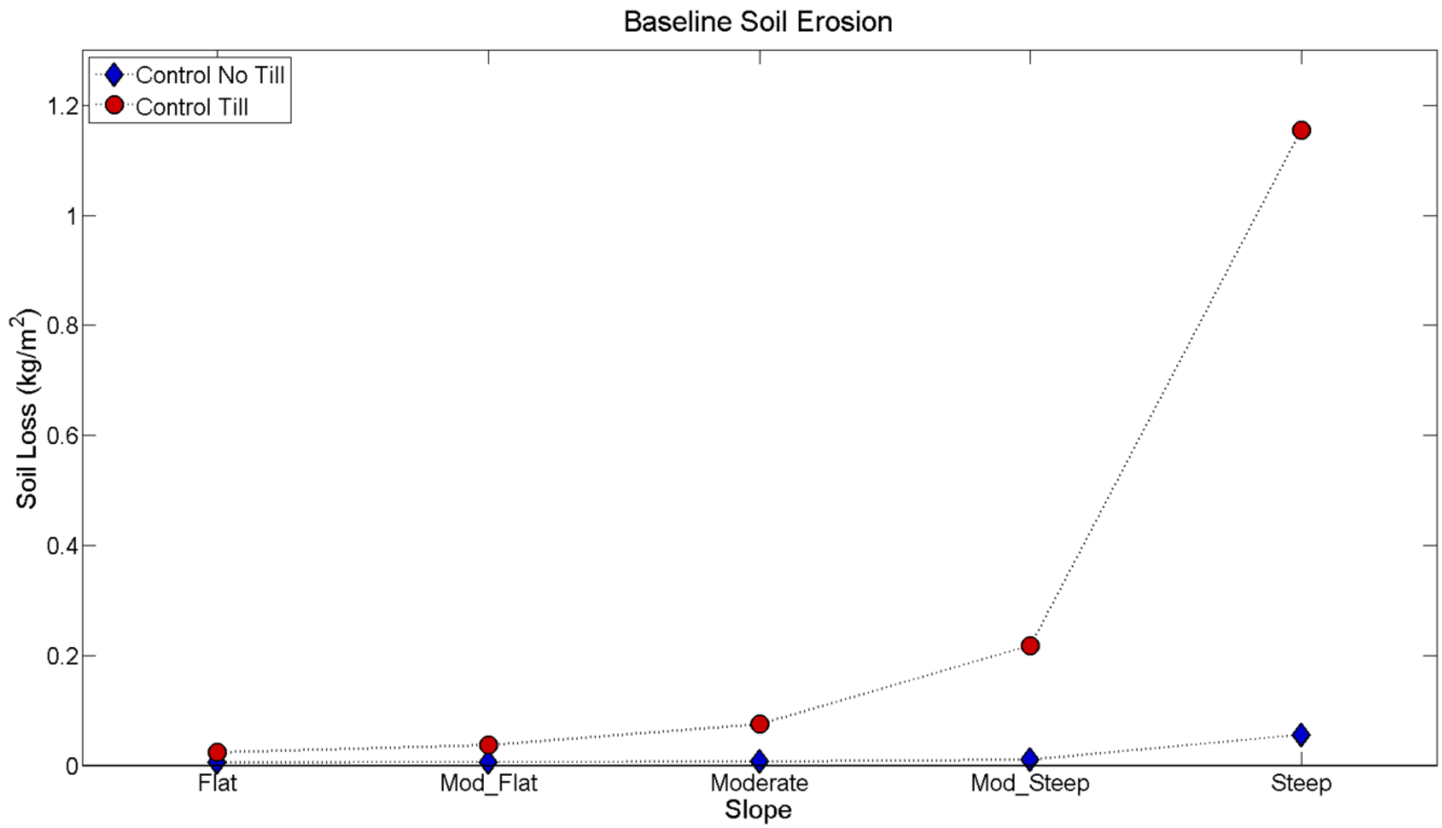

Figure 2.3: Annual mean soil erosion rates (kg/m2) for 30-year control runs across all hill slopes and both cropping managements.

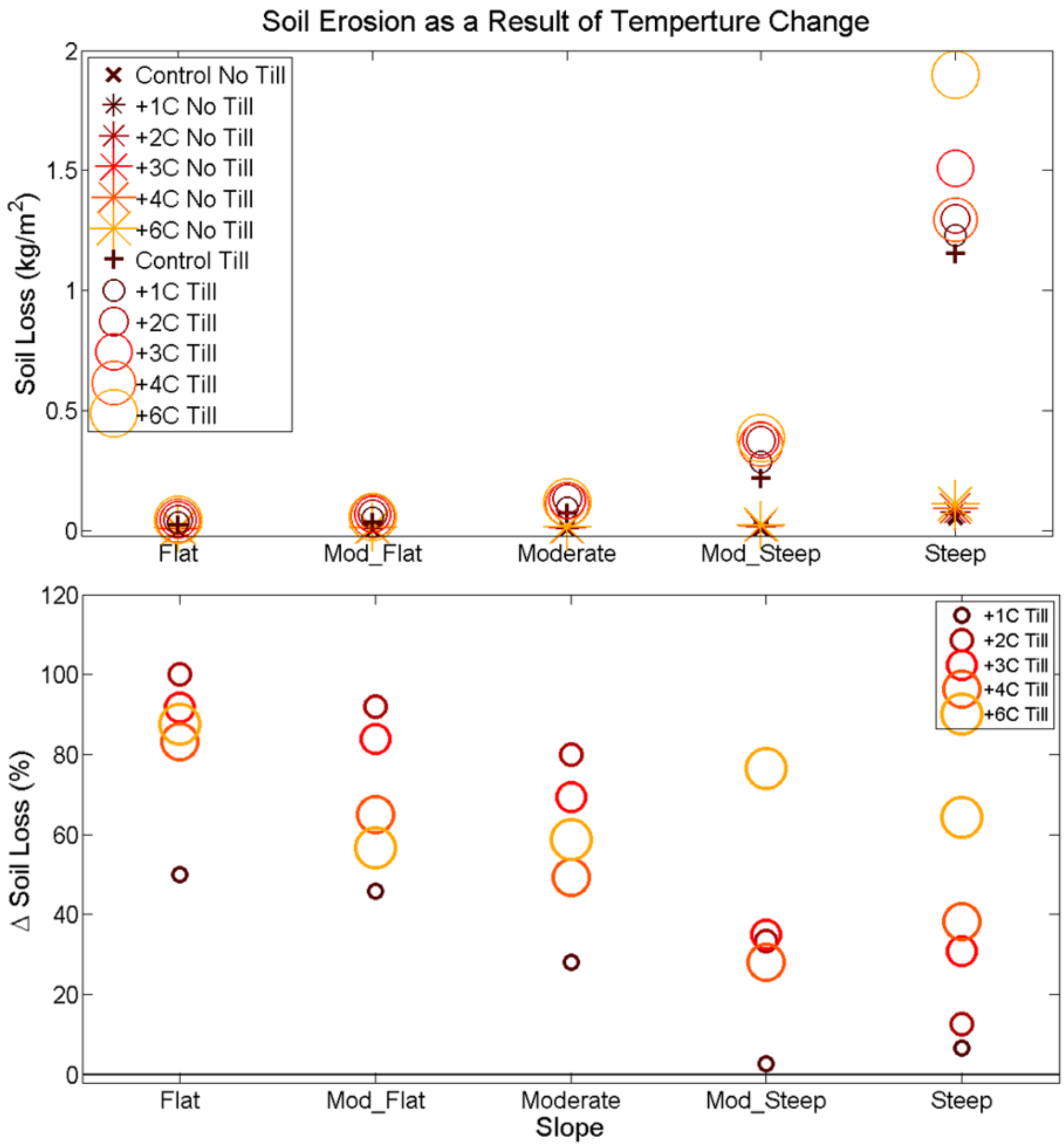

Figure 3.1: (top) Annual mean soil erosion for temperature sensitivity experiments over 5 hill slopes and two cropping practices (bottom) Relative changes in annual mean soil loss for temperature sensitivity experiments relative to the control run for conventional tillage.

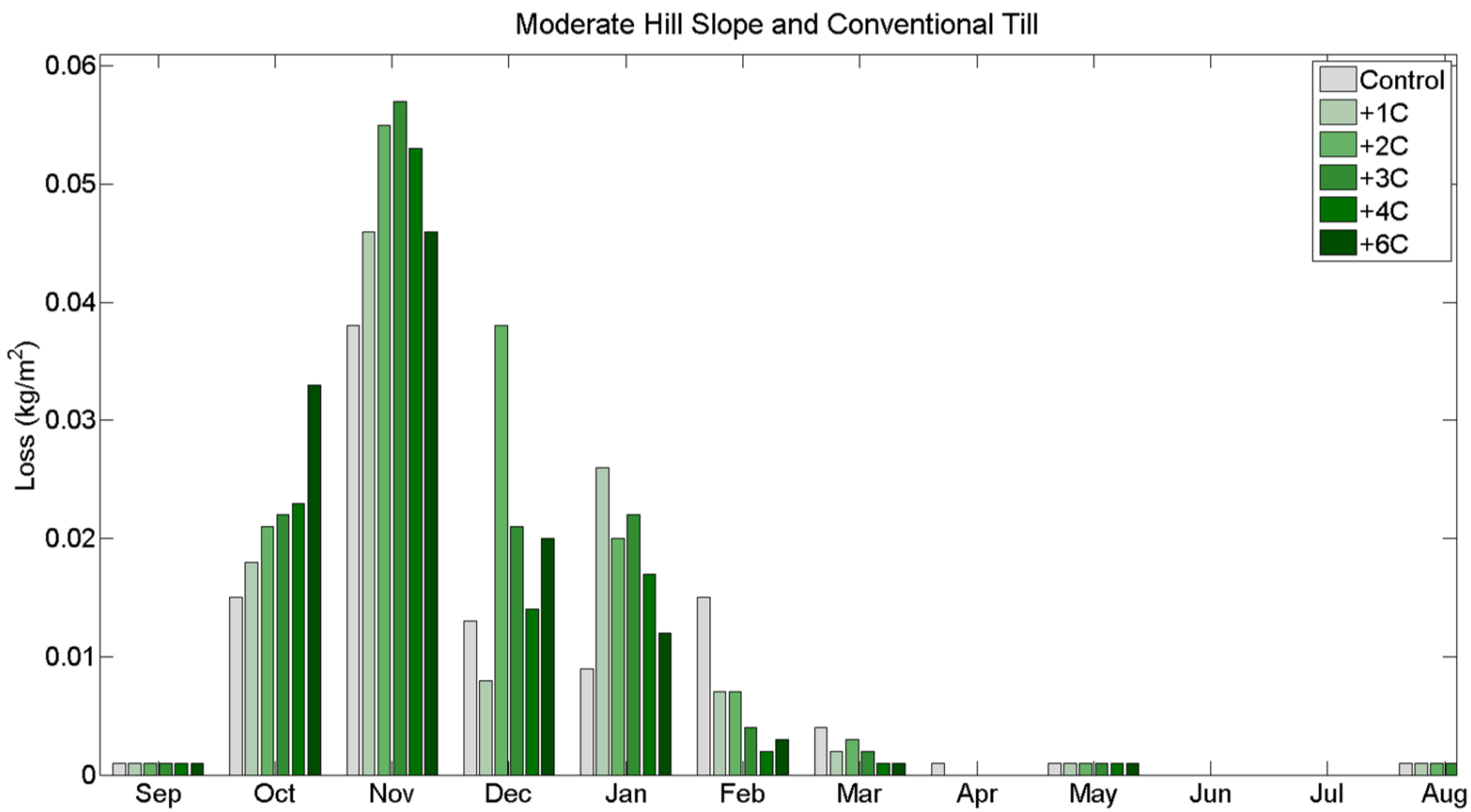

Figure 3.2: Average monthly soil loss over a moderate hill slope under conventional tillage practice for temperature sensitivity experiments. The reference or control case is shown in gray.

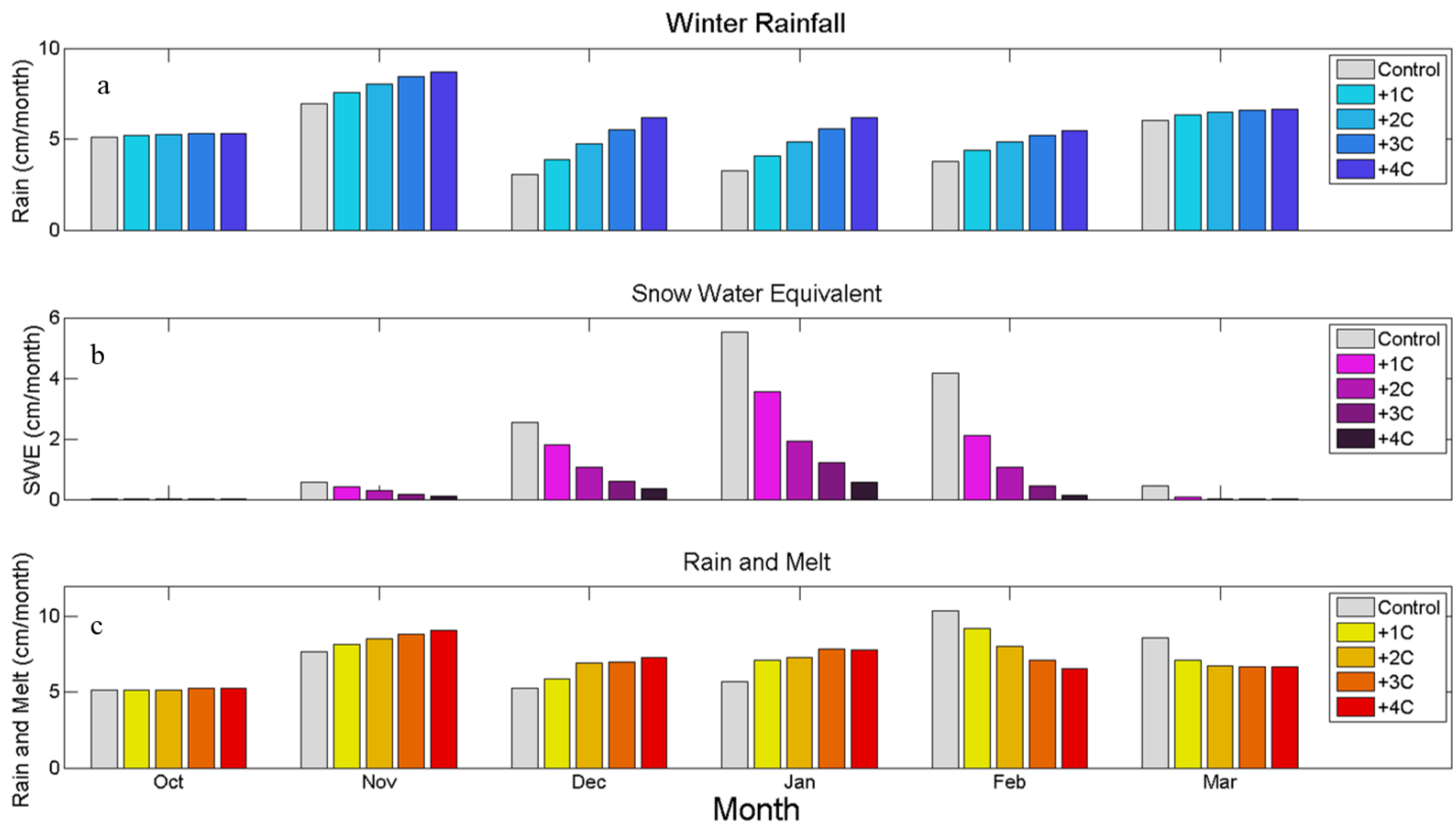

Figure 3.3: (a) Estimated mean monthly liquid precipitation accumulation, (b) average monthly snow water equivalent, and (c) average monthly combined rain and snow melt for different warming experiments. The reference or control case is shown in gray.

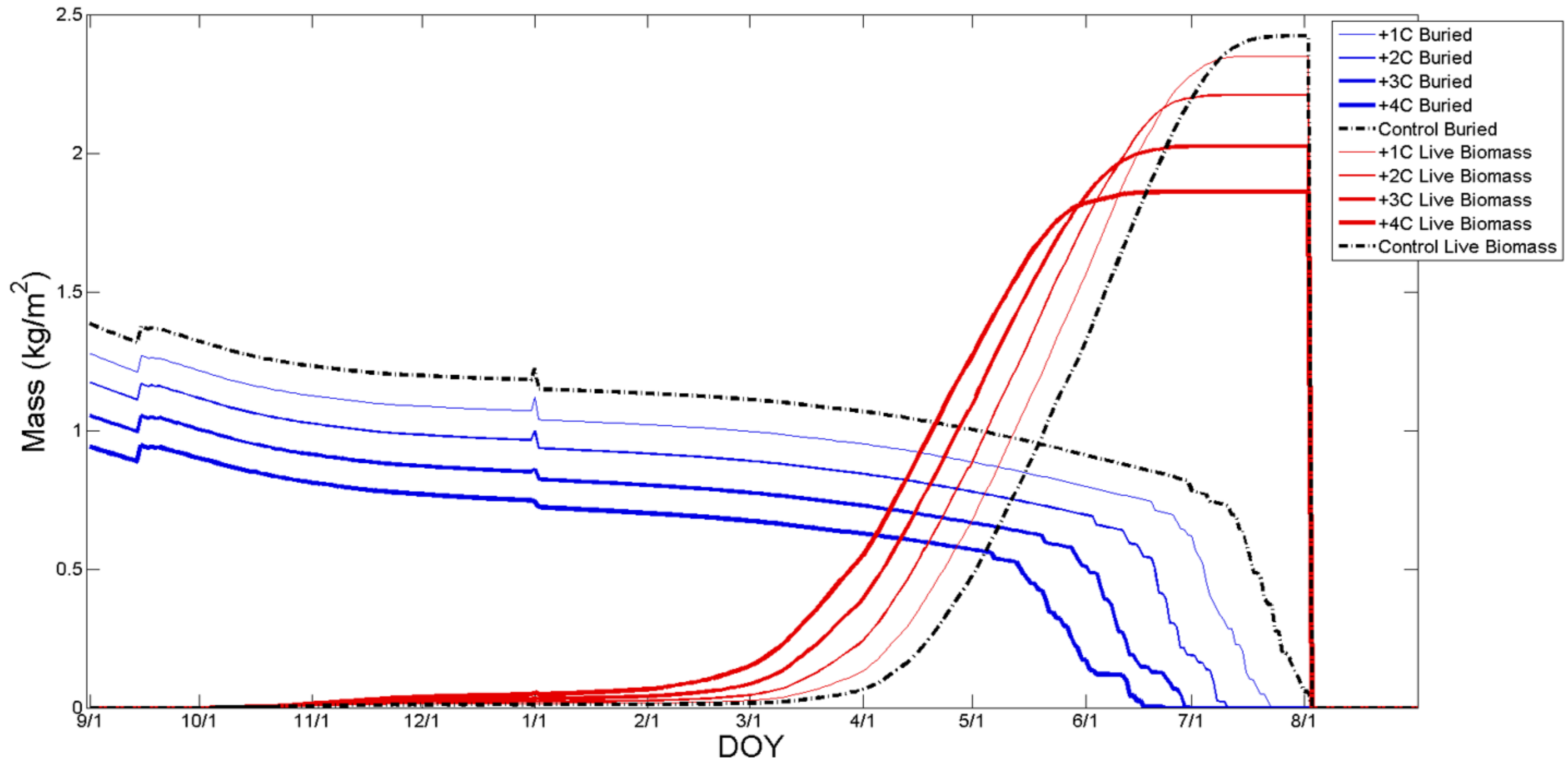

Figure 3.4: Daily averages of buried biomass (blue) under increasing temperature scenarios and daily average live biomass (red) under increasing temperature scenarios. The reference or control case is shown in black.

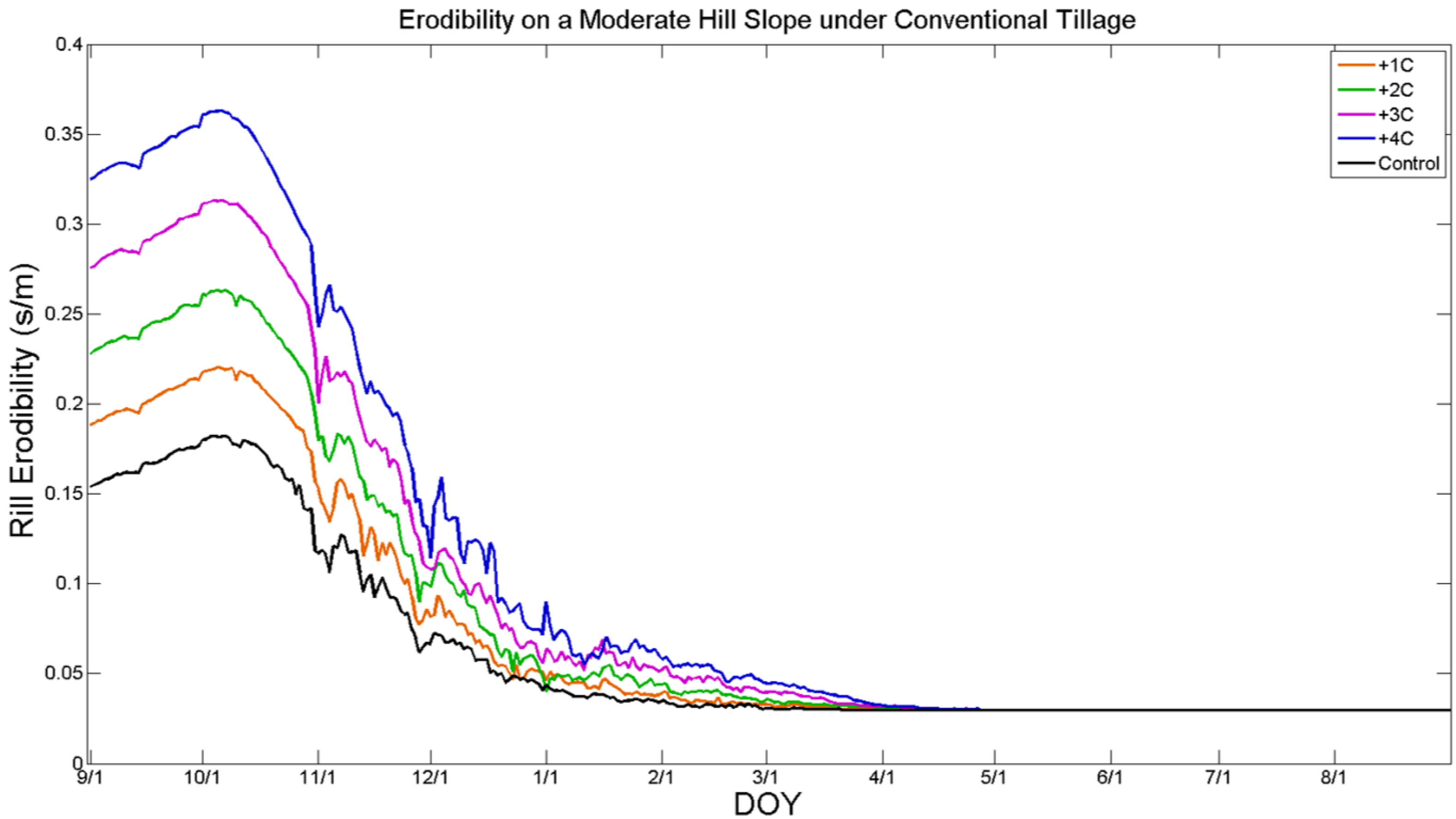

Figure 3.5: Climatological rill erodibility of the soil on a moderate hill slope under conventional tillage over increasing temperature scenarios. The reference or control case is shown in black.

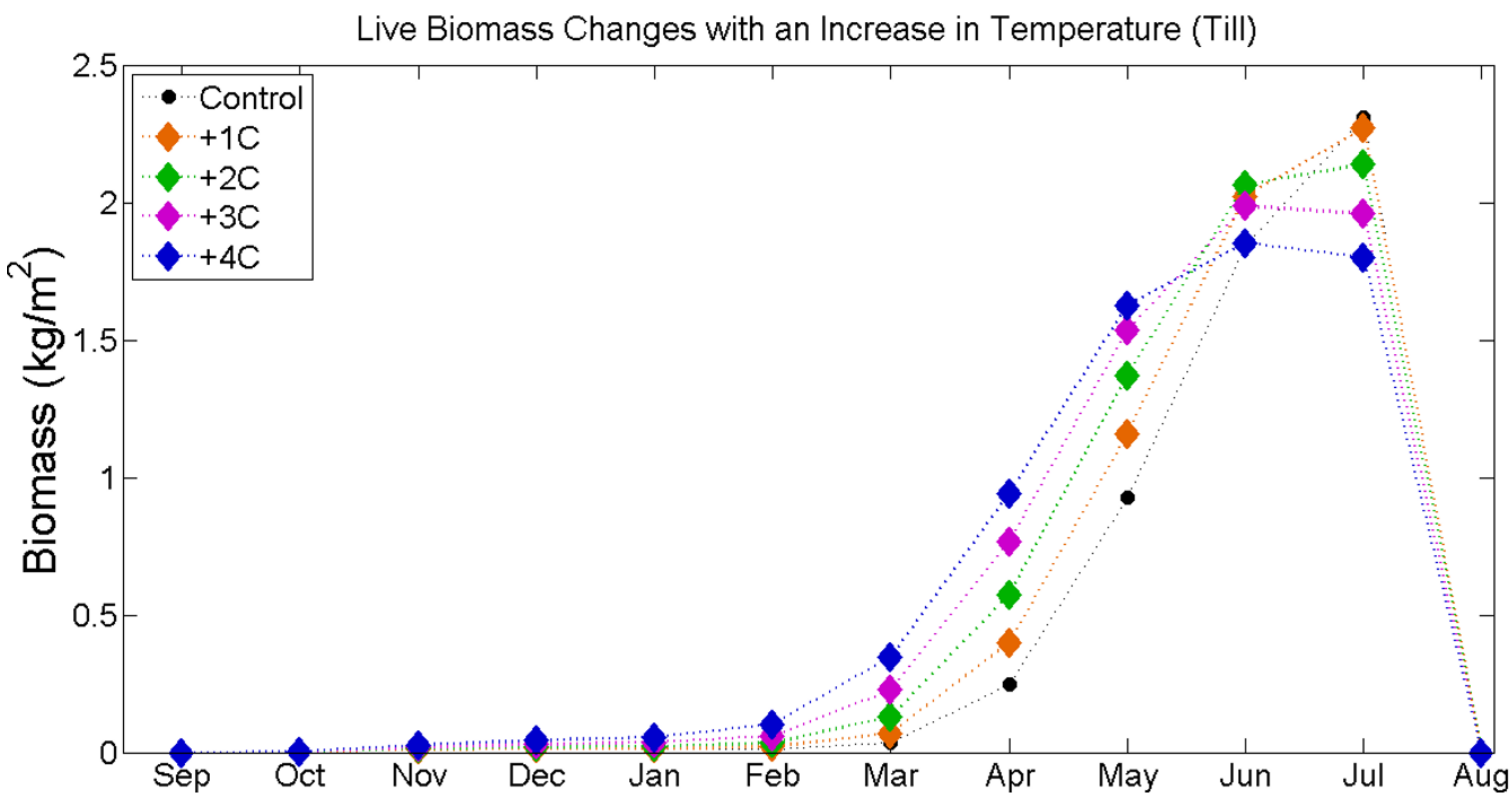

Figure 3.6: Monthly averages of live biomass for warming experiments for conventional till on moderate hillslope runs. The reference or control case is shown by the black dots. Harvest of winter wheat occurs in August.

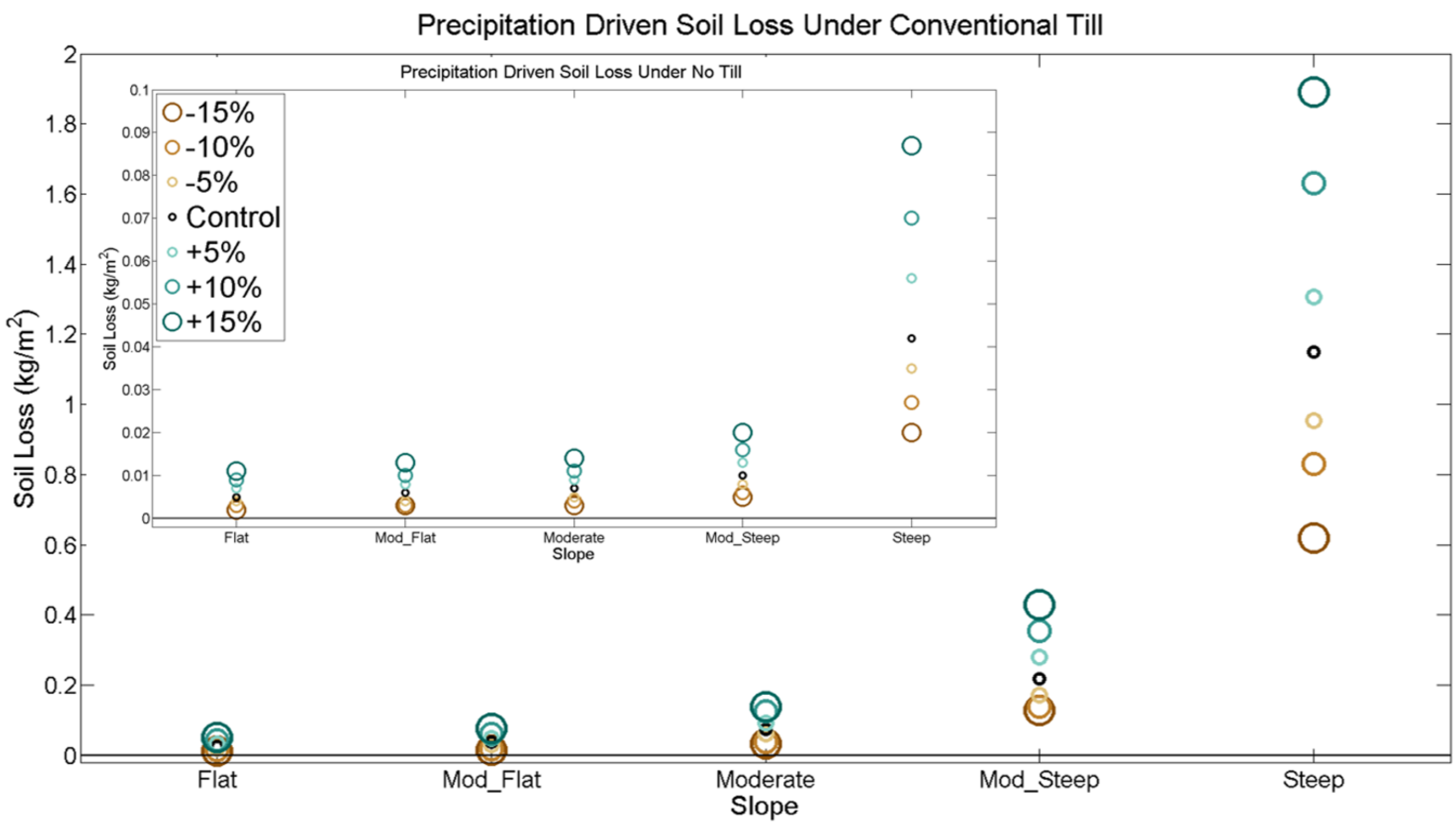

Figure 3.7: Average annual soil loss in kg/m^2 as a result of precipitation changes over all hill slopes under no tillage (inset) and conventional tillage. Note the difference in scales for the inset figure.

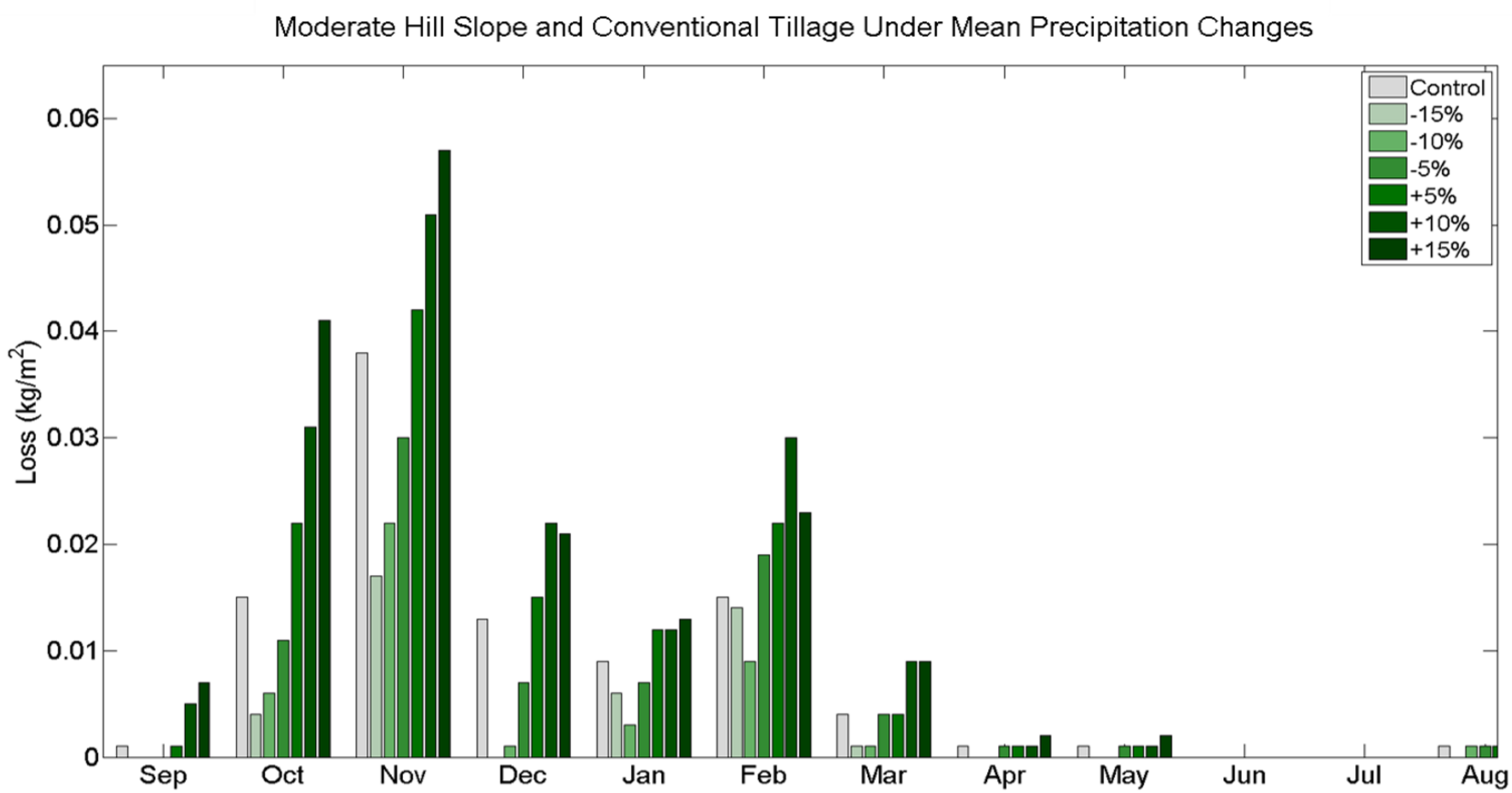

Figure 3.8: Monthly average soil loss on a moderate hill slope under conventional tillage practices for precipitation sensitivity experiments. The reference or control case is shown in gray.

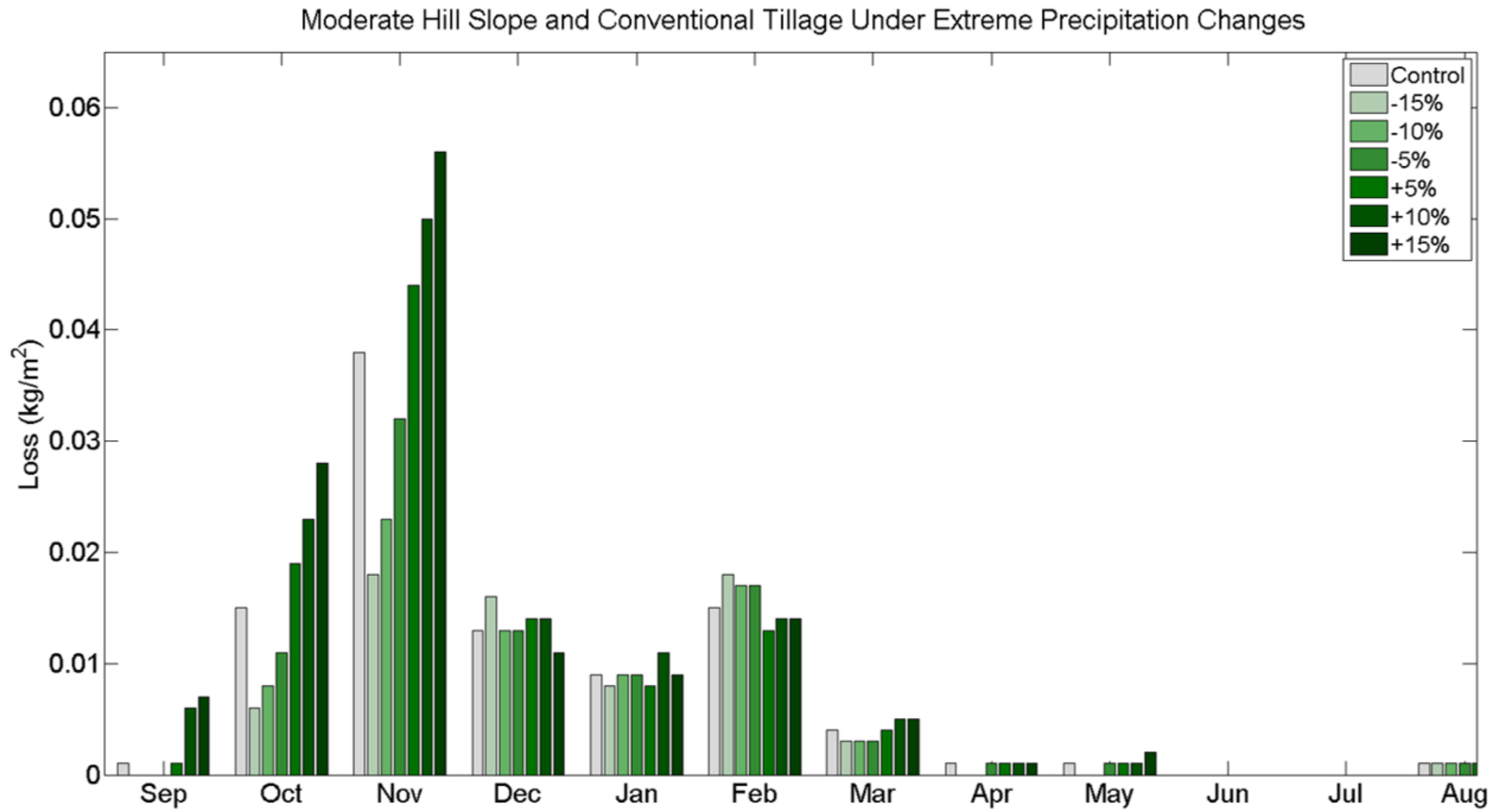

Figure 3.9: Monthly average soil loss on a moderate hill slope under conventional tillage practices for extreme precipitation sensitivity experiments. The reference or control case is shown in gray.

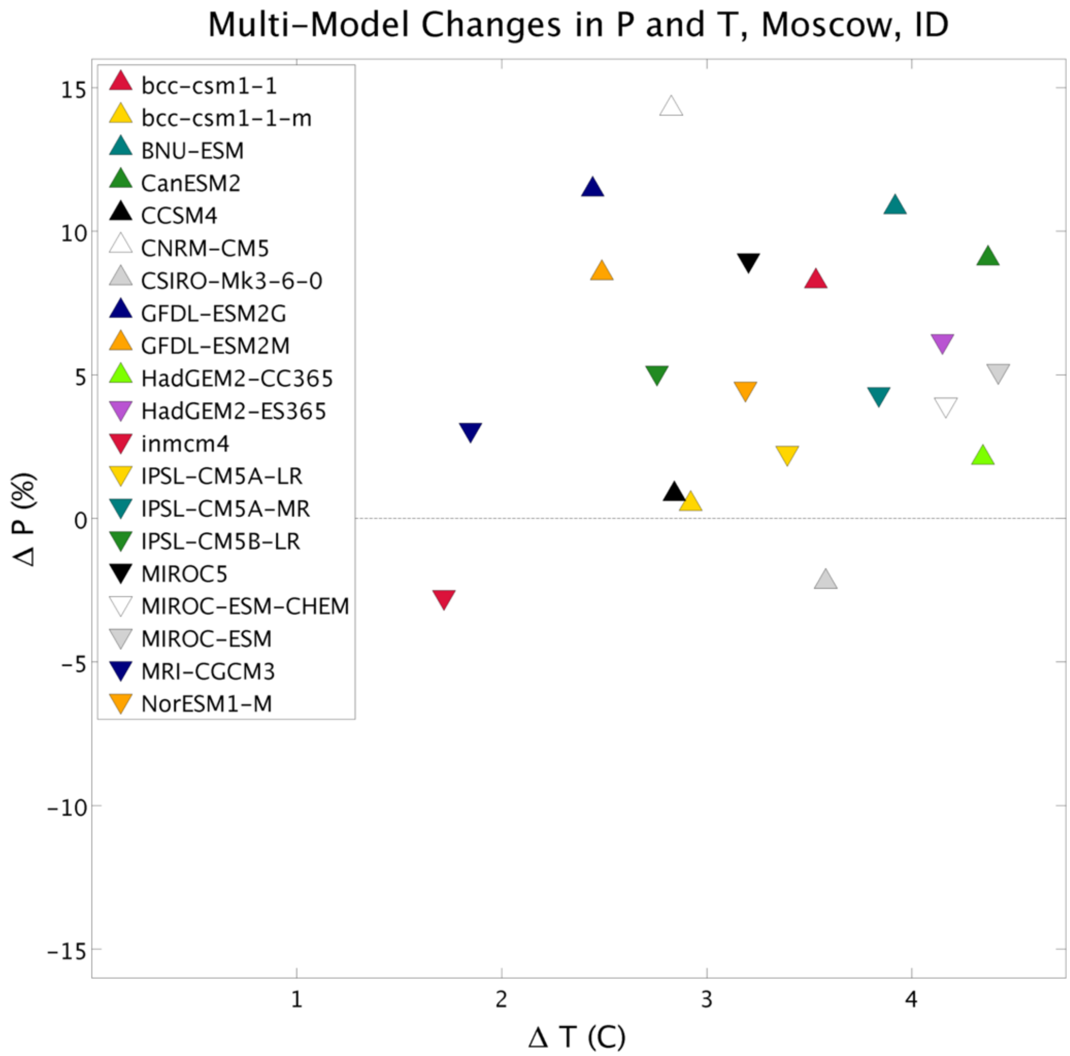

Figure 3.10: Changes in annual mean precipitation and annual mean temperature between Historical (1971-2000) and Future (2041-2070) GCMs under the RCP8.5 scenario.

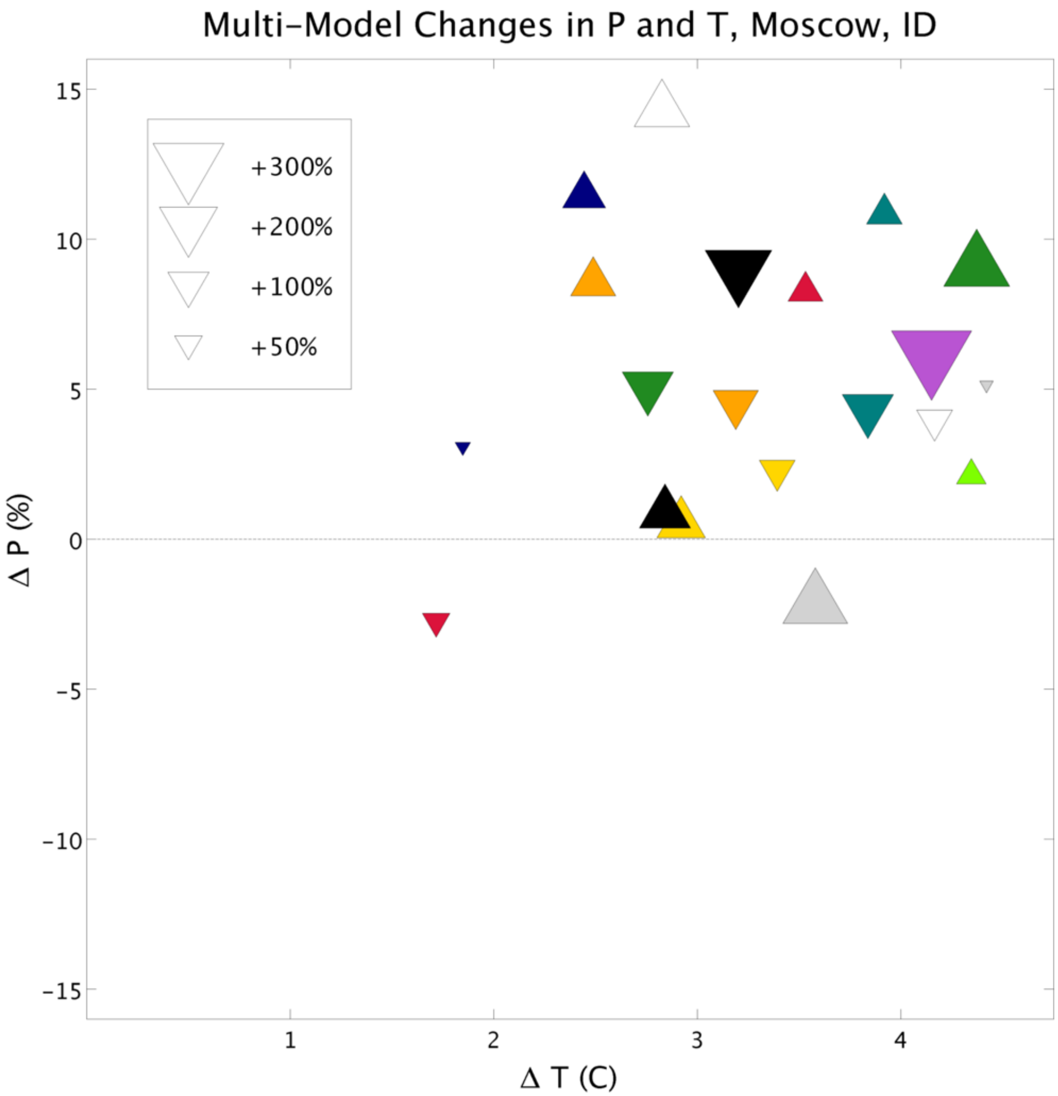

Figure 3.11: Changes in precipitation and temperature between Historical (1971-2000) and Future (2041-2070) GCMs under the RCP8.5 scenario with percent change in soil erosion represented by marker increasing marker size under a conventional tillage scenario and a moderate hill slope.

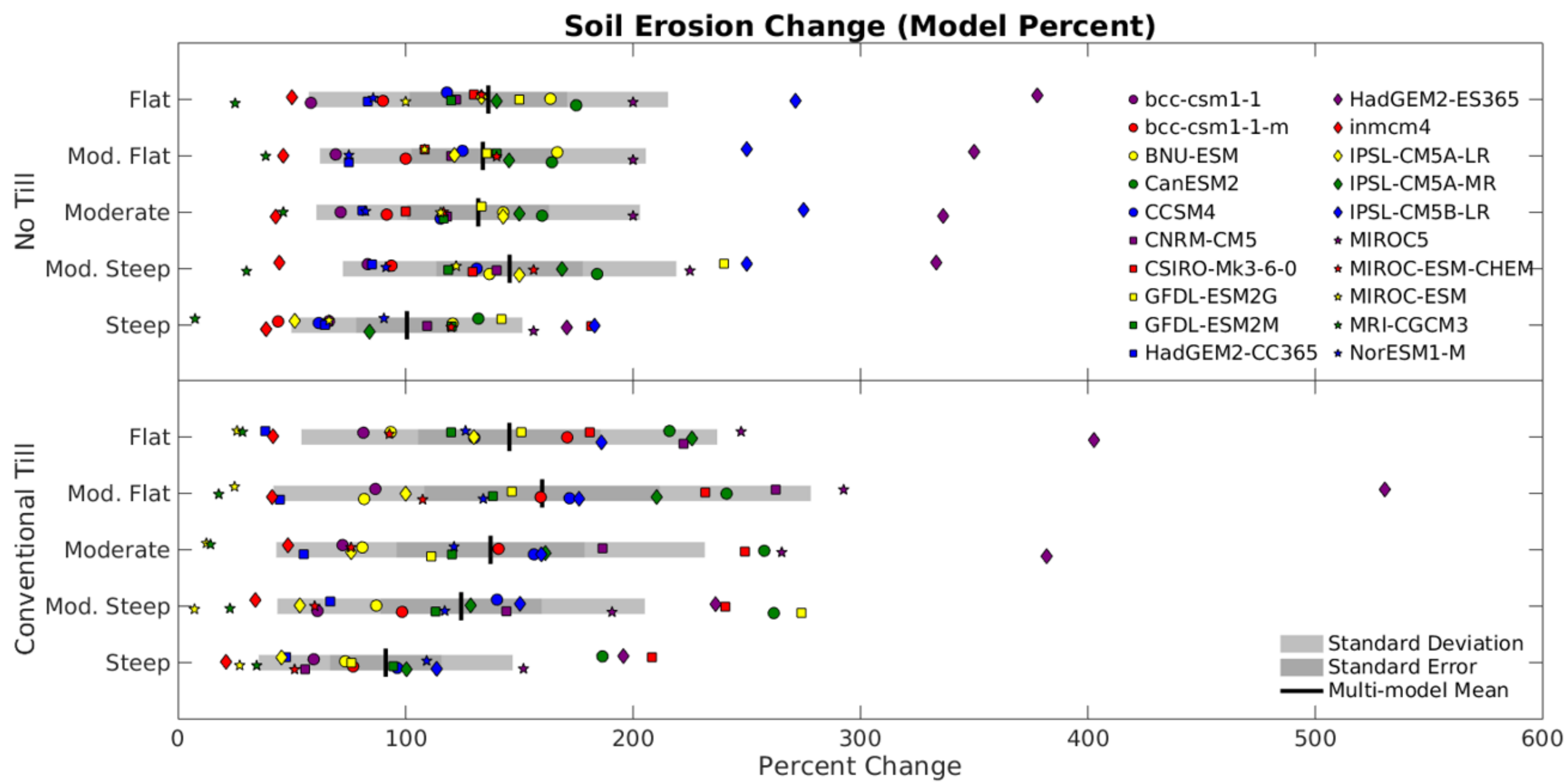

Figure 3.12: Changes in precipitation and temperature under the combined sensitivity experiment (as seen in Figure 10) with the GCM results (Figure 12).

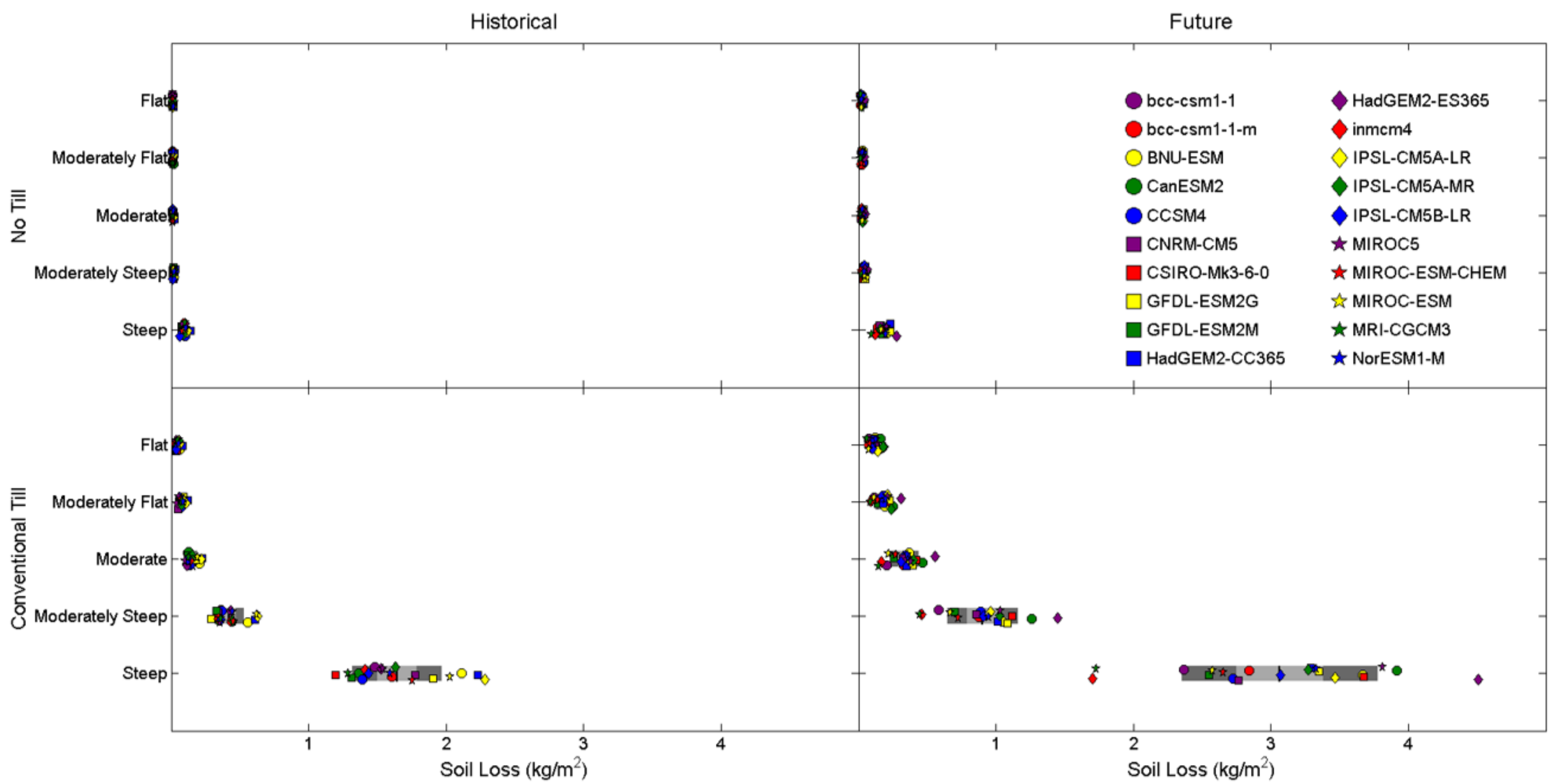

Figure 3.13: Annual average erosion (kg/m2) over all hill slopes under both tillage practices. The future GCMs (2041-2070) and the historical GCMs (1971-2005) are shown.

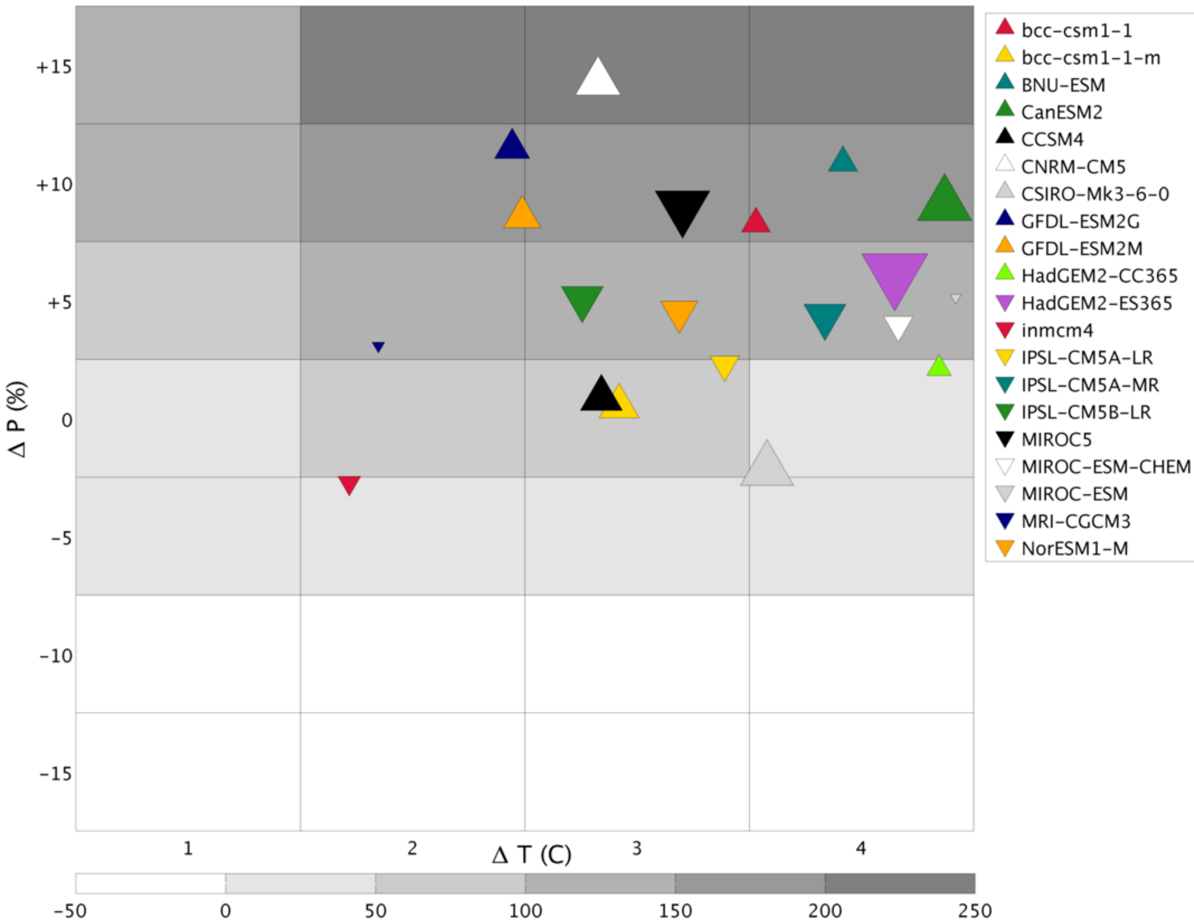

Figure 3.14: Changes in precipitation and temperature between Historical (1971-2000) and Future (2041-2070) GCMs under the RCP8.5 scenario with percent change in soil erosion represented by marker increasing marker size under a conventional tillage scenario and a moderate hill slope. Refer to legend in figure 3.11 for marker symbology.

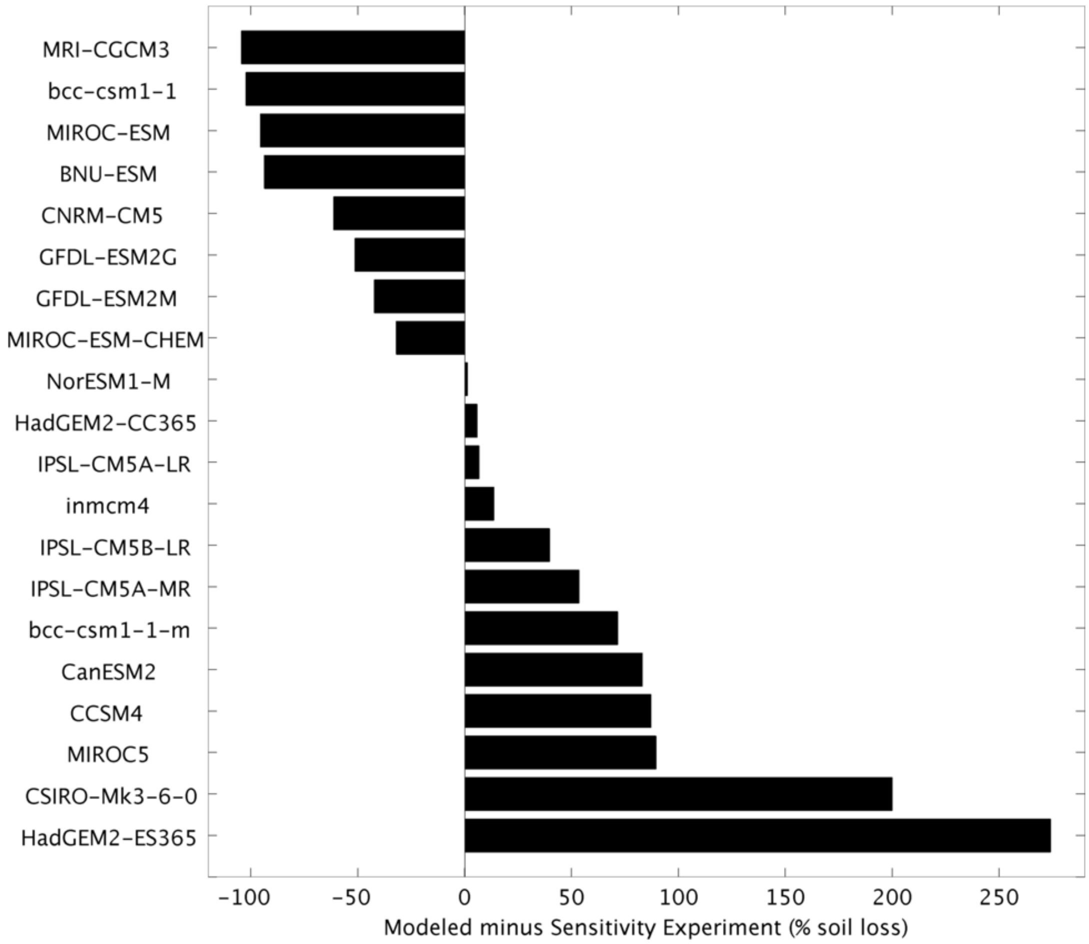

Figure 3.15: Difference between GCM simulated soil loss (2041-2070 vs. 1971-2000) minus soil loss projected by the joint sensitivity analysis for the modeled change in annual mean temperature and precipitation. Results are shown for moderate hill slope and conventional tillage are considered.

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