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Climate warming increases soil erosion, carbon and nitrogen loss with biofuel feedstock harvest in tallgrass prairie

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Abstract

Anthropogenic soil erosion severely affects land ecosystems by reducing plant productivity and stimulating horizontal carbon and nitrogen movement at the surface. Climate warming may accelerate soil erosion by altering soil temperature, moisture, and vegetation coverage. However, no experiments have been carried out to quantify soil erosion with warming. In a long-term field experiment, we explored how annual clipping for biofuel feedstock production and warming caused soil erosion and accompanying carbon and nitrogen losses in tallgrass prairie in Oklahoma, USA. We measured relative changes in soil surface elevation between clipped and unclipped plots with or without experimental warming. Our results show that average relative erosion depth caused by clipping was 1.65 ± 0.09 and $0.54 \pm 0.08\,mm\,yr^{-1}$, respectively, in warmed and control plots from November 21, 1999 to April 21, 2009. The soil erosion rate was $2148 \pm 121\,g\,m^{-2}\,yr^{-1}$ in the warmed plots and $693 \pm 113\,g\,m^{-2}\,yr^{-1}$ in the control plots. Soil organic carbon was lost at a rate of $69.6 \pm 5.6\,g\,m^{-2}\,yr^{-1}$ in the warmed plots and $22.5 \pm 2.7\,g\,m^{-2}\,yr^{-1}$ in the control plots. Total nitrogen was lost at a rate of $4.6 \pm 0.4\,g\,m^{-2}\,yr^{-1}$ in the warmed plots and $1.4 \pm 0.1\,g\,m^{-2}\,yr^{-2}$ in the control plots. The amount of carbon and nitrogen loss caused by clipping is equivalent to or even larger than changes caused by global change factors such as warming and rising atmospheric CO_2 concentration. In addition, soil erosion rates were significantly correlated with clipping-induced changes in soil moisture. Our results suggest that clipping for biofuel harvest results in significant soil erosion and accompanying losses of soil carbon and nitrogen, which is aggravated by warming.

Keywords: carbon loss, clipping, soil erosion, soil moisture, vegetation coverage, warming

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Introduction

Soil erosion is one of the most pressing global environmental challenges facing the world today, causing declining soil productivity and crop yields, which may cause difficulties in meeting the rising demand for food and energy (Brink *et al.*, 1977; Brown, 1981; Lal, 2004; MEA, 2005). Soil erosion is a natural process caused by water and wind, which occurs even in grasslands and forests (Stoltenberg, 1950). But it can be greatly aggravated by human activities such as grazing, mowing, and cropping through alteration of land coverage and disturbance of soil structure that reduces soil hydraulic conductivity and breaks down soil aggregates (Jacinthe & Lal, 2001; Lal *et al.*, 2004a). Worldwide, an estimated 1.6×10^9 ha of land is affected by human-induced erosion to varying degrees (Oldeman, 1994), and 75 billion tons of soil are removed from the land by water and wind erosion each year (Myers, 1993; Pimentel *et al.*, 1995), of which 2–2.5 billion tons of soil are transported into the oceans (Milliman & Syvitski, 1992). In the United States, croplands lose soil at an average rate of 17 tons $ha^{-1}\,yr^{-1}$ from combined water and wind erosion; pasture loses 6 tons $ha^{-1}\,yr^{-1}$; and 2.7 billion tons of eroded sediments are transported to small streams

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per year, (USDA, 1989; 1994; Trimble & Crosson, 2000). Soil erosion rates are especially high in Asia, Africa, and South America, averaging 30–40 tons $ha^{-1} yr^{-1}$ (Barrow, 1991). More recently, Yang *et al.* (2003) have used the Revised Universal Soil Loss Equation (Renard *et al.*, 1997) in a GIS-based model to determine global rates of soil erosion. This approach has yielded a global average rate of 10.2 tons $ha^{-1} yr^{-1}$ and values for Europe and North America of 11.1 and 9.3 tons $ha^{-1} yr^{-1}$, respectively.

Loss of surface soil with abundant nutrients and fine particles not only directly results in the decrease of soil fertility and productivity but also affects other ecosystem services. For example, soil erosion may regulate global climate change by altering the emission of CO_2 and other greenhouse gases from soil (Jacinthe & Lal, 2001; MEA, 2005; Berhe *et al.*, 2007). Water erosion, accounting for about 55% of total global erosion (Bridges & Oldeman, 1999), also effects lateral carbon movement to export soil organic carbon (SOC) and other biogeochemical elements to rivers (Lal, 2004), which alters net carbon fluxes between the soil and the atmosphere (Oost *et al.*, 2007, 2008). Jacinthe & Lal (2001) estimated that 30–260 $g C m^{-2} yr^{-1}$ is mobilized by water erosion in cultivated cropland in the United States. At a global scale, the mobilized carbon can either be emitted into the atmosphere to contribute to the buildup of greenhouse gases or can be buried in deep deposit sediments as an erosion-induced carbon sink. Depending on different estimations of carbon partitioning between emission and sedimentation, soil erosion on agricultural lands could be a net source of 0.37–1 $Pg C yr^{-1}$ (Jacinthe & Lal, 2001; Lal *et al.*, 2004b) or a net sink of 0.12–1 $Pg C yr^{-1}$ (Stallard, 1998; Smith *et al.*, 2001, 2005; Oost *et al.* 2007).

It is well documented that soil erosion is affected by vegetation cover and many environmental variables (Le Houérou, 1996; MEA, 2005). However, it is not well understood whether or not climate warming will enhance soil erosion, accelerate lateral carbon movement and then amplify or offset climate warming. Average global temperatures have increased 0.76 °C in the last century and are predicted to increase 1.8–4.0 °C further by the end of this century (Solomon *et al.*, 2007). It has been speculated that global warming may exacerbate soil erosion based on an assumption that warming decreases biodiversity and infiltration, increases evapotranspiration, and changes soil texture (MEA, 2005). However, the speculated warming effects on soil erosion have not been tested and may not hold true if an ecosystem responds to climate warming differently. Indeed, experimental warming induced increases in aboveground biomass (Luo *et al.*, 2009) may slow down soil erosion to some degree. Nevertheless, no experiments have ever been carried out to evaluate warming effects on soil erosion.

Climate effects on soil erosion may be confounded by land use change. In the Southern Great Plains of the USA, biomass harvest for hay use is an important land use practice. In Oklahoma, hay production occupies nearly as much acreage as wheat (3.25 million acres vs. 3.5 million acres, USDA National Agricultural Statistic Service). Both hayfields and Conservation Reserve Program lands (over 1 million acres in Oklahoma, USDA Economic Research Service) may in the future be converted to Switchgrass (*Panicum virgatum*), a large component of the tallgrass prairie and a major biofuel feedstock (Sanderson & Adler, 2008). Additionally, native mixed prairie grasses are being touted as an alternative biofuel feedstock with even fewer environmental impacts than a switchgrass monoculture (Tilman *et al*. 2006). Both hay and biomass production may have considerable effects on soil erosion. First, removal of vegetation coverage can create barren soil surface, which encourages runoff and increases soil erosion (Walker *et al*., 1999). Second, removal of vegetation positively interacts with experimental warming to increase the soil temperature and surface evaporation (Dahlgren & Driscoll, 1994; Wan *et al*., 2002), perhaps leading to changes in soil texture and infiltration capacity by influencing weathering rates of soil. These physical properties can strongly influence runoff and soil erosion. Third, aboveground biomass and litter removal can significantly reduce C inputs to soil (Wan & Luo, 2003), influence soil microaggregate formation, and thus accelerate soil erosion. This conceptual line of reasoning about the impacts of clipping on soil erosion has yet to be verified by long-term experimental data.

This study was designed to quantify soil erosion from the influences of annual clipping in a 10-year warming experiment with natural rainfall in a tallgrass prairie ecosystem in the US Great Plains. Many data sets are available from this comprehensive research project including soil and microclimate (Wan *et al*., 2002; Zhang *et al*., 2005), plant and soil gas exchange (Luo *et al*., 2001; Zhou *et al*., 2007a, b), and plant and soil carbon balance (Wan *et al*. 2005; Luo *et al*., 2009), to support and complement this study. Here, we measure relative changes in soil elevation between clipped and unclipped plots to estimate erosion depth and the erosion rate of top soil due to clipping in control and warmed plots. We then estimate the erosion-induced loss of SOC and nitrogen in the plots.

Materials and methods

Site description

The research site for this study is located at the Kessler Farm Field Laboratory (34°58′54″N, 97°31′14″W) in

McClain County, Oklahoma, approximately 40 km southwest of the University of Oklahoma, Norman, on the Central Redbed Plains of Oklahoma. Mean annual temperature at the site is 16.0 °C, with monthly air temperature ranging from 3.1 °C in January to 28.0 °C in July. The mean annual precipitation is 967 mm (averaged from 1948 to 1999, Oklahoma Climatologically Survey). Precipitation is usually highest in May and June (240 mm), followed by September and October (192 mm), and lowest in January and February (82 mm), and July and August (125 mm).

The site is an old field tallgrass prairie, abandoned from agriculture 40 years ago and left ungrazed long before the experiment by the exclusion of large herbivores. The site is dominated by perennials, the C_4 grasses *Sorgastrum nutans* and *Schizrchyum scoparium*, and the C_3 forbs *Ambrosia psilostachya*, *Solidago rigida*, and *S. nemoralis*. Being on a ridge, the experiment site has shallow soils, averaging 50 cm deep. These soils typically have moderate permeability and natural fertility and an easily penetrable root zone.

Experiment design

The experiment used a paired factorial design with a clipping treatment nested within six pairs of 2 × 2 m warmed and control plots (12 plots total). Within a pair, plots were selected for similarity of aboveground biomass and species composition, but between pair differences have been consistently noted (unpublished results). Warmed plots have been subjected to continuous warming since November 21, 1999, whereas the other served as the control, with ambient temperature. A single infrared heater (165 × 15 cm, Kalglo Electronics, Bethlehem, PA, USA), with a radiation output of 100 W m^{-2}, was suspended 1.5 m above the ground in each warmed plot. Reflector surfaces of the heaters were adjusted so as to generate evenly distributed radiant input to soil surface (Kimball, 2005). As a result, temperature increments generated by the infrared heaters were relatively even over the entire area of each plot and were similar at different soil depths (Wan *et al*. 2002). The control plot had a 'dummy' heater with the same dimensions as the infrared heater suspended at a similar height to mimic the shading effects of the heater. For each paired plot, the distance from plot centers is about 5 m. The distances between the paired plots varied from 20 to 60 m.

Each 2 × 2 m plot was divided into four 1 × 1 m subplots. Plants in two diagonal subplots were hand clipped at a height of 10 cm above the ground once a year at peak biomass (usually in July) while the other two subplots were unclipped. Clipped material was not returned to the plots. The clipped treatment mimics hay or biofuel feedstock harvesting in unfertilized, unimproved pastures in central and western Oklahoma in the frequency and height of cutting, but not the soil compaction of a harvester. Thus, this experiment has four treatments: unclipped control (ambient temperature, UC), unclipped warmed (UW), clipped control temperature (CC), and clipped warmed (CW).

Temperature, moisture content, and vegetation coverage measurements

Air temperature, soil temperature, and soil moisture content were used as environmental data to analyze the relation between climate warming and soil erosion in this study. Detailed methods for these background measurements have been described by Wan *et al*. (2002) and Luo *et al*. (2009).

To understand its impact on erosion rate, vegetation coverage (including plant and litter) was measured using a self-made 1 m × 0.5 m double grid frame with 36 points. From 2000 to 2004, the frame was placed in each subplot to measure the vegetation coverage. At each point on the grid, it was recorded whether a point touched bare ground, litter, or a plant species. The proportion of absolute coverage was calculated by the number of hits of bare ground or litter or plants divided by 36. Then, it was turned into a percentage (%) by multiplying by 100. After 2004, the method was changed to combine the recording of coverage with biomass estimation. Aboveground biomass was measured using the pin-contact method which has also been described elsewhere (Sherry *et al*., 2008; Luo *et al*., 2009). This method involved placing a frame with 10 pins into the plot in four different directions, resulting in 40 pins that had the potential to hit the ground. Only the hit recorded by the bottom of the pin was used in the study. In this case, the number of hits of bare ground or litter or plants was divided by 40.

Relative erosion depth measurement and erosion rate calculation

In this study, we measured clipping-induced relative erosion depth using a self-made apparatus (Fig. 1a) on April 2009. This apparatus consisted of a frame 60 cm high and 100 cm long, with four adjustable feet, two horizontal panels with a gradienter on top, and 25 moveable pins held 4 cm apart by the two panels. The frame was placed over the clipped and unclipped subplots in four different segments of each plot (Fig. 1b). In each segment, the middle pin was set on the juncture of clipped and unclipped subplots, and 12 pins were separately set on the clipped and unclipped subplots. Before measurements were taken, the feet were

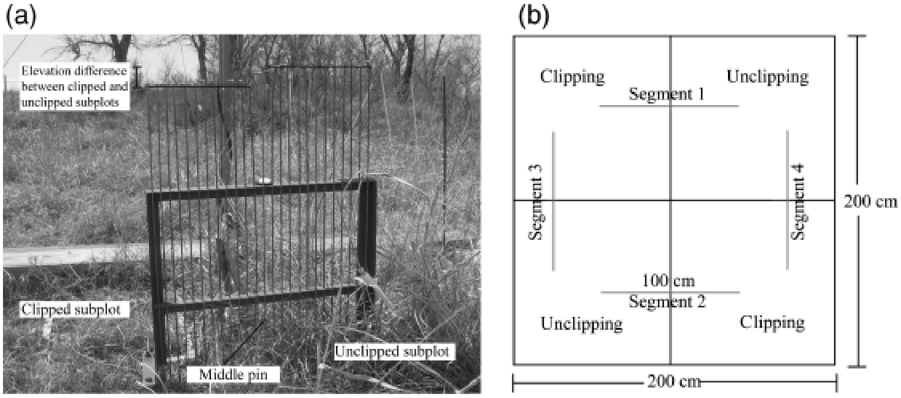

Fig. 1 Self-made apparatus for measuring the relative erosion depth in this study (a), and the placement of apparatus in each plot (b).

adjusted to level the frame horizontally. The distance from the ground to the top panel was recorded for each pin. The boundary area between clipped and unclipped subplots, covered by middle pin, was not being considered in this measure process because deposition from low-cover areas to high cover areas may occur. The clipping-induced soil erosion depth is the difference between the average distance for the 12 pins in the clipped subplot and the average distance for the 12 pins in the unclipped subplot. Four replicates were made in each segment so that 16 clipping-induced soil erosion depths were taken for each plot. The average value of 16 clipping-induced soil erosion depths in each plot was used to stand for the erosion depth of this plot. By that, we can get six erosion depths in six warming plots and six erosion depths in six control plots separately (Table 1). The erosion depth in warming treatment is the average value of six erosion depths in six warming plots, and the erosion depth in control treatment is the average value of six erosion depths in six control plots. So, we can compare clipping in control to clipping in the warmed plots.

Soil samples were taken from 0 to 15 cm depth in each plot with four replicates to measure soil bulk density by the weighing method. Soil samples sealed in soil tins were oven-dried to a constant weight at 65 °C, and analyzed for gravimetric water content (percentage water, measured as g water/g dry soil × 100). Then the erosion rate in each plot was calculated by the function:

$$\mathrm{Rate}_{\mathrm{erosion}} = \frac{\mathrm{Density}_{\mathrm{soil}} \times (\mathrm{RED} - D)}{\mathrm{Time}_{\mathrm{erosion}}}.$$

In which, $\mathrm{Rate}_{\mathrm{erosion}}$ is the erosion rate, $\mathrm{Density}_{\mathrm{soil}}$ is the soil density, RED is the clipping-induced relative erosion depth, and D is the soil loss depth by the subsidence due to compaction. D was calculated by the soil bulk density in different years, and the value of D is 0.2 ± 0.01 mm. We defined D as zero in this study, considering its small value compared with the relative erosion depth.

Losses of SOC and total nitrogen

Erosion-induced losses of SOC and total nitrogen were estimated from soil samples, taken at 0–5 cm depth from each subplot on April 2009. The soil samples were dried at 60 °C overnight and ground through a 2 mm sieve before being sent to the Soil, Water and Forage Analytical Laboratory, Oklahoma State University, OK (SWFAL, http://www.soiltesting.okstate.edu/) for chemical analysis. All samples were analyzed for NO_3–N and SOC. Soil NO_3–N and NH_4–N were extracted with 1 M KCl solution and quantified by the cadmium reduction method on a Lachat QuikChem 8000 (LACHAT, 1994, QuickChem Method 12-107-04-1-B. LACHAT Instrument, Milwaukee, WI). SOC and total nitrogen were determined using a LECO Truspec dry combustion carbon analyzer (3000 Lakeview Avenue St. Joseph, Michigan, USA) (Nelson & Sommers, 1996). The transportation rate of SOC and total nitrogen were calculated by multiplying their respective concentrations separately for each subplot by their soil erosion rate.

Surface soil particles distribution measurement

Clay (particle size $d < 2\,\mu$m) content of surface soil usually can be used to express the erosion extent. In our study, soil samples in the depth of 0–5 cm were taken in each subplot and soil particle size distribution was measured by laser-light diffraction instrument (Malvern Instruments Ltd. located in Enigma Business Park, Malvern, Hereford and Worcester, UK).

Table 1 The relative erosion depth, erosion rate, soil carbon loss, nitrogen loss and average soil bulk density of different plots with warming and control treatments in this experiment

Plot no.	RED ($mm\,yr^{-1}$)		RER ($g\,m^{-2}\,yr^{-1}$)		SCL ($g\,m^{-2}\,yr^{-1}$)		SNL ($g\,m^{-2}\,yr^{-1}$)		SBD ($g\,cm^{-3}$)	
	Warming	Control	Warming	Control	Warming	Control	Warming	Control	Warming	Control
1	1.24 ± 0.015a	0.86 ± 0.048b	1602.8 ± 19.260a	957.6 ± 53.616b	67.00 ± 0.805a	35.43 ± 1.984b	3.69 ± 0.044a	2.11 ± 0.118b	1.29 ± 0.091a	1.12 ± 0.184a
2	1.29 ± 0.061a	0.44 ± 0.033b	1721.9 ± 81.967a	593.0 ± 44.569b	59.41 ± 2.828a	24.31 ± 1.827b	2.93 ± 0.139a	1.13 ± 0.085b	1.34 ± 0.128a	1.34 ± 0.116a
3	0.81 ± 0.047a	0.84 ± 0.230a	1166.4 ± 68.305a	1095.3 ± 298.499a	37.32 ± 2.186a	33.95 ± 9.253a	2.45 ± 0.143a	1.64 ± 0.448a	1.44 ± 0.059a	1.30 ± 0.105a
4	2.07 ± 0.113a	0.37 ± 0.101b	2687.8 ± 146.539a	485.5 ± 133.939b	118.26 ± 6.448a	17.48 ± 4.822b	8.60 ± 0.469a	1.31 ± 0.362b	1.30 ± 0.062a	1.33 ± 0.040a
5	1.62 ± 0.075a	0.14 ± 0.020b	1938.0 ± 89.867a	162.4 ± 23.678b	52.91 ± 2.453a	3.90 ± 0.568b	4.07 ± 0.189a	0.28 ± 0.040b	1.20 ± 0.067a	1.16 ± 0.037a
6	2.88 ± 0.244a	0.60 ± 0.090b	3769.5 ± 320.007a	861.6 ± 128.485b	82.93 ± 7.040a	19.82 ± 2.955b	5.65 ± 0.480a	1.72 ± 0.257b	1.31 ± 0.030a	1.43 ± 0.025a
Average	1.65 ± 0.093	0.54 ± 0.087	2147.7 ± 120.991	692.6 ± 113.798	69.64 ± 3.627	22.48 ± 3.568	4.56 ± 0.244	1.36 ± 0.218	1.32 ± 0.038	1.28 ± 0.050

Note. RED, clipping-induced soil erosion depth, which was gotten by measuring the elevation difference between the clipping subplot and adjacent unclipping subplot in the same plot. RER, clipping-induced soil erosion rate, which was calculated according to the equation 1. SCL and SNL, soil carbon loss and soil nitrogen loss, which were calculated by multiplying their respective concentrations separately for each plot by their soil erosion rate. SBD, annual average soil bulk density, which were gotten by the weighing method. The data after ± are SD. The different letters represent the significant difference between warming and control treatments, $P<0.05$, $n=16$.

Statistical analysis

We used analysis of variance (ANOVA) to evaluate the statistical significance of warming and clipping on soil temperature, soil moisture content, and vegetation coverage and soil erosion depth. Differences between the treatments were compared using Tukey's multiple comparisons test at a significance level of 0.05. Bivariate Pearson's regression analysis was used in order to analyze the relationship of erosion depth with soil temperature, soil moisture content, vegetation coverage, and ground slope. All statistical analyses were performed using SPSS for Windows 13.0 software (SPSS Inc., Chicago, IL, USA, 2004).

Results

Soil temperature, soil moisture content, and vegetation coverage

Annual precipitation varied from 522 mm in 2005 to 1300 mm in 2007 with a mean of 860 mm during the past 9 years (2000–2008). Air temperature was elevated in warming treatment by an average of 1.47 °C with yearly increases values of 1.17, 1.34, 0.79, 1.08, 1.12, 2.15, 2.16, 1.92, and 1.46 °C from 2000 to 2008. Warming increases soil temperature by 1.31 °C in unclipping subplots (UW–UC) and 1.98 °C in clipping subplots (CW–CC) from 2000 to 2008. Clipping also significantly ($P<0.05$) elevated the soil temperature by 1.07 °C (CC–UC) in control plots and 1.74 °C (CW–UW) in warmed plots (Fig. 2a).

From 2000 to 2008, soil moisture was lowered by an average of 1.43% volumetrically under warming in comparison with unwarmed plots. Warming effects on soil moisture were statistically significant ($P<0.05$) in four pairs of plots, but not in the average of six pairs of plots over all years (Fig. 2a). However, the average warming effects on soil moisture over six pairs of plots were statistically significant ($P<0.05$) in spring and fall (Fig. 2b). Overall, annual clipping did not significantly affect soil moisture content, but warming significantly decreased the soil moisture content (Fig. 2a and b).

No significant warming effects on vegetation coverage were found in this study (Fig. 2a), although warming stimulated plant biomass growth and net primary production (Luo *et al.*, 2009). In contrast, the clipping-induced decrease of vegetation coverage was highly significant ($P<0.01$) with an average decrease of 9.46% without warming and 9.38% with warming from 2000 to 2008.

Soil erosion depths, erosion rates, and nutrient transportation rate

We observed soil erosion depth and soil loss over the nearly 10-year study period. Our results show that the

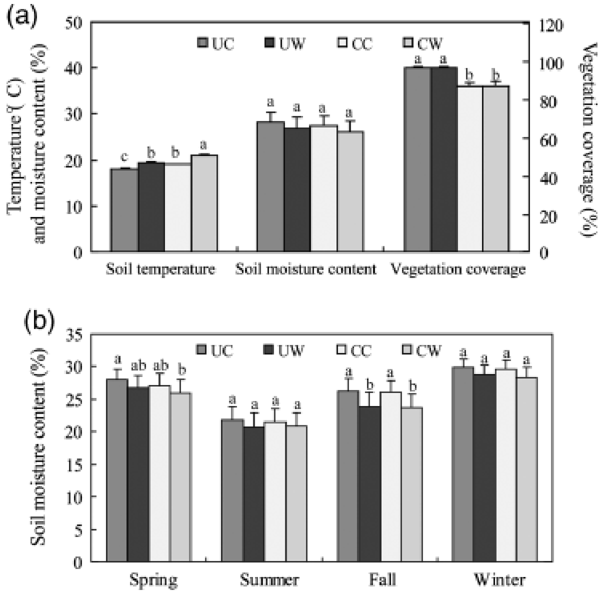

Fig. 2 Average soil temperature and average soil moisture content at the depth of 5 cm and average vegetation coverage of different plots under different treatments from 2000 to 2008 (a), and soil moisture content in different seasons at the depth of 5 cm under different treatments (b). Soil temperature measurements were taken monthly during the daytime. Different letters indicate statistical differences at $P<0.05$ among the different treatments in each pair of plots. Bars mean standard deviation and $n=6$. UC, unclipped and control; UW, unclipped and warmed; CC, clipped and control; CW, clipped and warmed.

Table 2 Results of one-way ANOVA analysis of soil erosion depth, soil erosion rate, soil carbon loss and soil nitrogen loss between warming and control treatments in the experiment

Dependent variables	df	*F*	*P*
Soil erosion depth	1	47.634	0.000
Soil erosion rate	1	50.211	0.000
Soil carbon loss	1	57.210	0.000
Soil nitrogen loss	1	46.350	0.000

Note. There were two treatments (warming and control). Each treatment had six replicates.

clipping-induced decrease in average relative erosion depth is 1.65 cm in the warmed plots and 0.54 cm in the control plots from November 21, 1999 to April 21, 2009 (Tables 1 and 2 and Fig. 3a). The clipping-induced erosion rates in warmed plots are significantly higher than that in control plots, averaging 2147.7 $g\,m^{-2}\,yr^{-1}$ in the warmed plots and 692.5 $g\,m^{-2}\,yr^{-1}$ in the control plots (Tables 1 and 2 and Fig. 3a).

SOC and total nitrogen loss rates from the experimental plots have a similar pattern to soil erosion depths and erosion rates (Tables 1 and 2 and Fig. 3b). The average SOC loss rate is 69.6 $g\,m^{-1}\,yr^{-1}$ in warmed plots and 22.5 $g\,m^{-1}\,yr^{-1}$ in control plots, and the average soil total nitrogen loss rate is 4.56 $g\,m^{-1}\,yr^{-1}$ in warmed plots and 1.36 $g\,m^{-1}\,yr^{-1}$ in control plots. Warming tripled the clipping-induced erosion rate and nutrient transportation rate.

Clay content change

Erosion usually decreases the soil fine particle content of eroded lands by selectively carrying away fine particles. In our study, clipping-induced erosion decreased the clay content (particle size $<2\,\mu m$) by an average of 2.0% without warming and 3.8% with warming compared with the respective clipped plot. Clipping-induced erosion effects on clay content were statistically significant between warming treatment and control treatment (Fig. 4).

Discussion

Impact of clipping and vegetation cover on soil erosion

The average soil erosion depth in the clipped treatment was 0.54 cm over 10 years with a maximum value of 0.86 cm under ambient temperatures. This erosion intensity is relatively low due to high vegetation coverage (>80%), although annual clipping caused a significant decrease in vegetation coverage of 11–12% in spring and 7–8% in the summer and fall. It is well known that vegetation significantly influences soil erosion rates. Gyssels *et al*. (2005) found that water erosion rates decreased exponentially with increasing vegetation coverage. Generally, vegetation slows down soil erosion in the short term mainly by intercepting rainfall and runoff and protecting the soil surface against the impact of raindrops. Complete canopy coverage can lower the effective energy of raindrops, resulting in a large percentage of the incident rainfall entering the soil and thus reducing horizontal transport of water and nutrients in runoff. Conversely, reduced vegetation coverage by clipping can increase runoff on the surface. The increased runoff makes surface soil subject to water erosion and crusting by raindrop splash, which in turn reduces water intake and storage of soil water and increases edaphic aridity (Le Houérou, 1996).

In our experiment, by removing biomass, clipping also reduced the total accumulated litter mass (standing and surface) by 82% and 78% in the control and warmed treatments, respectively, (unpublished results). Reduced vegetation from clipping can influence soil structure by raising soil temperature. Soil temperature (surface and subsurface) is primarily controlled by absorbed shortwave radiation. Destruction of the vege-

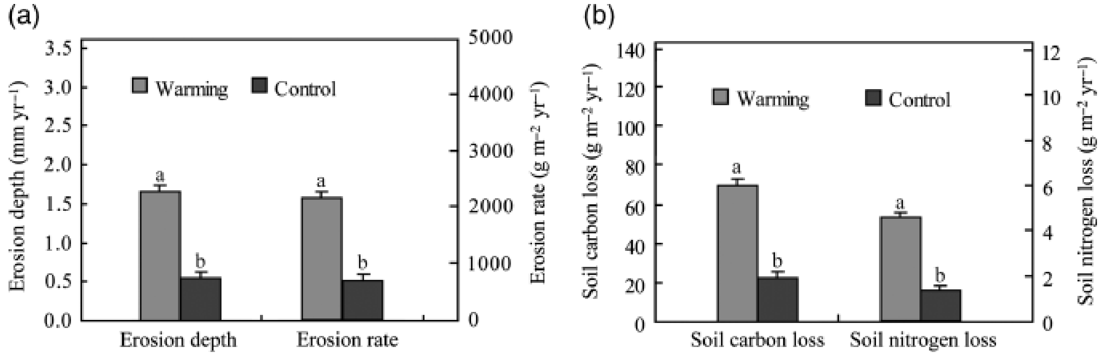

Fig. 3 Clipping-induced annual soil erosion depth and erosion rate in warmed and control plots (a), erosion-induced soil organic carbon and total nitrogen loss rate in warmed and control plots (b) in the past 10 years. (Different letters indicate statistical differences at $P<0.001$ between warmed and control at each pair of plots. Bars mean SD and $n=6$.)

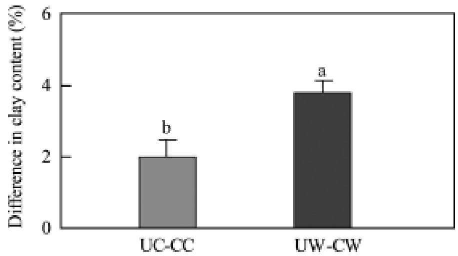

Fig. 4 Clay (particle size <2 μm) content difference between unclipped and clipped plots in different treatments. (Different letters indicate statistical differences at $P<0.05$ among different treatments at each plot. Bars mean SD and $n=6$.) UC−CC, unclipped control minus clipped control; UW−CW, unclipped warmed minus clipped warmed.

tation covering reduces shading of the soil surface, decreases rugosity (which increases surface wind speeds), and increases absorbed radiant energy, all of which result in increased soil temperature leading to evaporation and soil drying. Our results indicate that soil temperatures in clipped plots are significantly higher than unclipped plots under control conditions (Fig. 2a), which confirms the influence of clipping on soil temperature. Consistent with our results, many studies have also found that high coverage soil surfaces commonly have a more moderate temperature regime and greater soil moisture due to reduced evaporation (Sutherland *et al*., 1998). It is also speculated that lowering organic matter by clipping reduces the stability of soil aggregates and thus results in higher apparent soil density, lower porosity, lower permeability to air and water, lower water storage, and reduced oxygenation, which maybe accelerate the water erosion.

Reduced organic matter and a fragile structure leads to soil surface crusting by raindrop splash which may increase runoff by 30–50% or more (Le Houérou, 1996). This complex relationship between vegetation coverage and erosion rates has usually been reported as a negative exponential curve for a wide range of environmental conditions (Bochet *et al*., 2006). In our experiment, the greater soil erosion depth and erosion rate in the clipped plot after a decade of warming support these previous studies.

Impact of warming on soil erosion

The maximum erosion depth was 3 cm in warmed plots and 0.86 cm in control plots over 10 years, and maximum soil erosion rates reached $3770\,g\,m^{-1}\,yr^{-1}$ in warmed plots and $1095\,g\,m^{-1}\,yr^{-1}$ in control plots. The results show that the soil erosion and nutrient loss rates in warmed plots are significantly higher than those in control plots by a magnitude of two or three, although warming did not significantly decrease the vegetation coverage (Fig. 2a). In published researches, the warming effect on erosion has mainly been attributed to increased frequency of extreme rain events and decreased total rainfall in certain parts of the world (William *et al*., 1990; IPCC, 2001). The clipping-induced erosion difference between warmed and control treatments under the same rainfall background in this experiment suggests that mechanisms other than precipitation lead to accelerated water erosion by warming. Warming, for example, reduces soil moisture content by increasing soil temperature and potential evapotranspiration. (Holdridge & Tosi, 1967; Griffiths, 1972; Le Houérou, 1972, 1989a, b; Le Houérou *et al*., 1993; Le Houérou, 1996). In this experiment, the 1–2 °C increase in soil temperature reduced soil moisture, in accordance with results from climate model simulations (Manabe & Wetherald, 1986). Dry soil usually has unstable and poorly developed structure, resulting in high apparent density (compaction), low porosity, low permeability to air and water, low soil aggregates, and low water storage (Le Houérou, 1996). All those proper-

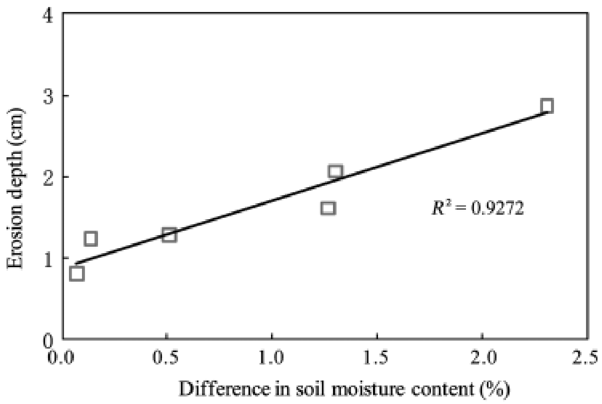

Fig. 5 The linear relationship between soil erosion depth and soil moisture difference under warmed treatments. Soil moisture difference means the soil moisture in unclipped plots minus that in clipped plots.

ties favor soil erosion (Verrecchia *et al*., 1995; Blanco & Lal, 2008), for example, the wind-blown dust emission mainly occurred in arid land surface with poor vegetation coverage. Figure 5 shows that the erosion depth significantly ($R^2 = 0.9272$) increased with increasing difference in soil moisture between adjacent clipped and unclipped plots under warming.

Soil erosion, carbon, and nitrogen movement

Our results show that greater runoff results in greater erosion and increases transport of soil, SOC, nitrogen, and other elements off of the site. In semiarid and subhumid grassland, the top few mm of soil contain a much higher percentage of soil fine particles than underlying soils. Soil fine particles are preferentially lost over larger sand particles. Loss of soil fines can reduce soil productivity, as essential nutrients for plants are often bound to these particles. Burial of nearby biological soil crusts from flow sediments generally means death for the photosynthetic components of the soil crusts, further reducing fertility (Belknap & Lange, 2001). In our study, the transportation rates of SOC and total nitrogen carried away from eroded sites are 30–129 and 2.3–9.4 $g\,m^{-2}\,yr^{-2}$ in warmed clipped plots, and 5–38 and 0.2–2.3 $g\,m^{-2}\,yr^{-2}$ in control clipped plots, which are lower than estimates made with the mass balance approach at some agriculture sites (between 30 and 260 $g\,m^{-2}\,yr^{-1}$; Jacinthe & Lal, 2001).

If CO_2 emission rates can be assumed to represent 20% (Lal, 1995; Jacinthe *et al*., 2001) of the total SOC displaced by water erosion, our data suggests that the erosion-induced CO_2 emission rate from clipped plots can be 6–20 and 1–7 $g\,C\,m^{-2}\,yr^{-1}$ under warmed and control treatments, respectively, in the tallgrass prairie. Additionally, surface soil lateral transportation can accelerate gaseous loss by activating the release of SOC. The result in our experiment site show that warming treatment significantly stimulated soil CO_2 efflux and its components (i.e. RA and RH) in most years (Zhou *et al*. 2007b). Thus, the movement of carbon on the earth's surface can not only reduce the productivity of eroded land, but also affect the carbon cycle between soil and atmosphere by increasing CO_2 emissions during the soil movement process. Most carbon balance studies (e.g., Luo *et al*. 2009) and estimates from eddy-flux measurements (Baldocchi, 2003) do not account for C loss via erosion. Given the magnitude of C loss via erosion, it will be important to include in any future C accounting studies.

Conclusion

Our experimental results have demonstrated that both warming and biomass removal by clipping for biofuel feedstock production resulted in substantial soil erosion. Lower vegetation coverage from clipping directly led to a decreased capacity to intercept raindrops and increased runoff. Clipping also causes decreases in soil micro-aggregate stability via reduced litter input and degrades soil structure. Both canopy and soil surface residue/litter coverage are essential to reducing water and wind erosion. Thus, harvesting should be effectively managed and controlled to protect the soil from erosion.

The effect of warming on erosion in our experiment is evident; however, the mechanism is not yet clear and is presumably related to changed soil physical characteristics. As described by Blanco & Lal (2008), changes in temperature regimes may significantly impact soil processes and properties with attendant effect on soil erodibility. Degradation of soil structure reduces macroporosity and water infiltration rates. Soils with degraded structure have the greatest losses from water and wind erosion. Changes in near-surface soil conditions (e.g., crusting, surface sealing, and compaction) are climate change-induced processes that can also increase soil erosion. Our results show that warming aggravated the erosion process. Erosion not only results in lateral movement of carbon but stimulates CO_2 emissions from enhanced decomposition during the erosion and transportation processes. The decreased litter coverage in clipped plots that exposed more surfaces to warming may explain why warming increased erosion in our experiment.

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