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Strong stoichiometric resilience after litter manipulation experiments; a case study in a Chinese grassland

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Abstract

Global climate change has generally increased net primary production which leads to increasing litter inputs. Therefore assessing the impacts of increasing litter inputs on soil nutrients, plant growth and ecological Carbon (C) : nitrogen (N) : phosphorus (P) stoichiometry is critical for an understanding of C, N and P cycling and their feedback processes to climate change. In this study, we added plant litter to the 10–20 cm subsoil layer under a steppe community at rates equivalent to 0, 150, 300, 600 and 1200 g (dry mass) m^{-2} and measured the resulting C, N and P content of different pools (above and below ground plant biomass, litter, microbial biomass). High litter addition (120 % of the annual litter inputs) significantly increased soil inorganic N and available P, aboveground biomass, belowground biomass and litter. Nevertheless small litter additions, which are more realistic compared to the future predictions, had no effect on the variables examined. Our results suggest that while very high litter addition can strongly affect C : N : P stoichiometry, the grassland studied here is quite resilient to more realistic inputs in terms of stoichiometric functioning. This result highlights the complexity of the ecosystem's response to climate change.

1 Introduction

Ecological stoichiometry is the study of the balance of multiple chemical elements in ecological interactions (Elser et al., 2000, 2010; Elser and Hamilton, 2007). Carbon (C), nitrogen (N) and phosphorus (P) are key elements in terrestrial ecosystems (Daufresne and Loreau, 2001; Elser et al., 2010; Hessen et al., 2013), and the C : N : P stoichiometry reflects complex interactions between evolutionary processes coupled to phenotypic plasticity. These complex interactions are, at least partially, controlled by patterns of element supply from the environment (Hessen et al., 2004). Ecological stoichiometry provides a valuable approach in assessing possible C, N and P cycling (Hessen et al., 2013). Over the past three decades ecological stoichiometry has ex-

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panded greatly (Hessen et al., 2013), and a lot of studies have concentrated on understanding the variation in plant C, N and P concentrations among and within species (Schmidt et al., 1997; Aerts and Chapin, 2000; Güsewell and Koerselman, 2002; Augustine et al., 2003; Güsewell 2004; Frank, 2008). However, relationships among soil nutrient availability, plant growth and ecological C : N : P stoichiometry of plants, litter, soil and soil microbes under global climate change in terrestrial ecosystems is not well understood.

Litter is an important nutrient pool which strongly alters nutrient availability and therefore affects cycling of C, N, and P in terrestrial ecosystems with significant feedback on plant growth and on climate (Hungate et al., 2003; Subke et al., 2004; Ryan and Law, 2005; Sayer, 2006; Cornelissen et al., 2007; Villalobos-Vega et al., 2011). The anticipated doubling of the atmospheric CO_2 concentration within the next 100 years (Houghton et al., 2001) due to continued anthropogenic carbon emissions is generally predicted to increase net primary production of most terrestrial ecosystems. Although uncertainty exists in the magnitude of the changes (e.g. Campbell et al., 1991; Arnone and Körner, 1995; Gill et al., 2002; Davidson and Janssens, 2006), an increase in net primary production will simultaneously increase litter inputs to soils. In past decades, the effects of litter addition on content of plant growth, and soil C content, cycling and priming effects have been reported and confirmed (eg. Sulzman et al., 2005; Guenet et al., 2010; Jin et al., 2010; Sayer et al., 2011; Villalobos-Vega et al., 2011; Ma et al., 2012). However, the impacts of litter addition on soil nutrients, plant growth and ecological C : N : P stoichiometry of plants, litter, soil and soil microbes remain highly uncertain.

Grassland is one of the most important global terrestrial ecosystems, covering about 25 % of the global terrestrial area and 40 % of the land area in China (Kang et al., 2006). The semi-arid and temperate grasslands of northern China account for about 78 % of the national grassland area, where the native vegetation is predominantly characterized by the abundance of grass species such as *Stipa* spp. and *Leymus chinensis* (Trin) Tzvel., with *Stipa krylovii* Roshev. being well-represented as one of the major steppe community types (Zhao et al., 2003). Plant recruitment, growth and nutrient cycling of

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the region often are limited by soil water, nitrogen and phosphorus, and the regional soil fertility and productivity are maintained by recycling of nutrients through plant litter decomposition as an essential mechanism (Liu et al., 2006) with little natural nitrogen deposition. A better understanding of the effects of litter addition on plant growth and ecological C : N : P stoichiometry of plants, litter, soil and soil microbes could help to reduce uncertainties in our predictions of C, N and P balance as well as cycling, and structure and function in grassland ecosystems under global climate change.

We conducted a field experiment in which we artificially added litter inputs to subsoils (i.e. 10–20 cm) under a *S. krylovii* steppe community in a temperate grassland of northern China to assess the effects on soil inorganic N and available P, plant growth, litter, C, N and P pools and the C : N : P stoichiometry of plant, litter, soil and soil microbes. The primary objectives of our study were:

1. To determine whether litter addition would increase soil inorganic N and available P and thereby enhance soil nutrient availability for plant growth.
2. To determine whether litter addition would affect plant growth, litter, and the C, N, P pools and the C : N : P stoichiometry of plants, litter, soil and soil microbes.
3. To better understand the relationships among soil nutrient availability, plant growth and C : N : P stoichiometry of plants, litter, soil and soil microbes under different treatments of litter addition.

We assumed that litter additions could increase nutrients release through a priming effect provoking an increase in plant biomass. Nevertheless, regarding the complexity of the mechanisms implied, we expected a non-linear relationship between litter additions and the plant biomass response. The objective of this study was to estimate such relationship in the temperate grassland of northern China.

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2 Materials and methods

2.1 Study site

This study was conducted at a field site of the Duolun Restoration Ecology Experimentation and Demonstration Station of the Institute of Botany, the Chinese Academy of Sciences, located in south-eastern Inner Mongolia, northern China (Latitude 42°02′ N, longitude 116°16′ E, elevation 1350 m a.s.l.). The long-term mean annual temperature at the site is 2.1 °C, with monthly mean temperatures ranging from −17.5 °C in January to 18.9 °C in July. Mean annual precipitation is about 380 mm, with 90 % of the precipitation falling in the growing season between May and October.

Total precipitation was 196, 369, and 187 mm in 2009, 2010 and 2011, respectively, and the precipitation between 1 May and 30 September was 164, 314, and 159 mm in 2009, 2010 and 2011, respectively. Mean annual air temperature was 2.96, 2.43 and 2.11 °C in 2009, 2010 and 2011, respectively (Fig. 1).

Soil type was classified as chestnut soil (Chinese classification) or Calcic Luvisols according to the FAO Classification (FAO, 1974). Soils are composed of 63 % sand, 20 % silt, and 17 % clay (Niu et al., 2010), with concentrations of soil organic C, N and P of 1.55 %, 0.17 % and 0.03 %, respectively. The C : N : P ratio of soil is about 51.7 : 5.7 : 1. Mean bulk density is 1.31 g cm^{-3}, and the soil pH is 7.7. The native vegetation is represented by typical steppe communities, where *Stipakrylovii* Roshev., a perennial bunchgrass, dominates. Other common species include *Leymus chinensis* (Trin) Tzvel, *Cleistogenes squarrosa* (Trin.) Keng, *Agropyroncristatum* (L.) Gaertner, *Artemisia frigid* Willd., *Potentillaacaulis* L., and *Carexduriuscula* CA Mey. Total vegetation cover was relatively sparse, ranging from 85 to 90 %. Annual plant biomass production at the site was ca. 1000 g (dry mass) m^{-2} $year^{-1}$ (Li et al., 2004).

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2.2 Experimental design

On 1 October 2008, we established twenty-five 2 m × 1 m treatment plots. Treatments involved the addition of fresh organic matter to the soil in the 10–20 cm soil layer, at rates equivalent to 0 (control treatment), 150, 300, 600 and 1200 g (dry mass) m^{-2}, with all arranged as a complete randomized-block design including five replications. These additions correspond to litter input increases of 15, 30, 60 and 120 % respectively. It must be noted that net primary production is assumed to increase between 10 and 60 % at the end of the 21st century (Arora and Boer, 2014; Todd-Brown et al., 2014), which means that the first three addition amounts are very realistic. The applied fresh organic matter consisted of senescent above-ground tissues from an abundance-weighted mix of plant species occurring at the site. For this purpose, senescent plant biomass was harvested from an adjacent field, air-dried, fragmented, and passed through a sieve with a 2 mm mesh size. This plant litter had a C concentration of 400.8 mg g^{-1} (standard error (SE) = 1.3 mg g^{-1}, $n = 5$), an N concentration of 9.72 mg g^{-1} (SE = 0.04 mg g^{-1}, $n = 5$), and a P concentration of 0.768 mg g^{-1} (SE = 0.01 mg g^{-1}, $n = 5$), corresponding to 41.3, 521.9 and 12.6 for C : N, C : P and N : P ratio, respectively. Lignin concentration in litter was 190.9 mg g^{-1} (SE = 0.9 mg g^{-1}, $n = 5$).

Adding litter to the uppermost soil layers is impossible without drastically disturbing the soils. To minimize disturbance, we carefully removed the top 10 cm soil blocks, containing 60 % of the root system (Zhou et al., 2007), with a sharp spade, keeping the soil blocks and vegetation as intact as possible. The soil underneath was loosened to a depth of 20 cm, and a predetermined quantity of plant litter was mixed homogeneously with the soil in the 10–20 cm layer. The surface soil blocks were then placed back into their original positions. Remaining fissures between the soil blocks were carefully filled with soil from the 0–10 cm soil layer and gently compacted by hand. To create consistent soil disturbance across treatments, the plots with zero litter addition were processed in the same manner as the plots that received plant litter.

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2.3 Field sampling and measurements

Field sampling of above-ground biomass, root biomass, litter and soils was conducted from 1 to 3 August in 2009, 2010 and 2011.

Above-ground biomass and litter were simultaneously sampled in each plot using the 1 m × 0.3 m quadrat. Live and dead above-ground biomass were measured by clip-harvesting and dead parts were combined with the litter. Below-ground biomass in the 0–20 cm soil layer was determined by soil coring to a depth of 20 cm using a cylindrical root sampler (8 cm inner diameter). Roots were manually removed from the soil samples. All samples of above-ground biomass, below-ground biomass and litter were oven-dried at 65 °C to constant mass.

Soils were sampled in three different points of each plot within the 0–20 cm soil layer with a soil sampler of 3 cm inner diameter. The samples were pooled and mixed to produce one composite sample. The fresh samples were sieved using a 2 mm sieve. Visible plant tissues were removed, and air dried in the shade. Additionally, soil bulk densities of the 0–20 cm soil layers of each plot were determined concurrently with soil sampling by a special coring device (volume = 100.0 mL).

In the lab, chemical analysis was performed on samples of above-ground biomass, below-ground biomass, litter and soil in the 0–20 cm soil layer for organic C and total N using an automatic elemental analyzerVario EL III (Elementar Analysensysteme Comp., Hanau, Germany). Total P was determined by the H_2SO_4-$HClO_4$ fusion method (Sparks et al., 1996). Soil microbial C and N biomass was measured by the fumigation-extraction method (Vance et al., 1987). Briefly, the fresh soil samples were adjusted to approximate 60 % of water holding capacity and then incubated for one week in dark at 25 °C. Next 20 g (dry weight equivalent) of fumigated with CH_3Cl for 24 h and non-fumigated soil samples were extracted with 0.5 M K_2SO_4. The extracts were filtered through 0.45 µm filters and the extractable C and N was analysed by dichromate and Kjeldahl digestion as described by Lovell et al. (1995). Soil microbial C and N biomass was calculated as the difference in extractable C and N contents between the fumigated

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and the unfumigated samples using conversion factors (k_{ec} and k_{en}) of 0.38 and 0.45 (Lovell et al., 1995), respectively. Mass ratios of C : N, C : P and N : P in plant, litter and soil samples and of C : N in soil microbial biomass were calculated and used to facilitate comparisons with previous studies (He et al., 2008). Additionally, 10 g dry soil samples in the 0–20 cm layer were extracted with 50 mL of 2 M KCl. Inorganic N (NH_4^+-N and NO_3^--N) of the filtered extracts of soils in the 0–20 cm soil layer were determined using a flow injection autoanalyzer (FIAstar 5000 Analyzer, Foss Tecator, Denmark). Available soil P in soils in the 0–20 cm soil layers was measured using the Olsen method (Olsen et al., 1954).

2.4 Statistical analysis

Data management and statistical analyses were performed using the SPSS software package (SPSS, Chicago, IL, USA). Two-way analysis of variance (ANOVA) was used to detect the effects of litter addition and year (sampling time) on soil inorganic N and available P, aboveground and belowground biomass, total biomass, litter, the C, N, P pools and C : N : P stoichiometry of plant, litter and soil, and C and N pools and C : N of soil microbial biomass. Multiple comparisons were also performed to permit separation of effect means using the Duncan test at a significance level of $P < 0.05$.

3 Results

3.1 Soil inorganic N and available P

Litter addition significantly enhanced soil inorganic N and available P in 2009, 2010 and 2011 ($P < 0.05$; Fig. 2), and there were significant differences in soil inorganic N and available P among different years ($P < 0.01$; Fig. 2). Nevertheless, these effects were mainly due to the highest input treatments. Indeed, for the years 2009 and 2011, only the highest litter inputs, corresponding to 1200 g DM m^{-2}, induced significant highest inorganic N and available P contents in soils. For the year 2010, the two highest litter

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inputs treatments induced significant increases of the inorganic N and available P contents in soils. There were no significant interactions between litter addition and year for soil inorganic N and available P ($P > 0.05$; Fig. 2).

3.2 Plant biomass and allocation and litter

Significant effects of litter addition were observed for above-ground biomass and litter in 2009, 2010 and 2011 as well as for below-ground biomass and total biomass in 2010 and 2011 ($P < 0.05$; Fig. 3). Moreover, the ratio of belowground biomass to aboveground biomass in 2010 was significantly affected by litter inputs ($P < 0.05$; Fig. 4). However, it must be noted that the Duncan post hoc test showed that the effects described above are mainly due the highest input treatments, which is generally the sole treatment significantly different from the control when significant effects were detected by the two-ways ANOVA. The highest litter addition increased biomass in all the compartments except for the belowground biomass and the total biomass in 2009. Furthermore, the highest litter addition treatment decrease the ratio of belowground biomass to aboveground biomass in 2010, while others treatments produced no effect. There were no significant interactions between litter addition and year for on aboveground biomass, belowground biomass, total biomass, litter and ratio of belowground biomass to aboveground biomass ($P > 0.05$; Figs. 3 and 4).

3.3 C, N and P pools in plants, litter, soil and soil microbial biomass

Litter addition did not affect significantly the C, N and P pools of aboveground biomass and litter as well as soil C pools in 2009, 2010 and 2011 for all but the highest treatment. The C, N and P pools of belowground biomass in 2010 and 2011, and the C and N pools of soil microbial biomass were also not affected by litter addition except for the highest treatment ($P < 0.05$; Fig. 5). There were no significant differences in the C, N and P pools of aboveground biomass, the N and P pools of litter, the C pool of soil and the C and N pools of soil microbial biomass among different years for all treatment but

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the highest treatment ($P < 0.05$; Fig. 5). There were no significant interactions between litter addition and year on the C, N and P pools of aboveground biomass, belowground biomass, litter, soil and the C and N pools of soil microbial biomass ($P > 0.05$; Fig. 5).

3.4 C, N and P stoichiometry in plant, litter, soil and soil microbe

Litter addition did not significantly modified C : N and C : P ratios of aboveground biomass and litter in 2010 and 2011 and the C : N ratio of soil microbial biomass in 2009, 2010 and 2011 for all but the highest treatment where a decrease was observed. The highest treatment significantly increased soil C : N and C : P ratios in 2009, 2010 and 2011 ($P < 0.05$; Fig. 6). But no effect was detected for the other treatments. Litter addition did not affect N : P of aboveground biomass, belowground biomass, litter and soil ($P > 0.05$; Fig. 6). There was significant difference in the C : N of aboveground biomass and soil microbial biomass among different years ($P < 0.05$; Fig. 6). There were no significant interactions between litter addition and year in effects on the C : N : P stoichiometry of aboveground biomass, belowground biomass, litter, soil and soil microbial biomass ($P > 0.05$; Fig. 6).

4 Discussion

4.1 Effect on litter additions on plant growth

Plant growth is limited by the rate of resource supply, for example nutrients and water (Enquist et al., 2003). Furthermore, soil N and P are the main nutrient sources for plant growth (Elser et al., 2007; Vitousek et al., 2010; Alvarez-Clare et al., 2013; Fageria et al., 2013). Litter amendments we did were a substantial supply of nutrients and must released nutrients during decomposition. It was partially the case since the availability of N and P, which represent soil nutrient availability to plant growth (Padgett et al., 1999; Zhang et al., 2005; Yano, 2013), were modified for the two highest inputs in 2010 and for the highest input in 2009 and 2011. Additionally, high litter addition also greatly increased soil microbial biomass C and N, and soil microbial biomass does indeed represent an important labile pool of nutrients in soils (Henrot and Robertson, 1994), and its activity plays a significant role in nutrient transformation, conservation, and availability to plants (Wardle, 1992; Zaman et al., 1999; Tu et al., 2003). Nevertheless, other litters additions had no effect.

In spite of the important nutrient inputs through litter additions, the observed effect on plant biomass is quite limited, suggesting that the plant did not benefit from these inputs. Indeed, litter addition significantly increased aboveground biomass in 2009, 2010 and 2011, and belowground biomass and total biomass in 2010 and 2011 but only for the highest input level. One plausible explanation for the lack of effect on plant biomass in spite of the important amount of organic nutrients added might be the imbalance between the C : N : P ratio of the litter added and the C : N : P ratio of the soil, the plants and the microbial community. For instance, the C : N and C : P ratios of the added litter were 41.3 and 521.9, respectively. Compared to the C : N ratio of microbial biomass around 12 and the C : N and C : P ratio of soil around 9 and 55, respectively, added litter decomposition might immobilize available mineral nutrients, which would increase the competition between plants and microorganisms for mineral N and available P. Since plant biomass only responded to the highest litter treatments, it suggests that, in our case, microorganisms might be more efficient in using nutrient resources. Nevertheless, soil microorganisms benefited only slightly from the litter inputs as suggested by the small observed increase in microbial biomass (Fig. 5m and n). Therefore, carbon use efficiency probably decreased when litter was added, increasing heterotrophic respiration. Furthermore, when litter additions significantly affected plant biomass, aboveground biomass and belowground biomass were higher in 2010 than in 2009 and 2011. The main reason may be that the precipitation in growing season of 2010 (314 mm) was much higher than that of the 2009 and 2011 growing (164 and 159 mm, respectively), and a much higher precipitation caused the higher soil nutrient availability for plant growth in 2010.

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4.2 Biomass allocation

Biomass allocation is often affected by factors such as soil nutrient conditions and plant habitat (Vogt et al., 1983; Schmid, 2002; Mokany et al., 2006). Plants respond to lower nutrient supply by increasing allocation of photosynthates to their root system resulting in higher root biomass (Vogt et al., 1983; Schmid, 2002). In our study, high litter addition decreased the ratio of belowground biomass to aboveground biomass, and the decrease reached a significant level in 2010. The reason for this decrease may be that litter addition greatly increased soil organic N and available P and soil microbial biomass C and N, allowing the plant to invest more photosynthates in aboveground biomass in 2010. Sims et al. (2012) found that adding nitrogen increased plant growth and allocated more biomass toward shoots than roots. The plastic response of increased allocation to shoots corresponds to theoretical predictions of increased aboveground competition when nutrient availabilities are high (Tilman, 1988). Li and Xiao (2007) also found that the soil water content, soil organic matter, and soil N and P contents and plant total biomass increased from the shifting dune, semi-fixed dune to fixed dune, but the ratio of belowground biomass to aboveground biomass decreased. Such an increase in photosyntates concentration is also suggested by the significantly decreased C : N and C : P concentrations in aboveground biomass and litter upon high litter addition, but not for belowground biomass.

4.3 Effect of litter addition on plant N : P ratio

Plant N and P are essential nutrients for primary producers and decomposers in terrestrial ecosystems, and N : P ratios of plant biomass or litter have been widely used as indicators of nutrient limitation for primary production (Koerselman and Meuleman, 1996; Tessier and Raynal, 2003; Güsewell, 2004; Güsewell and Verhoeven, 2006). In our study, litter addition did not affect the N : P of aboveground biomass, belowground biomass and litter. Our results showed that the N : P of aboveground biomass (ranging from 13.3 to 13.9 under different litter additions) is higher that of belowground biomass

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(ranging from 11.6 to 12 under different litter additions). Similar results were observed in the study of Xu et al. (2010). The N : P of aboveground biomass and belowground biomass is lower than 14 on a community level, suggesting that our *S. krylovii* steppe community N limited (Koerselman and Meuleman, 1996). Additionally, the N : P of litter ranged from 12.1 to 12.5 after different litter treatments and were much lower than 25 (the threshold between N and P limitation for graminoid leaf litter; Güsewell and Verhoeven, 2006), also indicating that our *S. krylovii* steppe community is subject to N limitation. This result is consistent with the conclusion of Bai et al. (2012) who found that meadow steppe, typical steppe and desert steppe communities of temperate grasslands in northern China are N-limited systems. Nevertheless, the lack of response for realistic litter additions suggested CO_2 fertilization might not change the plant-limiting factor in our site.

5 Conclusions

Fertilization often affects the natural ecological stoichiometry and causes imbalances that will have consequences for biogeochemical cycles including C-sequestration and long term structure and function of ecosystems (Lambers et al., 2010; Vitousek et al., 2010; Peñuelas et al., 2012). Surprisingly, in our study, litter addition significantly affected the stoichiometry of the systems only when they where quite high (twice the natural inputs). Previous modeling exercises have not predicted an increase of primary production sufficient to double litter inputs (Arora and Boer, 2014; Todd-Brown et al., 2014). This suggests that, the grassland studied here is quite resilient in terms of stoichiometry and this resilience is the result of complex interactions between C and nutrients cycles as well as between plants and microbial biomass.

In conclusion, our results showed that very high litter addition increased soil inorganic N and plant available P, in addition to the C and N pools of soil microbial biomass, aboveground plant biomass and belowground plant biomass, while realistic additions according to the models predictions for the coming decades had no effect. This sug-

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gests that the expected increase of NPP associated with nutrients imbalance may not have important consequences on the stoichiometric functioning for some particular ecosystems, such as grasslands in northern China. Nevertheless, it must be noted that climate change will also affect temperature and soil moisture, which will largely affect the response of plants to modifications of NPP due to the atmospheric CO_2 increase.

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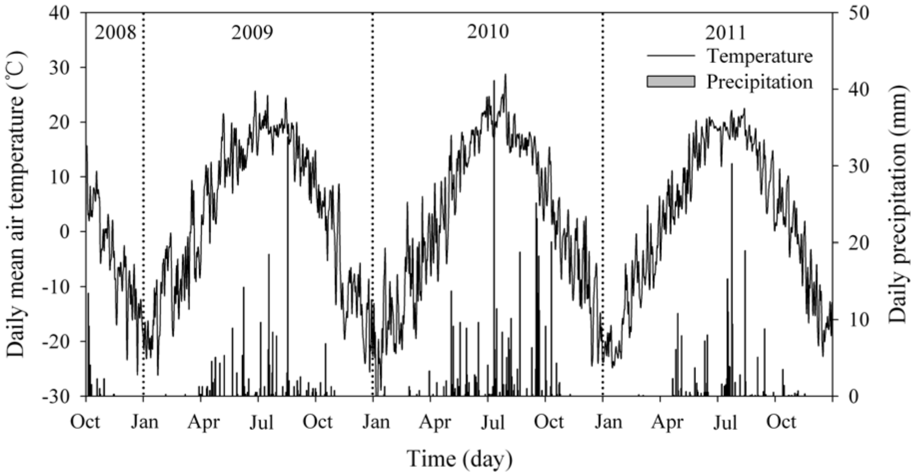

Figure 1. Seasonal variations of daily mean air temperature and daily precipitation during the experimental period from 1 October 2008 to 30 September 2011.

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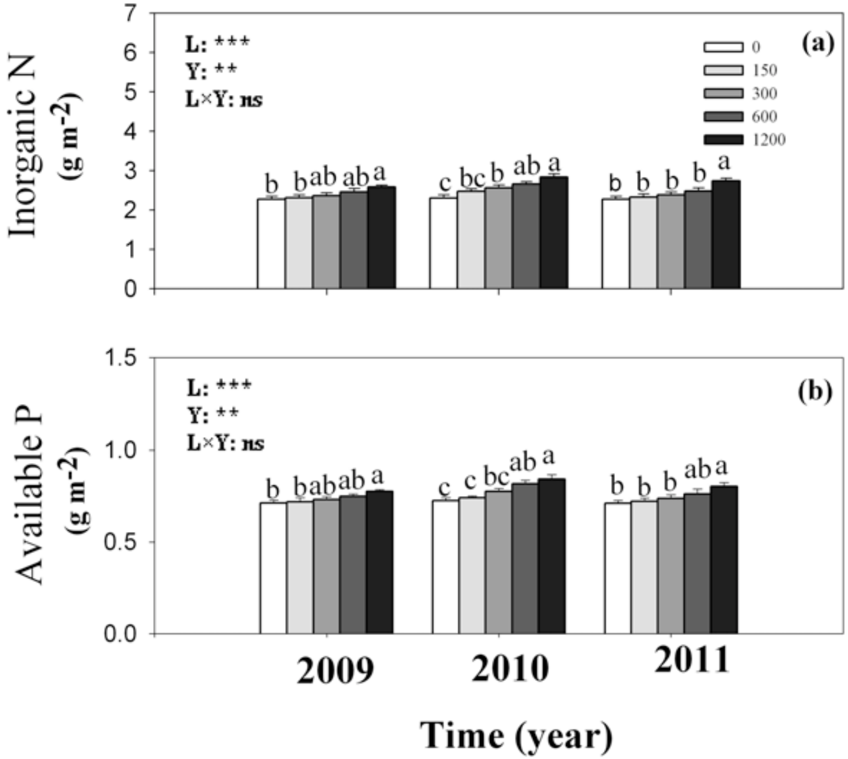

Figure 2. Soil inorganic N **(a)** and available P **(b)** in 2009, 2010 and 2011 under different amounts of litter addition in a steppe community of northern China. Vertical bars indicate one standard error about the mean ($n = 5$). Treatments with different letters are significantly different ($P < 0.05$) according to the Duncan test. Absence of letters implies that no significant differences were detected. The significance of the effects of litter addition (L), year (Y) and their interaction ($L \times Y$) were determined with two-way ANOVA. Significance level: ns (not significant) $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

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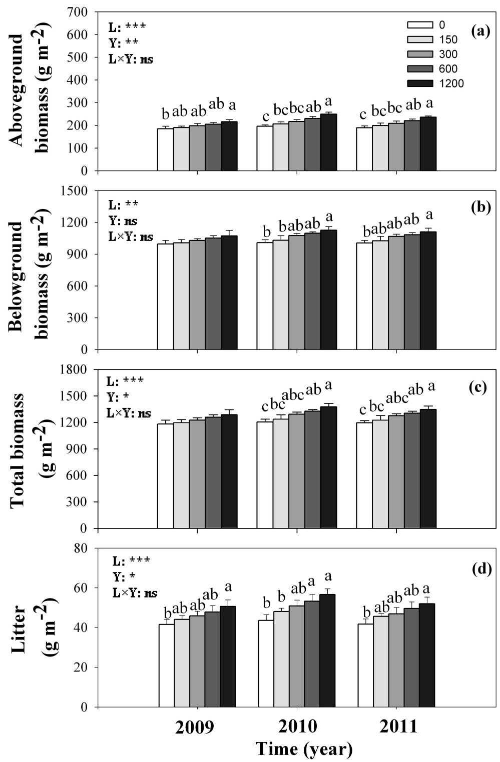

Figure 3. Aboveground biomass **(a)**, belowground biomass **(b)**, total biomass **(c)** and litter **(d)** in 2009, 2010 and 2011 under different amounts of litter addition in a steppe community of northern China. Vertical bars indicate one standard error about the mean ($n = 5$). Treatments with different letters are significantly different ($P < 0.05$) according to the Duncan test. Absence of letters implies that no significant differences were detected. The significance of the effects of litter addition (L), year (Y) and their interaction ($L \times Y$) were determined with two-way ANOVA. Significance level: ns (not significant) $P > 0.05$; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

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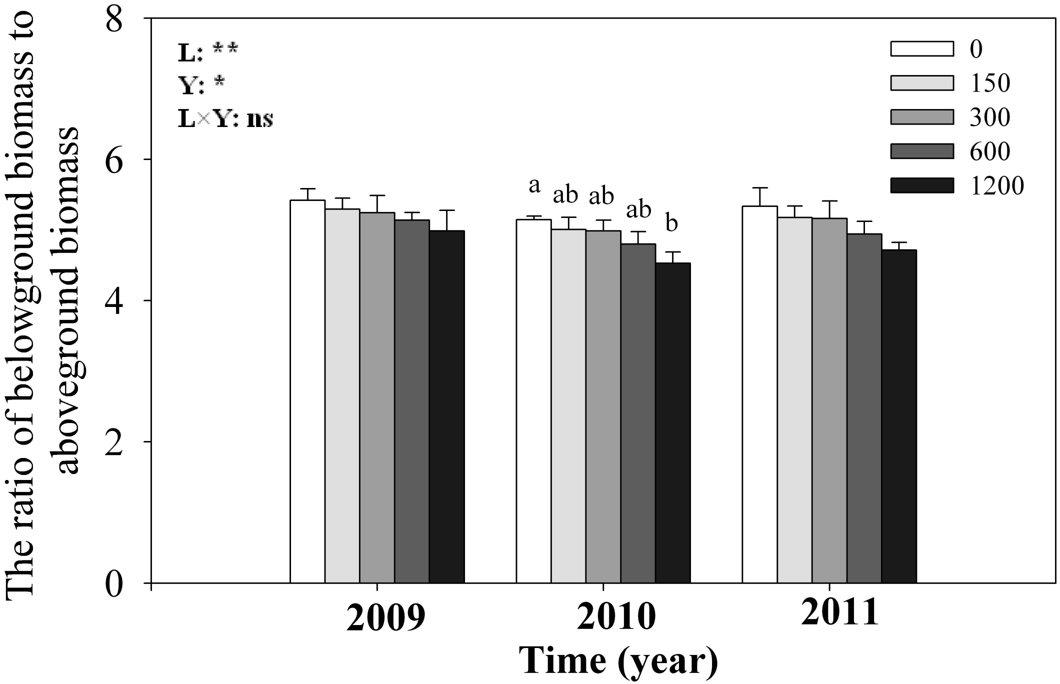

Figure 4. Ratio of belowground biomass to aboveground biomass in 2009, 2010 and 2011 under different amounts of litter addition in a steppe community of northern China. Vertical bars indicate one standard error about the mean ($n = 5$). Treatments with different letters are significantly different ($P < 0.05$) according to the Duncan test. Absence of letters implies that no significant differences were detected. The significance of the effects of litter addition (L), year (Y) and their interaction ($L \times Y$) were determined with two-way ANOVA. Significance level: ns (not significant) $P > 0.05$; $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

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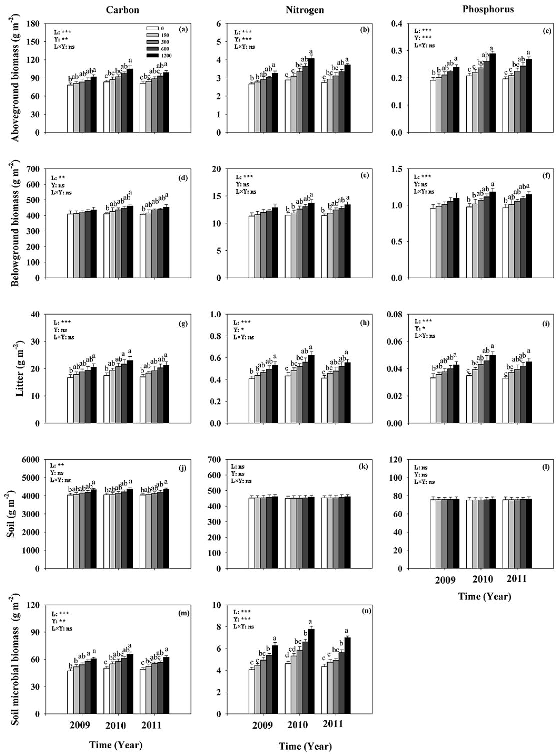

Figure 5. The C, N, and P pools of plant, litter and soil and the C and N pools of soil microbial biomass in 2009, 2010 and 2011 under different amounts of litter addition in a steppe community of northern China. Vertical bars indicate one standard error about the mean ($n = 5$). Treatments with different letters are significantly different ($P < 0.05$) according to the Duncan test. Absence of letters implies that no significant differences were detected. The significance of the effects of litter addition (L), year (Y) and their interaction ($L \times Y$) were determined with two-way ANOVA. Significance level: ns (not significant) $P > 0.05$; $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

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Strong stoichiometric resilience after litter manipulation experiments

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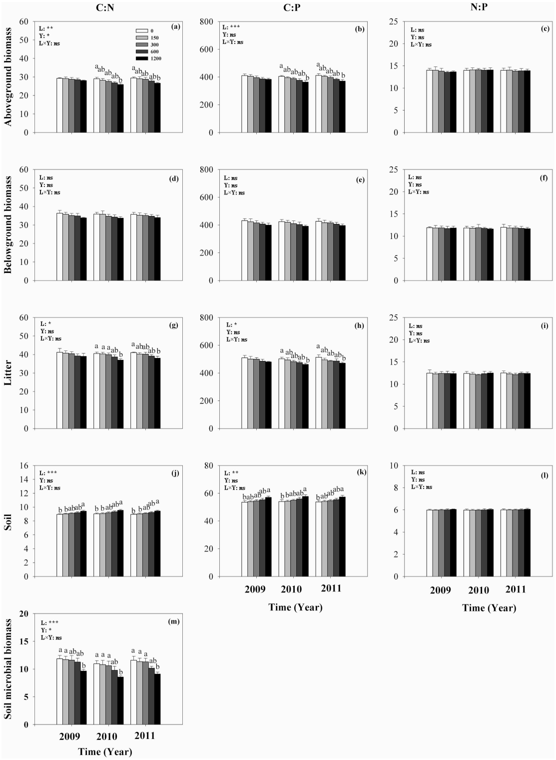

Figure 6. The C : N, C : P and N : P ratio of plant, litter and soil and C : N ratio of soil microbial biomass in 2009, 2010 and 2011 under different amounts of litter addition in a steppe community of northern China. Vertical bars indicate one standard error about the mean ($n = 5$). Treatments with different letters are significantly different ($P < 0.05$) according to the Duncan test. Absence of letters implies that no significant differences were detected. The significance of the effects of litter addition (L), year (Y) and their interaction ($L \times Y$) were determined with two-way ANOVA. Significance level: ns (not significant) $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

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