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Effects of warming and clipping on plant and soil properties of an alpine meadow in the Qinghai-Tibetan Plateau, China

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Abstract: Climate warming and livestock grazing are known to have great influences on alpine ecosystems like those of the Qinghai-Tibetan Plateau (QTP) in China. However, it is lacking of studies on the effects of warming and grazing on plant and soil properties in these alpine ecosystems. In this study, we reported the related research from manipulative experiment in 2010–2012 in the QTP. The aim of this study was to investigate the individual and combined effects of warming and clipping on plant and soil properties in the alpine meadow ecosystem. Infrared radiators were used to simulate climate warming starting in July 2010, while clipping was performed once in October 2011 to simulate the local livestock grazing. The experiment was designed as a randomized block consisting of five replications and four treatments: control (CK), warming (W), clipping (C) and warming+clipping combination (WC). The plant and soil properties were investigated in the growing season of the alpine meadow in 2012. The results showed that W and WC treatments significantly decreased relative humidity at 20-cm height above ground as well as significantly increases air temperature at the same height, surface temperature, and soil temperature at the depth of 0–30 cm. However, the C treatment did not significantly decrease soil moisture and soil temperature at the depth of 0–60 cm. Relative to CK, vegetation height and species number increased significantly in W and WC treatment, respectively, while vegetation aboveground biomass decreased significantly in C treatment in the early growing season. However, vegetation cover, species diversity, belowground biomass and soil properties at the depth of 0–30 cm did not differ significantly in W, C and WC treatments. Soil moisture increased at the depth of 40–100 cm in W and WC treatments, while belowground biomass, soil activated carbon, organic carbon and total nitrogen increased in the 30–50 cm soil layer in W, C and WC treatments. Although the initial responses of plant and soil properties to experimental warming and clipping were slow and weak, the drought induced by the downward shift of soil moisture in the upper soil layers may induce plant belowground biomass to transfer to the deeper soil layers. This movement would modify the distributions of soil activated carbon, organic carbon and total nitrogen. However, long-term data collection is needed to further explain this interesting phenomenon.

Keywords: simulated warming; overgrazing; soil property; plant property; alpine meadow ecosystem; Qinghai-Tibetan Plateau

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Climate warming from rising concentrations of greenhouse gases has become an established fact (Oreskes, 2004). Global temperature is predicted to increase 1.4°C–3.0°C by 2050 compared to the average over the last century (Rowlands et al., 2012), and the temperature may continue to rise by 1.8°C to 4.8°C until the end of this century (Shi et al., 2012). The increment of temperature is predicted to be greater in high latitude and high altitude regions where ecosystems are more sensitive to the rising temperature (Grabherr et al., 1994; Thomas et al., 2004). This sensitivity is because plant growth in these regions is

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often adapted to low temperature and soil respiration is similarly more sensitive to warming at low temperature (Li et al., 2011a). In the alpine ecosystems, low temperature is considered to be one of the most important limiting factors for the performance of plants, whereas temperature enhancement reinforces photosynthetic capacities and growth rates of these plants (Li et al., 2011a). Compared to soils from temperate ecosystems, cold soils in alpine ecosystems comprise more labile soil organic matter, because the cold soil is associated with slower decomposition and humification processes (Sjögersten et al., 2003).

Climate change and human activity are two commonly cited factors resulting in grassland degradation. The effects of human activity on vegetation are greater than those of environmental factors, and human activity has become the dominant factor controlling plant community properties (Brown et al., 1997; Wang et al., 2006). In terms of the human activity, land use change is an important factor that could fundamentally change the ecosystem carbon cycling and the responding of ecosystem to climate change (Chapin et al., 2008). Grazing is one of the most prevalent land uses in grasslands and has the potential to substantially influence carbon cycling by: (1) altering microclimate as well as the availability of light, water and nutrients (Zhou et al., 2007); (2) changing photosynthetic activity of plants and stimulating compensatory growth (Zhao et al., 2008); and (3) modifying the species composition (Derner et al., 2006). Moderate grazing intensity not only prevents the grassland from being destroyed but also promotes the grassland primary productivity and the utilization rate of grassland; however, overgrazing could reduce grassland productivity and might prolong the restoration time of grassland (Belsky, 1986, 1993; Trilica and Rittenhouse, 1993).

The Qinghai-Tibetan Plateau (QTP), regarded as the third pole in the earth and the highest unique territorial unit in the world, is sensitive to the climate change and is considered as an ideal region for studying the responses of terrestrial ecosystems to climate change (Zhao and Zhou, 1999; Cao et al., 2004; Li et al., 2011b; Shi et al., 2012). The climate in the QTP is experiencing a warming trend, which significantly changes the active layer of the frozen soil (Zhang, 2007; Yang et al., 2010). Climate warming is predicted to stimulate the release of a substantial portion of soil carbon by increasing soil respiration thereby turning alpine ecosystems from a net sink to a net source of atmospheric CO_2 (Tarnocai, 1999; Knorr et al., 2005; Biasi et al., 2008). In the QTP, the alpine meadow ecosystems comprise the representative vegetation and the major pastureland (Cao et al., 2004). These alpine meadows are adapted to the uplift and low temperature environments of the QTP (Zhao and Zhou, 1999). In the alpine meadow, the upper species of sedges and grasses belong to the high quality forages and are gnawed frequently by livestock, resulting in abnormal growth and low ability to compete with other species (Niu et al., 2010). Thus, grazing greatly influences the plant community composition, vegetation development and ecosystem function. (Niu et al., 2010; Yang et al., 2011).

In order to understand the dynamic responses of alpine ecosystems to climate warming and livestock grazing, we conducted a manipulation experiment in 2010–2012 to investigate the individual and combined effects of warming and clipping on plant and soil properties in an alpine meadow in the QTP. We hypothesized that: (1) the responses of plant and soil prosperities to warming and clipping are slow and weak on the short-term scale; and (2) the reduction of soil moisture due to warming in the upper soil layers may cause the plant belowground biomass to transfer to the deeper soil layers, and thus to alter the distributions of soil properties at different soil depths.

1 Study area and methods

1.1 Study area

The research site is located on the Qinghai-Tibetan Plateau Research Base of the State Key Laboratory of Permafrost Engineering, Chinese Academy of Sciences (34°49'34"–34°49'37"N, 92°55'57"–92°56'06"E; 4,633.5 m asl; Fig. 1a). This base is also known as the Beiluhe Experiment Station. The site is in an arid and cold area of the QTP with an annual mean temperature of –5.9°C, a mean annual precipitation of 267.6 mm, a mean annual potential evaporation of 1,316.9 mm and an annual mean wind speed of 4.1 m/s. The frozen period lasts for 7–8 months from September to April next year. The depths of frozen soil generally range

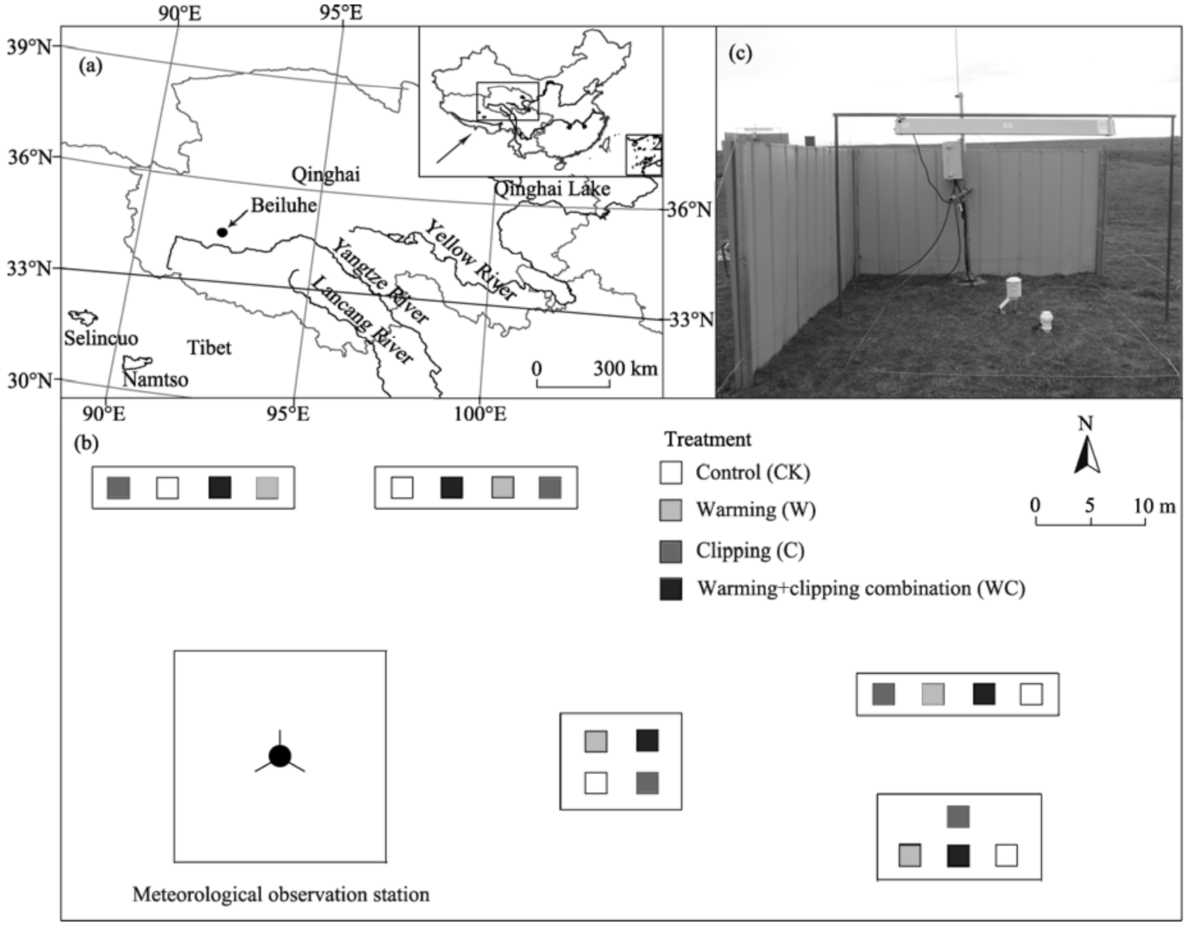

Fig. 1 Description of the research site (a), experimental design (b) and experimental plots with instrumentation (c)

from 2 to 3 m with a maximum of 3.4 m and a minimum of 1.7 m. The vegetation at this site belongs to the typical alpine meadow with *Kobresia pygmaea* as the dominant species as well as significant compositions of *Leontopodium nanum*, *Saussurea pulchra*, *Kobresia tibetica*, *Carex moorcroftii* and *Oxytropis pusilla*. The species of Cyperus and Compositae account for a large part of the vegetation composition, and *Polygonum viviparum* of Polygonaceae is also common. In total, the vegetation cover reaches 83%. The animal commonly present at this site is *Ochotona curzoniae*, which lives in groups. While they are nesting, the soils they dig from the ground can form small dunes. During grazing season in autumn pasture, the livestock is yak (*Bos grunniens*) in free grazing. The grazing frequency is from September to December every year. The soil type at the site belongs to the alpine meadow soil. The thickness of mattic epipedon is 5–15 cm and the content of soil organic matter is 8–25 g/kg.

1.2 Experimental design

Experimental plots were established in a typical alpine meadow at a distance of approximately 300 m from the Beiluhe Experiment Station. We chose areas that were flatter than surrounding areas and where the vegetation was distributed evenly and undisturbed by livestock or *Ochotona curzoniae*. The experiment was designed as a randomized block. There were five blocks in the experiment and each block had four treatments: control (CK), warming (W), clipping (C) and warming+clipping combination (WC) (Fig. 1b). There were 20 plots in total and each plot had an area of 2 m×2 m. The warming plots were heated with an average energy of 130 W/m^2 for 24 h per day starting in July 2010. Then, the energy was adjusted to 150 W/m^2 to increase the warming effects starting in October 2011. The grasses in the clipping plots were cut with a residual height of 1 cm. For simulating the local overgrazing in autumn pasture, the cutting was carried out once in October 2011. Furthermore, an aluminum frame with an area of 27 cm×27 cm was placed flat in the center of each experimental plot to measure vegetation species diversity.

In the plots with warming treatment (i.e. W and WC), single-tube infrared radiators (Kalglo Electronics, Bethlehem, PA, USA) were used to simulate the enhanced downward infrared radiation that occurs from anthropogenic warming. The housing of the radiator was 165-cm long and had an equilateral triangle cross-section (15 cm on a side); the heating element was rod-shaped with a diameter of 8 mm and a length of 150 cm. We suspended the reflector surface of the radiator at 1.5 m above the warming plots and modified it to distribute the radiation more evenly over the soil surface (Kimball, 2005). As a result, soil temperature increments generated by the radiator were relatively even over the entire area of each warming plot and were similar at different soil depths (Wan et al., 2002). Each of the control plots and clipping plots had a "dummy" radiator (no heating element) with the same dimensions as the infrared radiators which were suspended at a similar height to simulate the shading effects of the radiator (Xue et al., 2011). In order to weaken the effects of strong wind on the experimental plots (especially the warming plots), we placed two steel windshields with 1.5-m height at the northern and western points 1.5 m from the center of all the plots. We designed this placement based on the dominant wind direction from the west. Finally, a permanent meteorological observation station with the height of 4 m was set in an open and flat area to automatically record the climate data outside the experimental plots. The experimental plots and the meteorological observation station were finalized in late June 2010 and were all fenced in by iron wires to protect from livestock.

Experimental plots were established for long-term warming and clipping experiments. We established additional temporary plots (unwarming and unclipping) that shared the similar vegetation height and cover with neighboring experimental plots to destructively harvest for vegetation aboveground biomass at a distance of 3–5 m outside the experimental plots. In these temporary plots, we designed quadrats with dimensions of 20 cm×20 cm or 30 cm×30 cm to measure vegetation height, cover and aboveground biomass, and species number. The survey was taken during the growing season of the alpine meadow, i.e. from May to September in 2011 and 2012. Five or ten quadrats were surveyed every month and eighty quadrats were obtained in total from the temporary plots. In the experimental plots, vegetation height and cover, and species number were directly measured from May to September in 2012 after 2 years of warming treatment and 1 year of clipping treatment. Because the temporary plots were delineated near the experimental plots, they possessed the similar habitat, vegetation height and cover as the experimental plots. Therefore, a stepwise regression equation (see data analyses) could be established between vegetation aboveground biomass, height and cover, and species number in the temporary plots so as to indirectly obtain the vegetation aboveground biomass in the experimental plots.

1.3 Measurements of temperature and moisture of air and soil

Temperature and moisture of air and soil were measured in the experimental plots beginning in July 2010. Temperature measurements included air temperature at 20-cm height (AT20) and surface temperature (ST0), as well as soil temperatures at the depths of 5 (ST5), 15 (ST15), 30 (ST30), 60 (ST60) and 100 cm (ST100). Moisture measurements included relative humidity at 20-cm height (RH20) and vapor pressure at 20-cm height (VP20), as well as soil moistures at the depths of 10 (SM10), 20 (SM20), 40 (SM40), 60 (SM60) and 100 cm (SM100). The data of W–CK are from July 2012 after 2 years of warming treatment, and the data of WC–CK and C–CK are from October 2012 after 1 year of clipping treatment.

The methods used to measure the above mentioned factors were as follows. Infrared radiation sensors (SI-111) measuring ST0 were suspended 80 cm above the soil surface at a 45° angle with the vertical direction and were pointed at the soil surface. Temperature and humidity probes (HMP45C) measuring air temperature, relative humidity and vapor pressure were placed above the plant canopy at 20 cm above the soil surface and were surrounded in a naturally ventilated louvered radiation shield. However, it is possible that the ventilation of the radiation shield was inadequate because wind speeds were reduced at canopy height via the windshields, and therefore, the heaters might have warmed the probes more than they warmed the air. Temperature probes (109SS-L) and FDR moisture probes (Envior SMART) were set in soils and measured soil temperatures (ST5, ST15, ST30, ST60 and ST100) and soil moistures (SM10, SM20, SM40, SM60 and SM100), respectively. These data were automatically recorded every 10 min by a data acquisition instrument (CR1000) and the daily average values were used in this study. These instruments (Campbell Scientific Inc, USA) were set up inside the experimental plots which did not include the meteorological observation station (Figs. 1b and c).

1.4 Measurements of vegetation properties

Vegetation properties in all plots (experimental and temporary plots) were measured by the following methods. Vegetation height was measured by using a ruler. The experimental plot (2 m×2 m) was divided evenly into 4 sections (1 m×1 m) and 10 height measurements from each section were taken at random. The temporary plot was not divided due to its small size (20 cm×20 cm or 30 cm×30 cm). Vegetation cover was measured by using a frame with the interior dimensions of 27 cm×27 cm. Then, a hard iron net (double grid) was employed according to the size of the frame with 100 grids, and each grid was measured 2.5 cm×2.5 cm. At each grid on the net, we recorded whether a grid touched bare ground, litter or a plant species. The proportion of absolute vegetation cover was calculated by the number of hits of litter or plants divided by 100. In the experimental plot, the vegetation cover of each section was measured, and then the mean vegetation cover of the 4 sections was calculated for each experimental plot. The vegetation cover of each temporary plot was measured directly once.

Vegetation aboveground biomass in the temporary plot was measured by cutting the aboveground part in an area of 20 cm×20 cm or 30 cm×30 cm. Vegetation belowground biomass in the experimental plot was sampled by using a soil corer with an internal diameter of 7 cm. One core was made at the depth of 0–50 cm at an interval of 10 cm (i.e. 0–10, 10–20, 20–30, 30–40 and 40–50 cm) in the middle of each experimental plot during the growing season (from May to September) in 2012. When the root and soil were sampled, they were immediately placed in a cooler and then transported to the laboratory. In the laboratory, the root and soil samples were air-dried and sieved by a mesh with 2-mm diameter to remove large particles from the fine soil; then, roots were separated from the root and soil samples and a 0.25-mm sieve was used to retrieve the fine roots. Live roots were distinguished from dead roots by their colors, consistency, and attached fine roots (Yang et al., 2009, 2010). The remaining soil was used to measure soil properties. The aboveground parts (plants and litters) and live roots were put into an oven to dry for 48 h at 75°C to a constant weight, and then the above- and belowground biomass were recorded. Height, abundance and frequency of all species were measured for each aluminum frame, and then Shannon-Wiener index (*H*), Simpson index (*H'*), Richness index (*R*) and Pielou index (*E*) (see data analyses) were calculated to study the responses of species diversity to warming and clipping.

1.5 Measurements of soil properties

In the experimental plot, we sampled soil at the depth of 0–50 cm during the growing season of the alpine meadow (from May to September 2012) to measure ammonium nitrogen (AN), nitrate nitrogen (NN), total nitrogen (TN), organic carbon (OC) and activated carbon (AC). In addition, soil microbial biomass carbon and nitrogen were sampled in the 0–10 cm soil layer in June and September 2012. The measuring methods followed to Blair et al. (1995) for AC (potassium permanganate oxidation), Li et al. (2012) for AN and NN (in a continuous flow analyzer), and Li et al. (2011a) for OC (in a VarioEL elemental analyzer), TN (in a VarioEL elemental analyzer) and microbial biomass (fumigation-extraction technique).

1.6 Data analysis

The stepwise regression equation was established via SPSS 16.0 (SPSS Inc. Chicago, USA) among vegetation aboveground biomass, height, cover, and species number in the temporary plots in 2011 and 2012. Then, vegetation aboveground biomass can be determined by Eq. 1.

$$ab=302.325c+15.908h-69.508 \quad (r^2=0.694, P<0.001, n=80). \quad (1)$$

Where *ab* is the vegetation aboveground biomass (g/m^2), *c* is the vegetation cover (fractional representation) and *h* is the vegetation height (cm).

In this study, we focused on the local and within-community vegetation characteristics under warming and clipping treatments in 2012, so the common indices of α-diversity were utilized, i.e. *H*, *H'*, *R* and *E*. These indices were calculated according to the following formulas (Agrawal and Gopal, 2013) in the Microsoft Office Excel 2007. First, the importance value (*IV*) was calculated according to the height, abundance and frequency of each species.

$$IV = \frac{rh + ra + rf}{3}. \quad (2)$$

Where *rh* is the relative height, *ra* is the relative abundance and *rf* is the relative frequency. Then, *H*, *H'*, *R* and *E* were calculated by Eqs. 4–7, respectively.

$$P_i = \frac{IV_i}{IV_{total}}, \quad (3)$$

$$H = -\sum_{i=1}^{S} P_i \ln(P_i), \quad (4)$$

$$H' = 1 - \sum_{i=1}^{S} P_i^2, \quad (5)$$

$$R = S, \quad (6)$$

$$E = \frac{H}{\ln(S)}. \quad (7)$$

Where *i* is the plant species *i*, P_i is the relative importance value of species *i* in each plot, and *S* is the total number of plant species in each plot.

No data transformation was done since data met the assumption of homogeneity of variances. The Origin 8.1 software (Origin Lab, Northampton, MA) was used to analyze the trends of plant and soil properties in response to warming and clipping. In the randomized block design, warming and clipping were treated as the fixed factors while block was treated as the random factor. In order to analyze the effects of warming, clipping and warming+clipping combination on plant and soil properties, we performed statistical significance tests via two-way ANOVAs with Tukey's multiple comparison tests at significance levels of $P<0.05$, $P<0.01$ and $P<0.001$ in the SPSS 16.0 (SPSS Inc. Chicago, USA). Soil microbial biomass and aboveground vegetation properties (vegetation height, cover and aboveground biomass, and species diversity) used for the ANOVA were from the replicated experimental plots in 2012. Other soil properties (AC, OC, AN, NN and TN) and vegetation belowground biomass for the ANOVA were from the growing season (from May to September) in 2012.

2 Results

2.1 Warming and clipping effects on moisture and temperature of air and soil

The differences of calculated W–CK, C–CK and WC–CK demonstrated the increased amplitudes from CK to W, C and WC, respectively (Table 1). In terms of soil moisture, the increased amplitudes of W–CK and WC–CK were smaller and negative at the depths of 10 and 20 cm, whereas they were greater and positive at the depths of 40, 60 and 100 cm. This indicates that the effects of W and WC on soil moisture were smaller in the upper soil layers than in the deeper soil layers. Moreover, W and WC significantly reduced relative humidity at 20-cm height ($P<0.05$). The increased amplitudes of C–CK were negative at all soil depths except for the 100-cm depth. Soil moisture showed a decreasing trend in the 0–60 cm soil layer and the differences of moisture were not significant between different soil depths. Air temperature at 20-cm height was significantly increased by 0.3°C in W treatment ($P<0.001$) and 0.35°C in C and WC treatments ($P<0.01$). Surface temperature was significantly increased by 1.66°C and 4.08°C in W ($P<0.05$) and WC ($P<0.001$) treatment, respectively. In W and WC treatments, soil temperature was increased significantly at the depths of 5, 15 and 30 cm ($P<0.05$) but slightly at the depths of 60 and 100 cm ($P>0.05$). This illustrated that the effects of W and WC on soil temperature were greater in the upper soil layers than in the deeper soil layers. Similar to the trend of soil moisture in the clipping plots, soil temperature also tended to decrease in the 0–60 cm soil layer in the clipping plots.

2.2 Warming and clipping effects on soil properties

The differences in AN and NN between different treatments were not statistically significant in all soil depths ($P>0.05$; Table 2). However, TN, OC and AC between different treatments had significant differences in the 30–40 ($P<0.05$) and 40–50 cm ($P<0.01$) soil layers (Table 2). TN and OC increased significantly under W treatment in the 20–30 cm soil layer and under C treatment in the 30–40 cm soil layer ($P<0.05$; Fig. 2). TN, OC and AC also significantly increased

Table 1 Effects of warming and clipping on moisture and temperature of air and soil

		Difference (mean±SE)		
		W–CK (July)	WC–CK (October)	C–CK (October)
Moisture (%)	RH20	–2.68±1.31*	–2.19±0.66*	–0.86±0.20n.s.
	SM10	–2.11±0.96ns	–0.73±1.51ns	–1.67±1.25n.s.
	SM20	–0.38±1.45ns	–0.41±1.64ns	–1.91±3.20n.s.
	SM40	3.32±2.26ns	2.38±1.86ns	–2.01±3.96n.s.
	SM60	7.42±3.51ns	1.30±1.66ns	–3.37±1.90n.s.
	SM100	6.75±4.17ns	3.56±5.49ns	1.57±5.96n.s.
Temperature (°C)	AT20	0.30±0.05***	0.35±0.06**	0.35±0.09**
	ST0	1.66±0.39*	4.08±0.96***	–0.64±0.41n.s.
	ST5	1.53±0.28**	1.83±0.26**	–0.69±0.42n.s.
	ST15	2.37±0.64**	1.75±0.30**	–0.49±0.29n.s.
	ST30	1.70±0.31*	1.07±1.90*	–0.25±0.28n.s.
	ST60	0.28±0.19ns	0.51±0.35ns	–0.77±0.25n.s.
	ST100	1.00±0.46ns	0.93±0.13ns	0.13±0.25n.s.

Note: CK is the control treatment, W is the warming treatment, C is the clipping treatment and WC is the warming+clipping combination treatment. W–CK, WC–CK and C–CK refer to the increments from CK to W, WC and C, respectively. RH20 refers to relative humidity at 20-cm height; SM10, SM20, SM40, SM60 and SM100 refer to soil moistures at the depths of 10, 20, 40, 60 and 100 cm, respectively; AT20 refers to air temperature at 20-cm height; ST0 refers to surface temperature; ST5, ST15, ST30, ST60 and ST100 refer to soil temperatures at the depths of 5, 15, 30, 60 and 100 cm, respectively. *, ** and *** indicate statistical significance at significance levels of $P<0.05$, $P<0.01$ and $P<0.001$, respectively. ns means no statistical significance ($P>0.05$). The degree of freedom is 3.

Table 2 Results (*F* values) of two-way ANOVA of soil properties between different treatments in different soil depths

Soil property	Soil depth (cm)				
	0–10	10–20	20–30	30–40	40–50
AN	0.585ns	0.182ns	0.267ns	0.007ns	0.650n.s.
NN	0.351ns	0.013ns	0.163ns	0.184ns	0.773n.s.
TN	0.007ns	0.278ns	1.938ns	4.608*	21.798***
OC	0.233ns	0.161ns	1.911ns	3.331*	18.888***
AC	0.281ns	0.184ns	0.217ns	3.197*	10.123**

Note: AN, ammonium nitrogen; NN, nitrate nitrogen; TN, total nitrogen; OC, organic carbon; AC, activated carbon. The degree of freedom is 3.

under W, C and WC treatments in the 40–50 cm soil layer ($P<0.05$). These results indicated that warming and clipping had greater effects on TN, OC and AC in the deeper soil layers. The increase ratios of soil properties from CK to W, C and WC were applied to further demonstrate the effects of W, C and WC on soil properties in different soil depths. No consistent trends with soil depths were observed in the increase ratios of AN and NN from CK to W, C and WC (Fig. 3). However, increasing trends with soil depths were observed in the increase ratios of TN, OC and AC from CK to W, C and WC, and significant differences between different treatments were reached in the 30–50 cm soil layer with greater effects from the C treatment than the WC treatment (Fig. 3).

2.3 Warming and clipping effects on aboveground vegetation properties

During the growing season, the effects of warming and clipping on aboveground vegetation properties showed single peak curves for consecutive months with the maximum values occurring mostly in July (Fig. 4). In July, the differences of vegetation height and aboveground biomass were statistically significant between W and C (W>C; $P<0.05$). For vegetation height, it was significant between CK and W (CK<W), WC and C (WC>C), as well as W and C (W>C) in June ($P<0.05$). For aboveground biomass, significant differences existed between CK and C (CK>C), WC and W (WC<W), as well as W and C

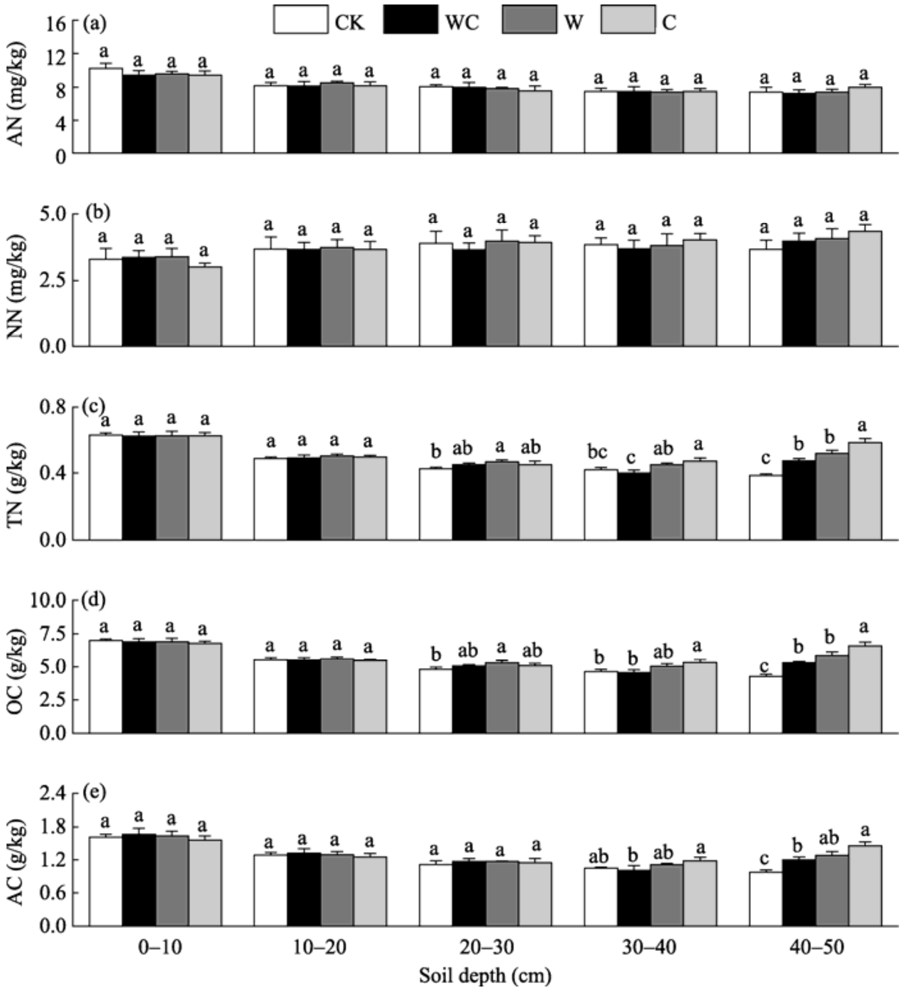

Fig. 2 Effects of warming and clipping on soil properties in different soil layers. CK is the control treatment, W is the warming treatment, C is the clipping treatment and WC is the warming+clipping combination treatment. AN, ammonium nitrogen; NN, nitrate nitrogen; TN, total nitrogen; OC, organic carbon; AC, activated carbon. Identical letters indicate non-significant differences between different treatments (P>0.05), whereas different letters indicate significant differences between different treatments (P<0.05). The error bars indicate standard error.

(W>C) in May and June (P<0.05). For species number, a significant difference was reached between CK and WC (CK<WC) as well as WC and C (WC>C) in May (P<0.05). However, all of the aboveground vegetation properties were not different significantly between different treatments in August and September (P>0.05), and vegetation cover had no significant differences between different treatments during the whole growing season (P>0.05). The effects of W, C and WC on vegetation growth were enhanced first and then weakened with passing months.

2.4 Warming and clipping effects on species diversity

There were no obvious trends for species diversity between different treatments during the growing season in the alpine meadow (Fig. 5). H, H' and R values were slightly greater in W and C treatments than in CK and WC treatments in all months except for May. E value was slightly greater in W treatment than in other treatments in all months except for June. The indices of species diversity were slightly greater in WC treatment than in CK treatment in May and June, whereas they were slightly smaller in WC treatment than in CK treatment in August and September. This suggested that the effects of WC on species diversity were weakened in the late growing season. However, the results from the ANOVA of all indices of species diversity were not statistically significant (P>0.05), demonstrating that species diversity was not sensitive to the short-term effects of W, C and WC in the alpine meadow.

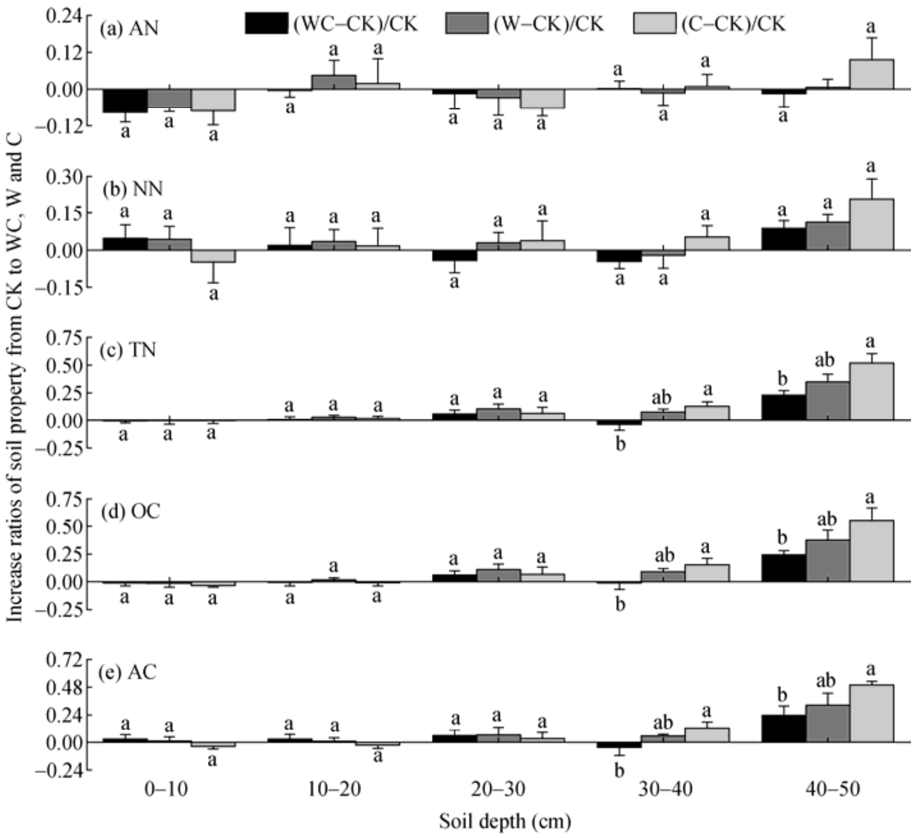

Fig. 3 The increase ratios of soil properties from CK to W, C and WC in different soil layers. WC–CK, W–CK and C–CK refer to the increments from CK to WC, W and C, respectively. The error bars indicate standard error.

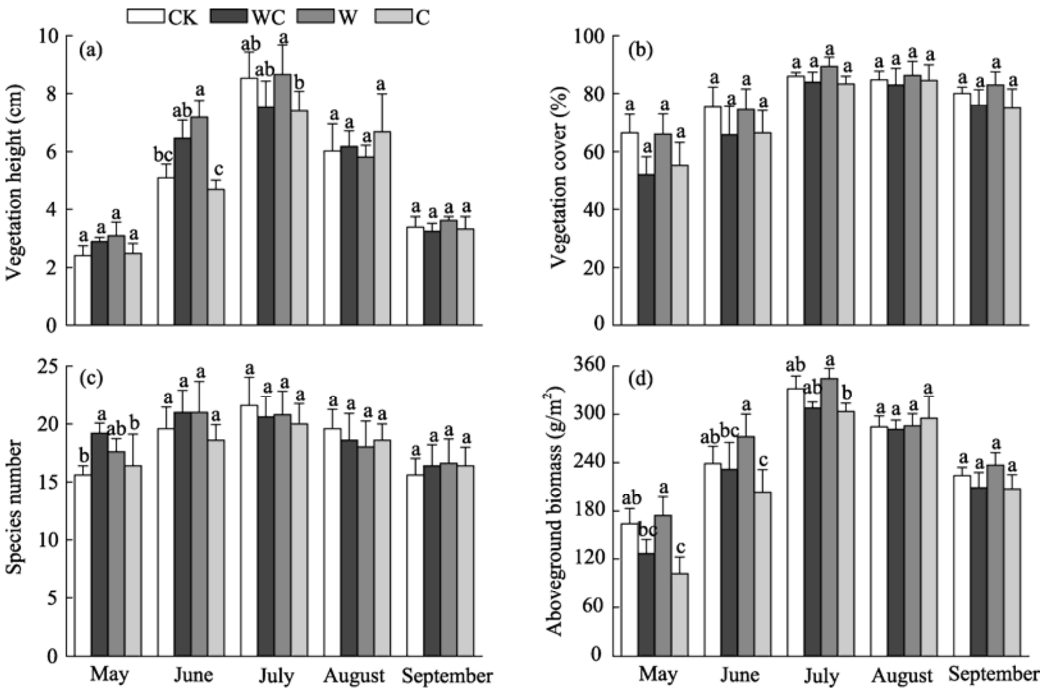

Fig. 4 Effects of warming and clipping on aboveground vegetation properties in the growing season (from May to September) of 2012. The error bars indicate standard error.

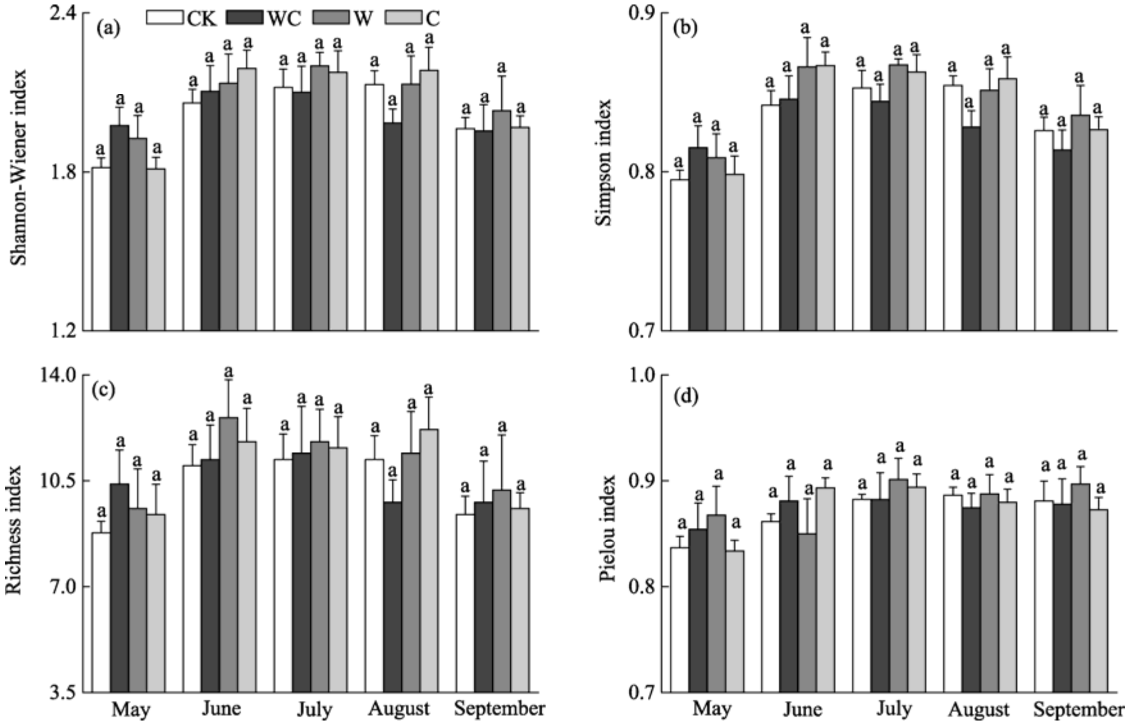

Fig. 5 Effects of warming and clipping on species diversity in the growing season (from May to September) of 2012. The error bars indicate standard error.

2.5 Warming and clipping effects on vegetation belowground biomass

Effects of warming and clipping on belowground biomass exhibited a tendency to decrease with increasing soil depths, which indicated that the roots were mainly distributed in the upper soil layers (Fig. 6a). Table 3 shows that the roots were mainly concentrated in the 0–10 cm soil layer with a biomass percentage of 46.54%, while the biomass percentage was only 4.53% in the 40–50 cm soil layer. Belowground biomass was slightly more abundant in the 0–20 cm soil layer in C treatment than in other treatments. However, it was larger in the 30–50 cm soil layer in W and WC treatments than in C treatment. This suggested that C had greater effects on belowground biomass in the upper soil layers while W had greater effects in the deeper soil layers. The increase percents of belowground biomass from CK to WC, W and C manifested an increasing trend with soil depths (Fig. 6b). In the 0–20, 20–30 and 30–50 cm soil layers, the increase percents of belowground biomass were 8.6%, 47.3% and 91.7% from CK to W, respectively; 20.6%, 47.7% and 53.8% from CK to C, respectively; and –2.4%, 26.0% and 85.5% from CK to WC, respectively. This trend showed that belowground biomass may shift to the deeper soil layers in W, C and WC treatments.

3 Discussion

3.1 Warming effects of infrared radiators

Warming experiments are valuable for studying the relationship between global warming and terrestrial ecosystems. They are helpful for explaining the inner mechanisms of ecosystems responding and adapting to climate changes and providing key parameter estimations for the predication and verification of models (Dunne et al., 2004). However, the responses of terrestrial ecosystems to warming are different due to the differences of temperature control devices, technologies and warming mechanisms (Niu et al., 2007).

In our experiments, warming decreased relative humidity and soil moisture in the 0–20 cm soil layer whereas increased air temperature and soil temperature in the 0–30 cm soil layer (Table 1). This is consistent with the results of Xiong et al. (2010) from a mountain ecosystem where warming decreased relative humidity and soil moisture but increased air temperature and soil temperature at the depth of 0–5 cm.

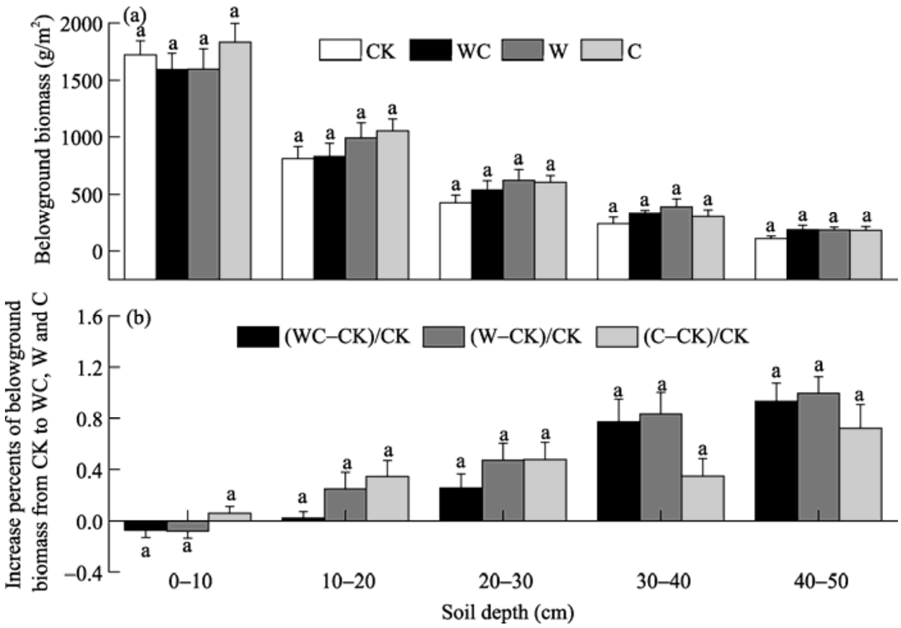

Fig. 6 Effects of warming and clipping on vegetation below ground biomass (a) and the increase percents of belowground biomass from CK to WC, W and C (b) in different soil layers. The error bars indicate standard error.

Table 3 Percentage of vegetation belowground biomass at different soil depths

Soil depth (cm)	Treatment				Mean (%)
	CK (%)	W (%)	C (%)	WC (%)	
0–10	52.05	42.17	46.08	45.85	46.54
10–20	24.49	26.20	26.49	23.85	25.26
20–30	12.92	16.47	15.22	15.43	15.01
30–40	7.28	10.29	7.65	9.45	8.67
40–50	3.26	4.87	4.56	5.42	4.53

The amplitudes of soil moisture and temperature under warming treatment were smaller in our study compared to the results of Xiong et al. (2010). This is potentially because the power of the heaters in our study was less than that in the study of Xiong et al. (2010). Kimball (2005) demonstrated that the amplitudes of warming effect on soil temperature were 1.6°C–4.1°C on average during the growing seasons of mountain, swamp and grassland ecosystems when heaters were 1,500 W and 1.5 m above ground. However, there were no consistent conclusions on whether air temperature was modified by infrared radiators. Nijs et al. (1996), Wan et al. (2002) and Kimball (2005) concluded that infrared radiators raised air temperature, but Harte et al. (1995) reported the opposite. Actually, the warming effects of infrared radiators were correlated with ecosystem type, season, power and position of heaters, as well as other environmental factors (e.g. the wind speed). For example, in the tallgrass prairie of the Oklahoma State of USA where the wind speed was small and the canopy was high and dense, infrared radiators increased the daily maximum and minimum temperatures of canopy (Wan et al., 2002); in a temperate typical steppe of North China where the wind speed was large and the canopy was low and sparse, infrared radiators raised soil temperature but did not modify air temperature (Niu et al., 2007).

In the alpine meadow of the QTP, the warming effects of infrared radiators on microclimate were different with open top chambers (OTCs). In a study by Klein et al. (2005), OTCs consistently elevated the mean daily air temperature, the diurnal air temperature range, and the mean daily soil temperature and moisture. Likewise, Li et al. (2011a) documented that the air temperature inside the OTCs was raised in the alpine meadow during the growing season. With temperature enhancement, soil temperature in the upper soil layer was passively increased, but soil moisture at the 20-cm depth showed non-significant decline (Li et al., 2011a). In our study, soil moisture also decreased non-significantly in the 0–20 cm soil layer (Table 1). These contrasting microclimate effects between active infrared radiator and passive OTC manipulations might be attributed to the different mechanisms driving the temperature changes. Klein et al. (2005) believed that there was an insufficient amount of gas in the path from the radiators to the ground for the air to absorb a significant amount of infrared radiation; with OTCs, the temperature gradient was not strong enough to produce a significant heat flux into the soil, especially in the presence of high biomass or litter cover. Thus, comparing ecosystem responses from studies using similar or different warming methods is dependent on whether the variable of interest was most sensitive to air temperature, soil temperature or soil moisture.

3.2 Warming and clipping effects on plant properties

Global warming not only directly affects terrestrial plants and ecosystems by raising temperature but also indirectly influences them by modifying soil moisture, litter decomposition, soil nitrogen mineralization and availability, species composition and plant phenology (Shaver et al., 2000; Wan et al., 2005). In our study, W and WC increased vegetation height and species number, respectively, but vegetation cover was not sensitive to W (Fig. 4). Moreover, W tended to transfer belowground biomass from the upper to deeper soil layers (Fig. 6).

The results were different from studies on the responses of vegetation growth and biomass to warming. Some studies showed that warming could reduce biomass production by decreasing soil moisture. For example, Melillo et al. (1993) and de Boeck et al. (2007) believed that the decrease of soil moisture after warming was able to induce the decreases of vegetation net primary productivity and the above- and belowground biomass. However, other studies also showed that warming could increase biomass production by improving plant photosynthetic capacity or enhancing plant nutrition absorption. For example, elevated temperature could improve plant vegetative growth and physiological activity in polar and high mountain regions (Danby and Hik, 2007). In our study, belowground biomass was mainly distributed in the upper soil layers, but the biomass tended to transfer to the deeper soil layers after warming (Table 3; Fig. 6). This phenomenon was also observed in the study by Li et al. (2011b), who found that after large amplitude warming the belowground biomass began to transfer to deep root zones due to the more obvious restriction of soil moisture. The soil moisture tended to transfer to the deeper soil layers in W and WC treatments in our study (Table 1). Increasing soil moisture in the deeper soil layers likely came from the downward water movement under the force of gravity due to the low water-holding capacity of coarse-textured sandy soils. Similarly, Yang et al. (2003) reported that the soil moisture increased with depths in certain soil layers (40, 80 and 130 cm) in the Tibetan Plateau. This moisture increase was related to the freezing/thawing processes and the temperature distribution. Therefore, we concluded that the effects of warming on plant growth and biomass are complex, and the downward movement of vegetation belowground biomass may be related to the downward movement of soil moisture.

The responses of plants and ecosystems to warming differed on short-term and long-term scales (Chapin et al., 1995). With a 5-week warming experiment, Zhang and Welker (1996) concluded that the total biomass of the plant community was not significantly affected during the short-term warming. The results of 2-year warming experiment in our study indicated that warming promoted vegetation height and a combination of warming and clipping increased plant species number (Fig 4). Similarly, results from 3-year warming experiments found that vegetation growth and biomass were enhanced in high-altitude regions (Chapin et al., 1995; Arft et al., 1999). After a 5-year warming experiment in a mid-latitude alpine ecosystem, Kudo and Suzuki (2003) determined that the artificial warming accelerated the growth of a few restricted species and led to a change in vegetation structure. It was inferred that plants and plant community have lagged the effects on long-term resource feedback, growth and completion; the long-term responses of plants and plant community to warming may be limited by soil moisture and nutrients, which cause differences between short-term and long-term responses (Niu et al., 2007).

Stresses from human activities are causing profound effects on the Earth system, including loss of species diversity (Sala et al., 2000). An example is climate warming, which is superimposed on other global changes (Parmesan and Yohe, 2003; Root et al., 2003; Thomas et al., 2004). In our study, W and C tended to improve species diversity and WC increased species number (Fig. 5). This is because more species moved into the WC plots from the surrounding species pool and species numbers in the CK plots declined due to the increasing dominance of fewer species (Klein et al., 2004). Our results regarding species diversity confirmed the hypotheses of Klein et al. (2004), which suggested that combined warming and grazing would result in an increase in species richness similar to that experienced under the clipping alone scenario. Yang et al. (2012) concluded that clipping had significant effects on increasing the species richness but little effects on aboveground biomass. However, in our study, WC increased species number while C reduced aboveground biomass due to the decreasing trend of soil moisture and temperature (Table 1; Fig. 4). Similarly, Gu et al. (2011) reported that clipping decreased primary productivity of cultivated meadows and increased the species abundance of *Elymus nutans*. Wang et al. (2013) also found that clipping increased species diversity and decreased aboveground productivity. Thus, the effects of clipping on species diversity and biomass were not only related to the time, frequency and intensity of clipping but also related to the species types, soil nutrients and plant compensation (Belsky, 1993; Han et al., 2007).

3.3 Warming and clipping effects on soil properties

Changes in climate have been predicted to stimulate the release of a substantial portion of soil carbon by increasing soil respiration, thereby turning alpine ecosystems from a net sink to a net source of atmospheric CO_2 (Tarnocai, 1999; Knorr et al., 2005; Biasi et al., 2008). In our study, TN, OC and AC had a tendency to increase with soil depths increasing, and significant differences between different treatments existed in the 30–50 cm soil layer (Table 2; Fig. 3). We concluded that warming and clipping can move soil TN, OC and AC from the upper to deeper soil layers. In a study by Li et al. (2011a), temperature increases resulted in the alpine meadow acting as a net carbon source and further warming intensified this process. We confirmed that the downward shift of soil AC, OC and TN might suppress the emission of atmospheric CO_2 to the air as a result of warming and clipping. This phenomenon might develop a negative feedback to the climate warming in the alpine meadow of the QTP. This conclusion was the same as that by Shi et al. (2012), who concluded that the inhibition of CO_2 and N_2O emission rates by warming and drying would intensify if the combined effects of these climatic factors tended to persist in the eastern Tibetan Plateau.

In our study, the alpine ecosystems were in permafrost habitats where soil and vegetation were greatly influenced by the permafrost. With the onset of the growing season, the permafrost melted and the active soil layers became thicker, and thus the soil OC and other nutrients could infiltrate into the deeper layers with soil water, and the allocation proportion of soil OC appeared to transfer from the upper to deeper soil layers (Li et al., 2011a). In addition, we concluded that W, C and WC transferred vegetation belowground biomass from the upper to deeper soil layers (Fig. 6). We inferred that the downward shift of soil moisture induced drought in the upper soil layers which led to the transfer of drought-affected plant belowground biomass to the deeper soil layers for more water, and thus resulted in changes in the distributions of soil OC and TN.

Soil microbial activity in cold-climate ecosystems is limited by low temperature conditions; in opposite, when the temperature increased, soil microorganisms could decompose the organic matter in litter and soil more rapidly, resulting in a decrease in the amount of both litter and soil organic matter (Emmett et al., 2004). Li et al. (2011a) believed that the litter might prevent the cold temperature from directly affecting the soil by acting as a thermal insulation and a water conservation tool. In our study, clipping seemed to decrease soil moisture and temperature in the 0–60 cm soil layer (Table 1). This indirectly indicated that the vegetation (including plants and litters) covered the effects of thermal insulation and water conservation to the soil of the alpine meadow. By sampling soil in the 0–10 cm soil layer to measure soil microbial biomass in June and September, we found that the microbial biomass was slightly smaller in the control plots than in the treated plots in June (Fig. 7). This pattern was reversed in September but neither of the effects were statistically significant (*P*>0.05). All differences in soil properties between different treatments were not significant in the 0–20 cm soil layer (*P*>0.05; Fig. 2). Therefore, we inferred that soil microorganisms were not sensitive to warming and clipping at the short-term scale due to the extreme environment in the alpine meadow, non-significantly transforming soil properties in the upper soil layers in our 2-year warming and 1-year clipping experiments.

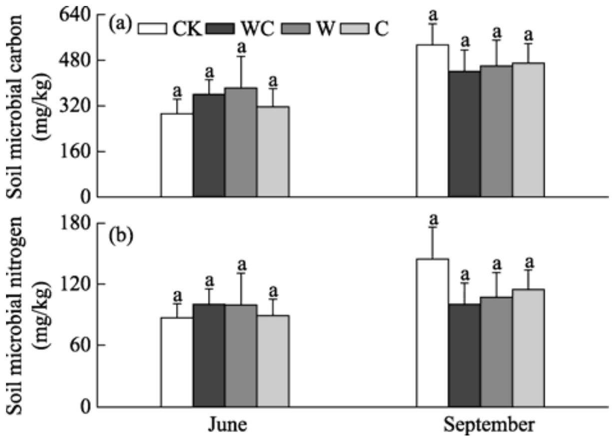

Fig. 7 Effects of warming and clipping on soil microbial biomass in June and September 2012. The error bars indicate standard error.

4 Conclusions

This study presented the results from an experimental warming and clipping experiment in an alpine meadow of the QTP. In the early growing season, warming increased vegetation height; clipping decreased aboveground biomass; and the combined warming and clipping increased species number. However, species diversity and soil microorganisms were not sensitive to the short-term effects of warming and clipping probably due to the low temperature environment in the alpine meadow. This study further verified the earlier reports that climate warming and overgrazing could affect the distributions of biomass and nutrients in soils. The downward shift of soil moisture, driven by increased radiation in the surface, was probably responsible for the migration of belowground biomass and soil nutrients to the deeper soil layers. These results are valuable for fueling prediction models and the comparisons with similar studies in different regions. Although there are the uncertainties due to the differences in instrumentation and artificial simulation of climate warming, the global warming is likely to change the soil properties and conditions for plant growth in permafrost environments.

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