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Deepened snow cover mitigates soil carbon loss from intensive land use in a semi-arid temperate grassland

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CONFLICT OF INTEREST

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AUTHORS' CONTRIBUTIONS

P.L. and L.L.L. conceived the ideas and designed methodology; P.L., Z.J., Y.T.W., C.L. and Y.W. collected the data; P.L. and L.L.L. analysed the data; P.L., L.L.L. and E.J.S. led the writing of the manuscript. M.F.D., X.W., B.W. and Y.F.B. revised the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

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Abstract

1. Carbon (C) loss due to soil erosion is a major issue in semi-arid grasslands. The extent of soil erosion is determined by soil properties and vegetation structure, especially during the non-growing season. In many Inner Mongolian grasslands, intensive land use, such as overgrazing and mowing, has severely reduced plant cover and damaged soil structure, which has exacerbated soil C loss by erosion. At the same time, increasing winter snowfall due to climate change is stimulating plant growth and altering plant composition. However, we do not know how changes in winter snow cover interact with land-use practices to regulate soil C loss due to erosion.
2. Here, we conducted a six-year snow manipulation experiment under different land-use practices (control; moderately mowed, MM; heavily mowed, HM) to measure net changes in soil depth, soil C, plant biomass and vegetation structure.
3. After six years, soil C loss under ambient snow was three times greater in the MM and

four times greater in the HM treatment compared with controls during non-growing season. However, deepened winter snow alleviated erosion-induced soil C loss by 14%, 47%, 16% in the controls, MM and HM treatments, respectively.

4. The severity of soil C loss declined with increasing aboveground biomass (AGB), surface root biomass and vegetation structure. Vegetation structure and AGB explained more of the variation in soil C loss than surface root biomass, possibly because a complex canopy and plant cover increases overall surface roughness, thereby reducing soil C loss. Intensified land-use reduced AGB, surface root biomass and vegetation structure, but deepened snow increased overall surface roughness by promoting AGB. Hence, our study demonstrates that deepened snow can alleviate soil C loss due to land use practices by promoting AGB.

Keywords: land use, plant biomass, soil carbon loss, soil erosion, vegetation structure, winter snow cover

1 | Introduction

Soil loss induced by wind erosion is a key process undermining soil carbon (C) storage in arid and semi-arid ecosystems (Chappell et al., 2013; Webb et al., 2012). Soil erosion is mainly regulated by climate, soil properties and vegetation structure (Kurosaki & Mikami, 2005; Kurosaki et al., 2011; Webb & Strong, 2011). The combination of wind strength and soil surface roughness plays a critical role, because the occurrence of strong winds determines the shear forces to the soil surface (erosivity), and soil surface roughness determines the susceptibility of soil particles to movement (erodibility; Kurosaki et al., 2011). Soil moisture influences erodibility because it can help bind clay and silt particles to form soil crusts (Webb & Strong, 2011). Soil crusts can increase surface roughness because they play a dominant role in aggregate formation and distribution (Leys & Eldridge, 1998), and have the ability to reinforce loose soils that are susceptible to mobilization (Neuman et al., 2005). Consequently, soil crusts increase surface roughness, which in turn enhances the ability of topsoil to resist the shearing forces of heavy wind (Webb & Strong, 2011). However, plant height and cover also play a key role in mitigating soil erosion by reducing wind speed and providing physical protection to the soil surface (Field et al., 2010). In addition, plant roots characterized by high tensile strength can effectively reinforce surface soils (De Baets et al., 2008; Gyssels et al., 2005), which mainly depends on the presence of shallow fine roots (Li et al., 1991; Ola et al., 2015). All of these key factors regulating soil erosion are being affected by a changing climate and human activities, which will inevitably affect the extent of soil C loss.

Soil erosion in arid and semi-arid grasslands can be triggered or exacerbated by grazing, mowing and tillage management practices, which can lead to irreversible soil C loss (Li et al., 2018; Wiesmeier et al., 2015). Many land management practices break down soil crusts and aggregates at the soil surface, thereby increasing soil erodibility (Webb & Strong, 2011) and promoting the movement of fine soil particles such as clay and silt under strong winds (Field et al., 2010; Webb et al., 2012). The loss of fine soil particles is important for soil C storage capacity, because the proportion of such fine particles can determine the ability of a soil to stabilize and store C (Feng et al., 2013; Six et al., 2002). Indeed, substantial losses of fine particles could alter soil texture and result in a permanent reduction of soil C sequestration potential (Li et al., 2018). Importantly, intensive land management can alter vegetation structure and the distribution patterns of plants, including plant type, cover and arrangement (Li et al., 2018). Plant productivity during the growing season (Wang et al., 2017b) promotes dust deposition via canopy interception (Li et al., 2007; Li et al., 2018), and the greater mass of standing litter and other dead plant material during the following non-growing season reduces wind speed and protects surface soils from shear forces (Bilbro & Fryrear, 1994; Li et al., 2018; Shinoda et al., 2011). Consequently, reduced protection of the soil surface by plants may exacerbate soil erosion processes both by increasing soil loss during the non-growing season and by reducing dust interception and deposition from the canopy during the growing season (Kurosaki et al., 2011; Li et al., 2018).

Climate change is likely to have a major influence on soil erosion by modifying winter precipitation, which affects soil moisture status and plant growth (Li et al., 2020; Peng et al., 2010). Global warming is projected to weaken cold air surges and increase winter snow cover in cold regions (Hartmann et al., 2013; Tsunematsu et al., 2011), which can influence vegetation structure and soil exposure throughout the year. Firstly, deepened winter snow enhances soil moisture in the spring (Dorji et al., 2013; Li et al., 2020), which directly reduces soil erodibility by promoting the formation of soil crusts and aggregates, and thus enhancing the stability of surface soil fine particles (Field et al., 2010; Webb & Strong, 2011). Secondly, increased spring snowmelt can promote plant growth in water-limited regions by alleviating water and nutrient limitation in the early growing season, which enhances plant cover and aboveground biomass throughout the growing season (Grippa et al., 2005; Li et al., 2020; Schmidt & Lipson, 2004). Finally, plants in arid grasslands predominately allocate more resources to surface root biomass under deepened winter snow (Li et al., 2020), which enhances aggregate stability and reinforces the soil (Moreno-Espíndola et al., 2007). Nevertheless, freeze-thaw cycles induced by snow cover could also accelerate soil erosion by breaking up soil aggregates (Bullock et al., 2001). However, although winter snow cover influences properties of both the soil and the vegetation, few studies have quantified the effects of increased winter snowfall on net changes in soil depth and C storage as a result of erosion.

Research into the combined effects of winter precipitation change and land management is urgently needed to understand how altered snow cover will affect soil erosion caused by human activities. Winter snow depth is increasing in North China because hydrological cycles are facilitated by cold air surges under changing climate conditions (Huang et al., 2016; Peng et al., 2010; Pulliainen et al., 2020). Enhanced winter snow cover in China's semi-arid grasslands could help stem soil C loss due to wind erosion during the non-growing season. At the same time, human activities resulting in excessive land-use such as overgrazing and heavy mowing have severely damaged soil texture and altered plant species composition in semi-arid grasslands, which in turn have intensified wind erosion (Li et al., 2018; Wiesmeier et al., 2015). To investigate whether deepened winter snow mitigates soil erosion and soil C loss under different land management types, we conducted a six-year field experiment in a temperate grassland in Inner Mongolia. We used snow fences to increase winter snow depth and assessed three mowing levels representing different land use intensities to test the following hypotheses:

H1) Intensive land use will increase soil erodibility by reducing plant biomass and vegetation structure, resulting in greater losses of soil depth and soil C than in unmanaged grasslands.

H2) Deepened winter snow cover will mitigate soil erosion and C loss under intensive land-use by promoting plant growth and soil reinforcement by roots.

2 | Materials and methods

2.1 | *Study site and experimental design*

Our experimental site was located at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS; 43°38'N, 116°42'E; 1200 m a.s.l) of the Chinese Academy of Sciences. The region belongs to the semi-arid continental climate zone and frequent strong winds (> 17 $m\ s^{-1}$) are the driving factor for soil erosion, explaining 31% of the variation in soil erosion (Li et al., 2018). Grasslands at the study site experience a mean annual temperature of 0.9 °C and a mean annual precipitation of 334 mm (Chen et al., 2019). Approximately 80% of the annual precipitation falls during the growing season (June-September), and winter precipitation at our study site has increased by 3.6 ± 0.7 mm $year^{-1}$ over the past four decades

(Li et al., 2020). The plant community is dominated by grasses and forbs, including *Leymus chinensis* (Trin.) Tzvel., *Stipa krylovii* Roshev., *Artemisia frigida* Willd. Sp. Pl. and *Potentilla chinensis* Ser. The soil is classified as a loamy sand according to USDA soil taxonomy, with 88.2 ± 1.19% sand, 0.30 ± 0.05% clay, 11.5 ± 1.14% silt (Jia et al., 2021) and a pH of 7.21 ± 0.03.

We conducted a snow manipulation experiment from October 2013 to October 2019 using a snow fence (1.25 m tall and 100 m long) to create two treatment levels: ambient snow and deepened snow. The experimental set-up is described in full by Li et al. (2020). Briefly, three blocks were established along a snow fence made of polyethylene mesh, which acted as a barrier to the prevailing north-westerly winter wind from October to March each year to increase snow depth, depending on winter precipitation levels (deep-snow treatment). The corresponding ambient snow treatment was established at least 20-m away from the snow fence. Within each deep-snow and ambient snow block, there were three nested 4-m × 8-m plots with land-use treatments comprising three mowing levels: unmowed controls (control), moderately mowed with 5 cm of stubble left aboveground (MM), and heavily mowed with 1 cm of stubble left aboveground (HM). During the growing season from June to September, vegetation under the MM and HM treatments was mowed at the beginning of each month. Thus, there were three replicate blocks of two snow treatments, with three nested land-use treatments, making 18 plots in total.

2.2 | *Environmental measurements*

To assess the effects of deepened snow, snow depth in each plot was measured at a distance of 1 m from the snow fence in deep-snow plots and in the corresponding direction and location in the ambient snow treatment during late January to early February. Mean snow depth was recorded as the mean values of eight measurements at 1 m intervals. Soil water content was measured daily at 10 cm soil depth in all plots from 2017 to 2019 (April to September), using a capacitance probe sensor (Diviner 2000, Sentek) via an access tube made of polyvinylchloride installed in the centre of each plot. Data for daily precipitation and wind speed from 2013 to 2019 were obtained from a weather station 0.5 km from our study site.

2.3 | *Net changes in soil depth and C via erosion*

To quantify the net changes in soil depth caused by soil erosion and dust deposition, we used stainless steel rulers as reference markers. In each plot, 21 rulers (20-cm length) were inserted into the soil at 1 m intervals with 10 cm left above the soil surface. We measured changes in soil depth once a month, and then subtracted the readings between consecutive months to compute net changes in soil depth. We determined soil C concentrations and soil bulk density at 0-5 cm depth each year in August. We collected three soil cores (7-cm diameter) per plot to measure soil C concentrations using a CHNOS elemental analyzer (Vario EL III; Elementar Analysensysteme GmbH, Hanau, Germany), and we measured soil bulk density on one sample per plot using a cylindrical metal sampler (5-cm diameter); bulk density was calculated as the ratio of oven - dried (105° C) mass to the core volume of the soil sample. Finally, soil C loss via erosion at each time-point was calculated by the following equation:

$$\text{soil C loss} = TC_t \times d_t \times S \times \rho_t - TC_{t-1} \times d_{t-1} \times S \times \rho_{t-1}$$

where *TC* is soil C concentration (%), *d* is the soil depth (cm) measured at time *t*, *S* is a conversion constant (10^4 cm^2), and ρ is soil bulk density (g cm^{-3}).

2.4 | *Plant biomass and height*

To assess how plant biomass and vegetation structure affects soil erosion, plant biomass and height were measured annually from 2014 to 2018. At the beginning of August each year, the height of all plants was measured within a randomly placed 0.5 m × 1 m quadrat in each plot, and the coefficient of variation (CV) for plant height was calculated as a measure of vegetation structure for each plot. Plant aboveground biomass (AGB) in control plots was estimated by harvesting all plants in each quadrat. In MM and HM plots, plant AGB was calculated by summing the mowed biomass from June to September in each quadrat, whereby biomass in September was harvested without leaving any stubble. Surface root biomass was estimated in August each year, using a 7-cm diameter corer to collect three soil cores at 0-5 cm depth diagonally across each plot, which were combined to create one composite sample per plot. Roots were cleaned under running water, and then sieved in deionized water using 0.2 mm mesh to remove residual soil and decomposition products. Dead roots were distinguished from live roots by colour, flexibility, and consistency under a magnifying glass and removed (Gao et al., 2008). All plant AGB and root samples were oven-dried at 65°C for 48 hr to constant weight and weighed to the nearest 0.1 g.

2.5 | *Statistical analysis*

All statistical analyses were performed in R version 3.5.3. We used linear mixed effects models (LMEs; *lmer* function in the lme4 package; Bates et al., 2014) to test the effects of deepened winter snow and land-use treatments on soil depth, soil C, and vegetation. We used separate models to assess responses during the growing season, non-growing season or over the whole year. First, we tested the effects of land-use over time on snow depth increment and monthly changes in soil depth under different snow treatments using LMEs with land-use and time (year or date) as fixed effects, and block as a random effect. Then we assessed how deepened winter snow, land-use, year and their interaction influenced annual, net changes in soil depth, cumulative changes in soil depth, soil moisture, AGB, surface root biomass and vegetation structure (the CV of plant height) during the six-year study; we fit LMEs with snow treatment, land-use, year and their interaction as fixed effects, and snow treatment nested within blocks as random effects. Finally, we evaluated the effects of deepened snow and land-use treatments on mean annual soil moisture, AGB, surface root biomass, and vegetation structure across the entire study period, as well as the mean annual changes in soil depth and soil C; we used LMEs with snow treatment, land-use and their interactions as fixed effects, and snow treatment nested within blocks as random effects. For ease of interpretation, we also performed pair-wise analysis to compare the differences between ambient snow and deep-snow under each land-use treatment. For all LMEs, the minimum adequate model was identified by sequentially dropping terms, using AIC and *p*-values to check for model improvement (Pinheiro & Bates, 2000). The final models were compared to appropriate null models using likelihood ratio tests, which only included random effects. We give the Chi-squared (χ^2) value for the total effects of deepened snow and land-use treatments from the comparison between the best-fit model and the corresponding null model. We also report significant effects of individual terms (snow treatment, land-use, year and their interactions) at $p < 0.05$, and marginally significant trends at $p < 0.1$ based on post-hoc tests using

Satterthwaite's approximation (lmerTest package; Kuznetsova et al., 2017).

To test the influence of vegetation on soil C change during the whole year, we used simple linear regressions of the net changes in soil C against the previous growing season's plant AGB, surface root biomass, or vegetation structure (CV of plant height). Finally, we compared the relative importance of plant AGB, root biomass or vegetation structure in mitigating soil C loss using a general linear model, in which we modelled soil C change over the whole year as a function of the previous growing season's AGB, surface root biomass, and CV of plant height. We assessed for collinearity of explanatory variables using the variance inflation factor (*vif* function in the car package; Fox & Weisberg, 2018) and we then apportioned the relative importance (R^2, %) of the predictor variables by averaging over orders (*calcrelimp* function in the relaimpo package, using the *pmvd* metric for weighted averages with data-dependent weights; Grömping, 2006).

3 | Results

3.1 | *Environmental conditions*

The precipitation and frequency of strong winds (> 17 m s^{-1}) at our study site were highly seasonal, with only 19% of annual precipitation but 61% of all strong wind events occurring during the non-growing season (Fig. 1a,b). The deep-snow treatment increased snow depth by an average of 29.88 $\pm$ 2.83 cm over the six years of the study (see Fig. S1 in Supporting Information), and the increments in snow depth were similar under all land-use treatments (Fig. S1). Soil water content was significantly higher in the deep-snow compared to the ambient snow treatment, but did not differ among land-use treatments (Fig. S2).

3.2 | *Net changes in soil depth and soil C*

Annual soil loss, measured as net changes in soil depth, increased each year during the first four years (2014-2017), but the trend declined in the last two years of the study (2018 and 2019; Fig. 2a,g). Our analyses based on monthly measurements revealed that net losses of soil depth and soil C occurred during the non-growing season (October to May; Fig. 2b,c), which were partially offset by increases in soil depth and soil C due to dust deposition during the growing season (June to September; Fig. 2e,f; Fig. S3). Over six years, we measured a small net gain in mean annual soil depth and soil C in control plots, but significant net losses in heavily mowed (HM) and moderately mowed (MM) plots (Fig. 2h,i).

The negative impacts of land-use treatments on soil depth and soil C during the non-growing season were partly alleviated by deepened winter snow (Fig. 2a,b,c). Given the large interannual differences in snow depth (Fig. S1), the effect of the deep-snow treatment on soil erosion and C loss also varied strongly among years (Fig. 2). Over six years, mean annual soil loss during the non-growing season under ambient snow was 0.1 $\pm$0.04 cm yr^{-1} in the controls, but 0.4 $\pm$0.01 cm yr^{-1} in the MM plots and 0.6 $\pm$0.01 cm yr^{-1} in the HM plots (Fig. 2b), which led to total soil C losses of 136.3 $\pm$36.5, 337.1$\pm$53.8, 409.6 $\pm$29.6 g C m^{-2} in control, MM and HM plots, respectively (Fig. 2c). However, despite significant interannual variation, deepened winter snow alleviated soil loss by 15%, 56%, and 24% in control, MM and HM plots, respectively (Fig. 2b), which reduced the corresponding soil C loss by 14% in the controls, 47% in MM and 16% in HM plots (Fig. 2c). Deepened winter snow did not influence dust deposition during the growing season but dust deposition in control plots under ambient snow increased soil depth by 0.3 ±0.04 cm yr^{-1}, adding a total of 278.7 ±39.8 g C m^{-2} over the six years. Moderate and heavy mowing reduced the increments in soil depth and soil C associated with dust deposition, which were 17% and 34% lower in MM plots and 47% and 56% lower in HM plots, respectively (Fig. 2e,f).

3.3 | *Effects of land-use and snow cover on the vegetation*

Land-use and snow cover influenced plant AGB and surface root biomass but only land-use affected vegetation structure (CV of plant height). Despite significant interannual variation in AGB, mean annual AGB was similar between control and MM plots but significantly lower in the HM plots (Fig. 3a,b). Deepened winter snow significantly enhanced plant AGB compared to the ambient snow treatment, and the effect of deepened winter snow was similar among land-use treatments (Fig. 3a,b). Surface root biomass was strongly influenced by land-use, with the lowest root biomass in the HM plots (Fig. 3c,d). Surface root biomass in the control plots was greater under deepened winter snow compared to ambient snow, but there was no effect of deepened snow on surface root biomass in MM and HM plots, resulting in lower surface root biomass in MM and HM plots compared to controls under the deep snow treatment (Fig. 3c,d). Finally, vegetation structure was significantly simpler and less variable in MM and HM plots compared to the controls, regardless of snow treatment, but there was no discernible effect of deepened winter snow cover (Fig. 3f).

3.4 | *Effects of vegetation on soil C loss*

As soil C loss mainly occurred during the non-growing season, the changes in soil C across the whole year were strongly related to the previous growing season's plant biomass and vegetation structure. Higher plant AGB and surface root biomass during the growing season significantly mitigated soil C loss over the whole subsequent year (Fig. 4a,b). Moreover, soil C loss was also reduced by greater structural complexity of the vegetation (Fig. 4c; Fig. S4). Reduced soil C losses with greater AGB and structural complexity of the vegetation were apparent during both the growing and the non-growing season, whereas root biomass only mitigated soil C loss during the non-growing season (Fig. S5). Together, vegetation structure, surface root biomass and AGB accounted for 38.85% of the variation in soil C change over the whole year (Fig. 4d). Vegetation structure was the most important factor affecting soil C change, accounting for *c*. 19% of the variation in soil C change, followed by AGB, which accounted for *c*. 15%, whereas the relative contribution of surface root biomass was not significant, explaining only 5% of the variation in soil C change (Fig. 4d). During the non-growing season, surface root biomass and vegetation structure explained more variation in soil C loss (each *c*. 12%) than AGB (*c*. 2%), whereas AGB explained most of the variation during the growing season (*c*. 16%; Fig. S5).

4 | Discussion

Our study demonstrates that land-use intensity exacerbates soil depth loss (henceforth soil erosion), resulting in substantial losses of soil C, but the extent of soil erosion was alleviated by deepened winter snow cover. We discuss how soil erosion and soil C losses are affected by land use and snow cover via changes in plant cover and vegetation structure.

One of the most striking results of our study was that vegetation structure, represented by the variation in plant height, was more effective in reducing annual soil C loss than plant AGB or surface root biomass (Fig. 4d). The importance of vegetation structure for mitigating soil erosion in managed grasslands has, to date, generally been largely ignored. Our study demonstrates that the structural complexity of the vegetation was particularly important for mitigating soil C loss during the non-growing season, whereas AGB played a greater role during the growing season (Fig. S5d,h). The plant canopy acts as a physical barrier that not only decreases wind erosion intensity but also captures windblown dust (Li et al., 2005; Li et al., 2007; Li et al., 2018). Hence, our study demonstrates that mowing not only increased soil erosion, but also diminished the interception of dust via plants by reducing plant canopy complexity as well as AGB (Fig. 2b,e; Fig. 3b,f; Fig. 4a,c; Fig. S5d,h). Thus, as hypothesised, the higher rates of soil erosion and soil C loss with increasing land-use intensity can be largely attributed to a simpler vegetation structure. The reduction of wind speed and the interception of dust by the vegetation might be particularly important for soil C change in Inner Mongolian grasslands (Shinoda et al., 2011), because, without sufficient vegetative cover, the limited precipitation and frequent heavy winds in early spring in these arid and semi-arid regions could accelerate soil loss (Kurosaki & Mikami, 2005; Li et al., 2018; Shinoda et al., 2011). Indeed, the greatest soil depth losses in the HM treatment coincided with heavy wind frequency during the non-growing season in 2015 and 2016, or low growing season precipitation in 2017 (Figs. 1 and 4). Hence, soil erosion and soil C losses are likely to be substantial in Inner Mongolian grasslands where vegetation cover and canopy surface roughness have been reduced by intensive land-use (Hoffmann et al., 2008; Li et al., 2007).

Our work highlights the importance of processes during the growing season in regulating soil erosion and soil C loss of the following year. In arid and semiarid grasslands, most of the aboveground plant biomass can remain standing for several months after death (Frouz et al., 2011; Wang et al., 2017a). This standing plant litter can thus effectively mitigate soil erosion by maintaining canopy surface roughness and reducing wind speed during the first months of the following non-growing season (Fig. S5c,d; Bilbro & Fryrear, 1994; Shinoda et al., 2011). Consequently, the simpler canopy structure and lower plant biomass induced by moderate and heavy mowing thus resulted in substantial soil erosion and soil C loss during the non-growing season, which accounted for most of the changes in soil depth and soil C throughout the year (Fig. 2; Fig. 3).

Given the substantial effects of vegetation structure and plant aboveground biomass on soil loss and dust deposition, the mitigating effect of deepened winter snow on soil erosion and soil C loss can be largely attributed to higher plant biomass under deepened snow cover (Fig. 4). Although deepened winter snow also enhanced soil water content in the early growing season (Fig. S2), the lack of differences in soil water content among land-use treatments suggests that soil erosion and soil C loss were mitigated by enhanced plant growth as a result of greater water availability after snowmelt (Li et al., 2020), rather than via a direct effect of soil moisture. Indeed, one of the years with the greatest mitigating effects of the deep-snow treatment on soil loss during the non-growing season was also the year of heaviest snowfall (2016; Fig S1). In addition, deepened winter snow could also alleviate soil erosion by altering plant community composition. Previous work in the study area demonstrated that deepened winter snow promoted the persistence of grasses and thus increased the ratio of grasses to forbs in the plant community (Li et al., 2020; Wang et al., 2020). Generally, grasses are more likely than forbs to produce standing litter (Wang et al., 2020), and greater grass cover under our deep-snow treatment might therefore be more efficient in protecting the soil surface from wind-shear stress in the following spring (Kurosaki et al., 2011; Shinoda et al., 2010).

Finally, we found that higher surface root biomass contributed to protecting the soil surface from erosion during the non-growing season (Fig. S5b,d). Plant root systems play a critical role in soil reinforcement owing to their strong tensile strength and proliferation (Gyssels et al., 2005; Ola et al., 2015). In our study, it is likely that lower surface root biomass in moderately and heavily mowed plots intensified soil erosion and soil C loss, whereas higher surface root biomass under deepened snow mitigated soil erosion and soil C loss in the control plots (Fig. 3c,d; Fig. 4b). Indeed, the particularly strong mitigating effect of deepened winter snow on soil loss in 2018 can be attributed to the substantial increase in surface root biomass under the deep-snow treatment during the previous growing season (2017; Fig. 2a,g; Fig. 3c; Fig. 4). Unlike AGB and vegetation structure, surface roots do not contribute to dust interception during the growing season, which explains the smaller contribution of surface root biomass to mitigating soil loss across the whole year (Fig. 4b,d). However, shallow fibrous roots can be particularly effective in improving soil cohesion and reducing the erodibility of the topsoil (De Baets et al., 2008; Gyssels et al., 2005; Li et al., 1991). Consequently, as grass species are charactered by fibrous roots with high branching intensity in surface soils (Li et al., 2017; Nippert & Knapp, 2007a; Nippert & Knapp, 2007b), the high grass:forb ratio under deepened snow might also contribute to reducing soil erosion. Hence, the impacts of both climate changes and land-use on plant species composition could greatly influence the extent of soil erosion and soil C loss by altering vegetation structure and surface root biomass.

Soil erodibility is also associated with intrinsic soil properties, especially the proportion of fine soil particles (Wang et al., 2001). The lower losses of soil depth and soil C in the final two years of our study (2018-2019; Fig. 2g; Fig. S7), despite the driest and windiest non-growing season (Fig. 1), are likely the result of substantial erosion of clay and fine silt particles from surface soils at the start of the study period (Li et al., 2018). The continued loss of clay and silt particles leaves a greater proportion of heavier sand particles in soils, which are less susceptible to wind erosion (Li et al., 2018; Webb et al., 2012). Consequently, the cumulative changes in soil depth attenuated over time (Fig. S7). Hence, although our study revealed a key role for vegetation cover in mitigating soil erosion and soil C loss, our results suggest that the soil texture might become a dominant abiotic factor affecting soil erosion when surface soils are severely degraded. Finally, it is important to note that most of the soil C lost by wind erosion was organic C, as inorganic C only comprised *c*. 6%-10% of total soil C and it was not affected by deep-snow or land-use treatments after six years (Fig. S6). Hence, our results indicate that changes in total soil C loss induced by erosion can be mainly attributed to losses of soil organic C (Fig. S6a,c) associated with soil fine particles (clay and silt).

In sum, our six-year field experiment demonstrates for the first time that deepened snow cover can mitigate soil erosion and soil C losses due to intensive land-use. Whereas most previous studies have primarily focused on changes in soil C via biotic process during the growing season, we demonstrate that changes in the vegetation as a result of deepened winter snow cover can also regulate soil erosion during the non-growing season, which largely determines the changes in soil C throughout the year. Land management to sustain soils and increase soil C storage in arid and semi-arid grasslands should focus on maintaining vegetation with a rough canopy and high aboveground biomass. In addition, leaving plant standing litter during the non-growing season could represent a simple but important management practice for regulating soil erosion and soil C loss. Given the importance of vegetation structure and canopy complexity in stemming soil erosion and C losses, including key vegetation parameters in predictive models could help identify and mitigate soil erosion across large regions of arid and semi-arid grasslands.

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Figure captions

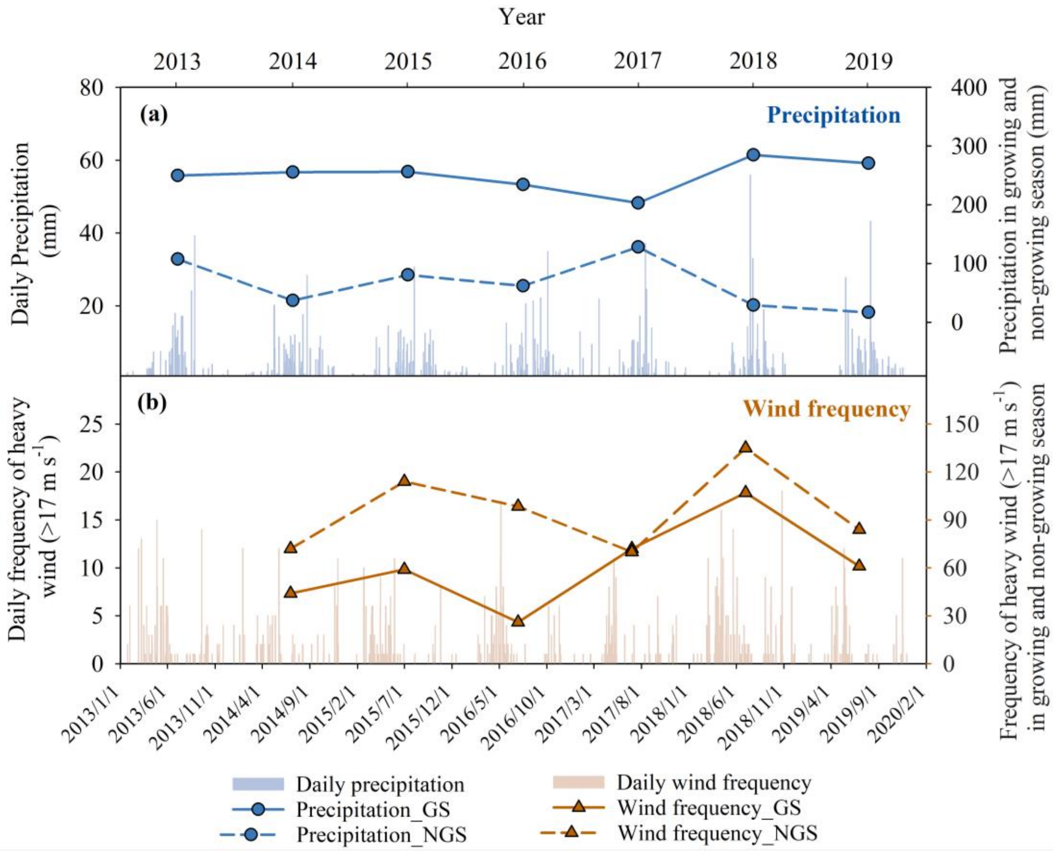
Fig. 1 Daily and annual **(a)** precipitation and **(b)** frequency of heavy winds at the study site; blue bars indicate daily precipitation and brown bars indicate daily frequency of heavy wind from 2013 to 2019; blue solid and dashed lines with dots indicate annual precipitation during the growing (GS) and non-growing season (NGS), respectively, from 2013 to 2019, whereas brown solid and dashed lines with triangles denote frequency of heavy wind (FW; > 17 m s^{-1}).

Fig. 2 Net changes in soil depth and soil carbon (C) from 2014 to 2019 under different snow depth and land-use treatments. **(a, d, g)** inter-annual changes in soil depth, **(b, e, h)** mean annual changes in soil depth, and **(c, f, i)** mean annual changes in soil C during the non-growing season, growing season and whole year, respectively. Colors represent ambient snow (red) and deep-snow treatments (blue); symbols and lines indicate control (circles), moderately mowed (MM; triangles) and heavily mowed (HM; squares) treatments; the effects of deep-snow (Snow), land-use (LU) treatments and year (Year) are shown as χ^2 and P values from the comparison between the best-fit linear mixed effects model and the corresponding null model, where '*ns*' is non-significant; pair-wise analysis was used to compare the difference between ambient and deep-snow treatments, where * indicates $0.01<P<0.05$ and *** indicates $P<0.001$; bars and symbols represent means and whiskers represent standard errors for $n = 3$.

Fig. 3 Inter-annual and total mean annual changes in **(a,b)** AGB, **(c, d)** surface root biomass at 5 cm depth and **(e,f)** CV of plant height at the plot scale from 2014 to 2019 under different snow depth and land-use treatments. Colors represent ambient snow (red) and deep-snow treatments (blue); symbols and lines indicate control (circles), moderately mowed (MM; triangles) and heavily mowed (HM; squares) treatments; the effects of deep-snow (Snow), land-use (LU) treatments and year (Year) are shown as χ^2 and P values from the comparison between the best-fit linear mixed effects model and the corresponding null model, where '*ns*' is non-significant; pair-wise analysis was used to compare the difference between ambient and deep-snow treatments (* indicates $0.01<P<0.05$); bars and symbols represent means and whiskers represent standard errors for $n = 3$.

Fig. 4 Relationships between changes in soil C during the whole year and **(a)** aboveground biomass **(**AGB) of the previous year, **(b)** surface root biomass of the previous year, **(c)** coefficient of variation (CV) in plant height (vegetation structure) of the previous year, and **(d)** the relative contribution of the predictors to the total explained variation in soil C change across snow-depth (Snow) and land-use (LU) treatments. Colors represent ambient snow (red) and deep-snow treatments (blue); symbols indicate control (circles), moderately mowed (MM; triangles) and heavily mowed (HM; squares) land-use treatments. In (a)-(c), P values and R^2 from simple correlations are given and solid black lines indicate significant relationships between variables. In (d), the P values and R^2 coefficients from general linear models are shown, indicating the significance of the predictor variables and the total explained variation in soil C change, where AGB is aboveground plant biomass of the previous year; RB.surface is root biomass at 5 cm soil depth of the previous year and CV.height is the coefficient of variation of plant height.

Fig. 1



Year
2013
2014
2015
2016
2017
2018
2019
(a)
Precipitation
Daily Precipitation (mm)
Precipitation in growing and non-growing season (mm)
(b)
Wind frequency
Daily frequency of heavy wind (>17 m s-1)
Frequency of heavy wind (>17 m s-1) in growing and non-growing season
2013/1/1
2013/6/1
2013/11/1
2014/4/1
2014/9/1
2015/2/1
2015/7/1
2015/12/1
2016/5/1
2016/10/1
2017/3/1
2017/8/1
2018/1/1
2018/6/1
2018/11/1
2019/4/1
2019/9/1
2020/2/1
Daily precipitation
Precipitation_GS
Precipitation_NGS
Daily wind frequency
Wind frequency_GS
Wind frequency_NGS

Fig. 2

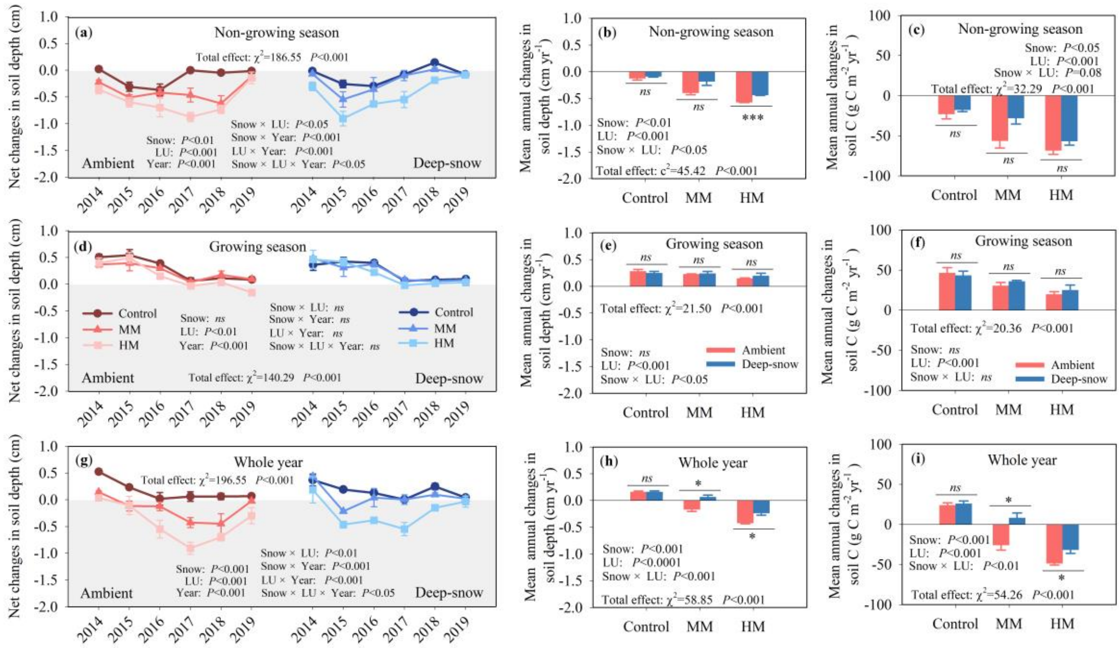

(a)
Non-growing season
Total effect: χ2=186.55 P<0.001
Snow: P<0.01
LU: P<0.001
Year: P<0.001
Snow × LU: P<0.05
Snow × Year: P<0.001
LU × Year: P<0.001
Snow × LU × Year: P<0.05
Ambient
Deep-snow
Net changes in soil depth (cm)
(b)
Non-growing season
Snow: P<0.01
LU: P<0.001
Snow × LU: P<0.05
Total effect: c2=45.42 P<0.001
Mean annual changes in soil depth (cm yr-1)
(c)
Non-growing season
Snow: P<0.05
LU: P<0.001
Snow × LU: P=0.08
Total effect: χ2=32.29 P<0.001
Mean annual changes in soil C (g C m-2 yr-1)
(d)
Growing season
Control
MM
HM
Snow: ns
LU: P<0.01
Year: P<0.001
Snow × LU: ns
Snow × Year: ns
LU × Year: ns
Snow × LU × Year: ns
Total effect: χ2=140.29 P<0.001
(e)
Growing season
Total effect: χ2=21.50 P<0.001
Snow: ns
LU: P<0.001
Snow × LU: P<0.05
Ambient
Deep-snow
(f)
Growing season
Total effect: χ2=20.36 P<0.001
Snow: ns
LU: P<0.001
Snow × LU: ns
(g)
Whole year
Total effect: χ2=196.55 P<0.001
Snow: P<0.001
LU: P<0.001
Year: P<0.001
Snow × LU: P<0.01
Snow × Year: P<0.001
LU × Year: P<0.001
Snow × LU × Year: P<0.05
(h)
Whole year
Snow: P<0.001
LU: P<0.0001
Snow × LU: P<0.001
Total effect: χ2=58.85 P<0.001
(i)
Whole year
Snow: P<0.001
LU: P<0.001
Snow × LU: P<0.01
Total effect: χ2=54.26 P<0.001
Control MM HM
2014 2015 2016 2017 2018 2019

Fig. 3

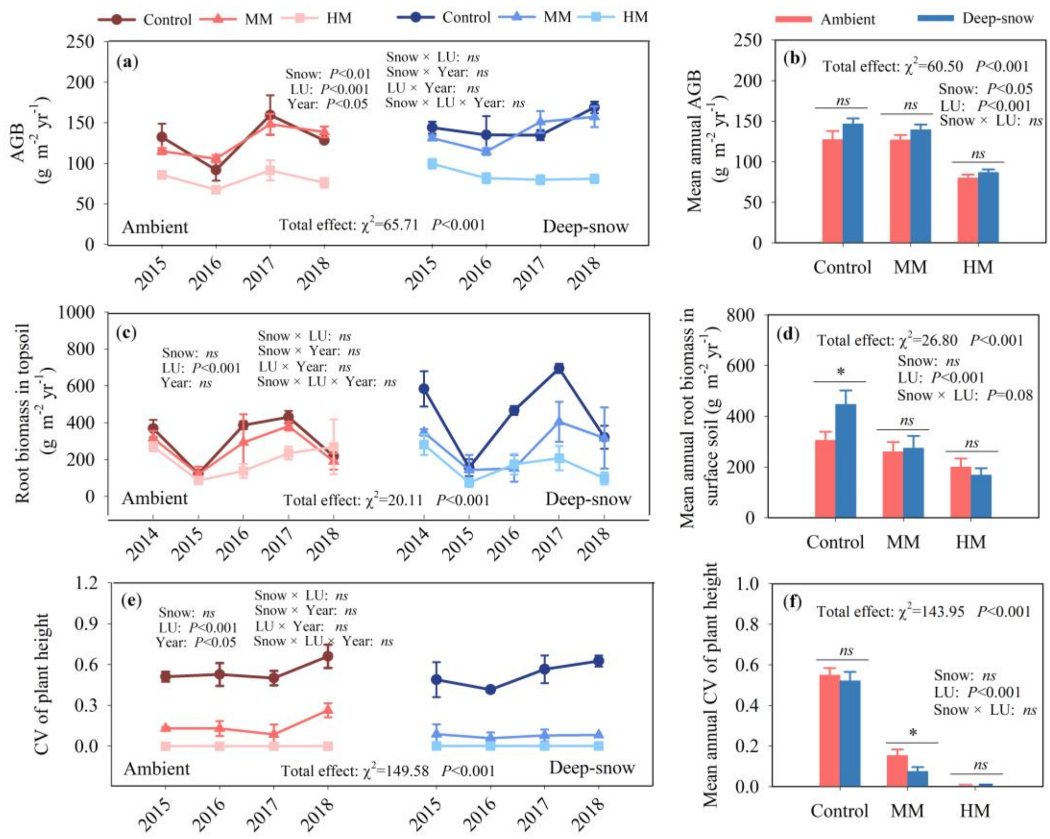
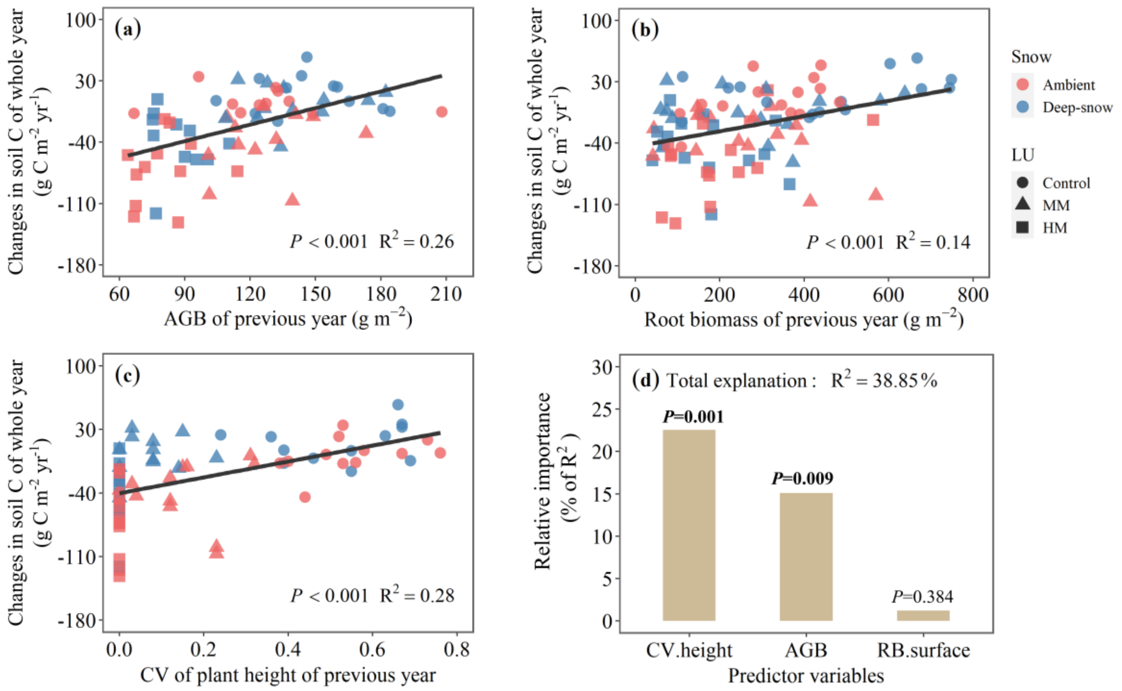

(a)
Control MM HM Control MM HM
Snow: P<0.01
LU: P<0.001
Year: P<0.05
Snow × LU: ns
Snow × Year: ns
LU × Year: ns
Snow × LU × Year: ns
AGB (g m-2 yr-1)
Ambient
Total effect: χ2=65.71 P<0.001
Deep-snow
(b)
Ambient Deep-snow
Total effect: χ2=60.50 P<0.001
Snow: P<0.05
LU: P<0.001
Snow × LU: ns
Mean annual AGB (g m-2 yr-1)
Control MM HM
(c)
Snow: ns
LU: P<0.001
Year: ns
Snow × LU: ns
Snow × Year: ns
LU × Year: ns
Snow × LU × Year: ns
Root biomass in topsoil (g m-2 yr-1)
Ambient
Total effect: χ2=20.11 P<0.001
Deep-snow
(d)
Total effect: χ2=26.80 P<0.001
Snow: ns
LU: P<0.001
Snow × LU: P=0.08
Mean annual root biomass in surface soil (g m-2 yr-1)
Control MM HM
(e)
Snow: ns
LU: P<0.001
Year: P<0.05
Snow × LU: ns
Snow × Year: ns
LU × Year: ns
Snow × LU × Year: ns
CV of plant height
Ambient
Total effect: χ2=149.58 P<0.001
Deep-snow
(f)
Total effect: χ2=143.95 P<0.001
Snow: ns
LU: P<0.001
Snow × LU: ns
Mean annual CV of plant height
Control MM HM

Fig. 4


(a)
Changes in soil C of whole year (g C m-2 yr-1)
P < 0.001 R2 = 0.26
AGB of previous year (g m−2)
(b)
Root biomass of previous year (g m−2)
P < 0.001 R2 = 0.14
Snow
Ambient
Deep-snow
LU
Control
MM
HM
(c)
CV of plant height of previous year
P < 0.001 R2 = 0.28
(d) Total explanation : R2 = 38.85%
Relative importance (% of R2)
P=0.001
P=0.009
P=0.384
CV.height
AGB
RB.surface
Predictor variables