



Effects of soil nutrients and climate factors on belowground biomass in an alpine meadow in the source region of the Yangtze-Yellow rivers, Tibetan Plateau of China

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Abstract: Improving our knowledge of the effects of environmental factors (e.g. soil conditions, precipitation and temperature) on belowground biomass in an alpine grassland is essential for understanding the consequences of carbon storage in this biome. The object of this study is to investigate the relative importance of soil nutrients and climate factors on belowground biomass in an alpine meadow in the source region of the Yangtze and Yellow rivers, Tibetan Plateau. Soil organic carbon (SOC), total nitrogen (TN) and total phosphorous (TP) contents and belowground biomass were measured at 22 sampling sites across an alpine meadow on the Tibetan Plateau. We analyzed the data by using the redundancy analysis to determine the main environmental factors affecting the belowground biomass and the contribution of each factor. The results showed that SOC, TN and TP were the main factors that influenced belowground biomass, and the contribution of SOC, TN and TP on biomass was in the range of 47.87%–72.06% at soil depths of 0–30 cm. Moreover, the combined contribution of annual mean temperature (AMT) and mean annual precipitation (MAP) on belowground biomass ranged from 0.92% to 4.10%. A potential mechanism for the differences in belowground biomass was caused by the variations in soil nitrogen and phosphorous, which were coupled with SOC. A significant correlation was observed between MAP and soil nutrients (SOC, TN and TP) at the soil depth of 0–10 cm ($P < 0.05$). We concluded that precipitation is an important driving force in regulating ecosystem functioning as reflected in variations of soil nutrients (SOC, TN and TP) and dynamics of belowground biomass in alpine grassland ecosystems.

Keywords: belowground biomass; soil organic carbon; soil nitrogen and phosphorus; climate factor; alpine meadow; Tibetan Plateau

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In a terrestrial ecosystem, the vegetation biomass is the major source of soil organic matter, a link into the global carbon cycle, and a major factor in greenhouse gas emissions (Jobbágy and Sala, 2000; Mokany et al., 2006; Ma and Stern, 2008; Wang et al., 2011). Grassland ecosystems occupy approximately 25% of the global land surface area and have 10% soil carbon stock of the global terrestrial biosphere (Hui and Jackson, 2006; Sun et al., 2013a), and they also have considerable effects on the global carbon cycle. The carbon pool of the grasslands on the Tibetan Plateau is considered as one of the most important carbon pools in the world (Wen et al., 2013a, b; Li et al., 2014) and plays a key role in the terrestrial carbon cycle (Li et al., 2013). The three rivers, i.e. the Yangtze, Yellow and Lancang-Mekong rivers, originate from the Tibetan Plateau (4,000 m asl on average). The grasslands of this region are an important component of the Eurasian grassland biomes (Zhou et al., 2005); and approximately 26% of the alpine grasslands are located in the source region of the Yangtze-Yellow rivers in Asia (Dong et al., 2012). Thus, grasslands on the Tibetan Plateau have attracted international attention because of their contribution to the global carbon budget, and the sensitivity and fragility of this ecosystem (Fan et al., 2006).

The spatial pattern of the above and belowground biomass is considered to reflect the plant optimized strategies for resources capture, and is largely dependent on environmental variables (Wu et al., 2013). Previous studies have examined the relationship between biomass distribution and environmental factors on the Tibetan Plateau (Sun et al., 2013a, b). Hui and Jackson (2006) investigated global geographical and temporal variability in the fraction of belowground net primary productivity (NPP) to the total NPP and the relationship of belowground NPP with climatic variables. They concluded that the proportion of belowground NPP decreased significantly with increasing annual temperature and precipitation.

Biomass is also influenced by soil nutrients (Schenk and Jackson, 2005); thus, soil nutrient availability is crucial for the above and belowground trophic interactions for ecosystem functioning (Ettema and Wardle, 2002). Wu et al. (2011) and Li et al. (2014) demonstrated significant positive correlations between belowground biomass and soil nutrient contents in alpine meadows on the Tibetan Plateau. Unfortunately, accurate quantification of belowground biomass has not been sufficiently studied in this region (Chen et al., 2015; Lu et al., 2015). Furthermore, the response of biomass and partitioning of the response to multiple environmental drivers such as soil conditions remain unclear (Kang et al., 2013). Because the alpine grasslands on the Tibetan Plateau is considered as one of the world's most important biomes (Wang et al., 2014), improving our knowledge of the effects of environmental factors on belowground biomass in such an alpine meadow is essential for understanding the consequences of carbon storage in this biome. Therefore, the aim of the present study is to identify the critical environmental factors that affect the belowground biomass in an alpine meadow on the Tibetan Plateau.

1 Study area and methods

1.1 Study area

The study area (32°23'–35°34'N, 95°53'–99°00'E) is located in the source region of the Yangtze-Yellow rivers, Tibetan Plateau of China (Fig. 1). It is characterized by a typical plateau continental monsoon climate, i.e. cold and dry climate with a large diurnal variation of temperature and high solar radiation. The region is dominated by the southeast monsoon from May to September in short and cool summers, and by the high pressure from Siberia in long and cold winters. Annual mean air temperature is from –6.4°C to 4.3°C. The monthly average air temperature ranges from 11.7°C to 21.0°C in July and –27.9°C to –14.3°C in January. Mean annual precipitation ranges from 374.2 to 721.2 mm, and over 80% of it occurs during the growing season. There is no period that is absolutely fog free (Dong et al., 2002). The vegetation is mainly composed of alpine meadow plants. Soil depth averages about 30 cm and the soil is of generally poor condition due to high elevation and cold weather (Liu et al., 2006; Xu et al., 2011).

1.2 Sample collection and measurement

We set a total of 22 sampling sites in permafrost regions (Fig. 1). Plant biomass was harvested

from three representative quadrats (50 cm×50 cm each) with similar topography and environmental conditions in each site at the peak time of plant growth in August 2012. Roots were extracted with an auger (8 cm in diameter) at 10-cm intervals to a soil depth of 30 cm. In each quadrat, three cores were taken, with a total of nine cores in each site. The core samples were soaked in water to remove the soil. After washing through a 0.2-mm mesh sieve, roots were placed in canvas bags, and transported to the laboratory, then oven-dried at 65°C to a constant mass, and then weighed.

In each site, three soil profiles with 30-cm depth and at an interval of 10 cm were excavated (the same locations as used for sampling belowground biomass) to collect soil samples. After being air-dried in a cool, well-ventilated place, the samples were passed through a 1-mm sieve and roots were removed. Soil organic carbon (SOC) and total nitrogen (TN) were determined by using a vario MACRO cube elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany), and soil total phosphorus (TP) was determined by the NaHCO₃ alkali digestion method and molybdenum antimony colorimetry (Lu et al., 2015).

Climatic variables, including annual mean temperature (AMT) and mean annual precipitation (MAP), were obtained from the 98 meteorological stations located on the Tibetan Plateau. Climatic data from 1960 to 2013 for each sampling site were estimated based on their geographic locations (latitude and longitude) by using the Kriging interpolation method with ArcGIS 10.0 (ESRI Company Inc., Redlands, California, USA).

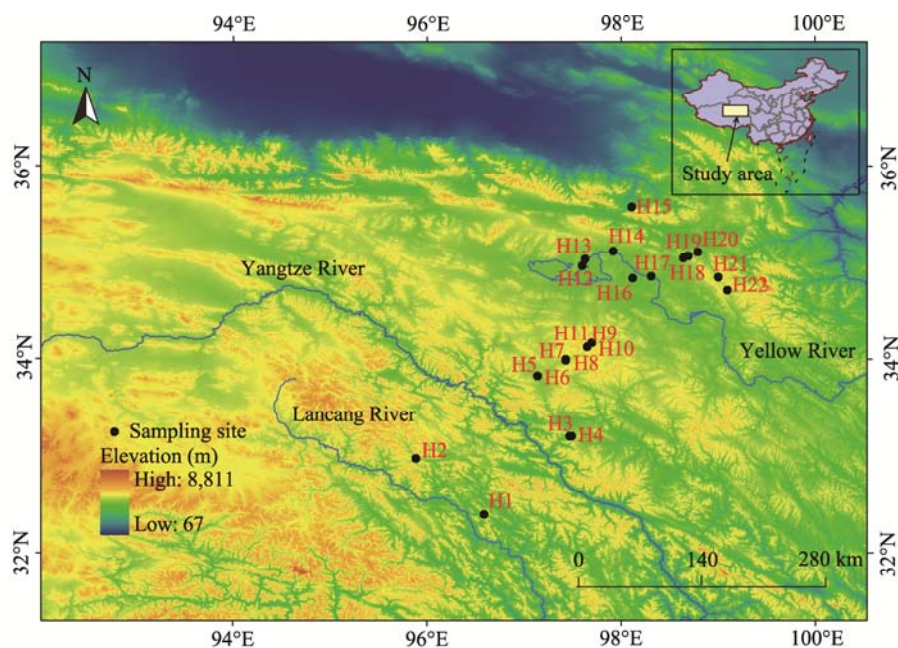


Fig. 1 Locations of the study area and sampling sites

1.3 Data analysis

The apparent effects of each environmental factor on belowground biomass were studied by the redundancy analysis. Correlation analysis and ANOVA were performed using the SPSS 19.0 software (IBM Company Inc., Armonk, NY, USA).

2 Results

2.1 Variations in climatic factors, soil nutrients and belowground biomass

Belowground biomass and environmental factors differed significantly among different sampling sites. The mean SOC, TN and TP contents were 56.71, 4.07 and 0.62 g/kg, respectively (Table 1).

MAP in the sampling sites varied from 325 to 516 mm with an average of 400 mm, and AMT ranged from -4.8°C to -1.0°C with an average of -3.1°C . The average belowground biomass ranged from 1.75 to 18.91 kg/m².

Table 1 Statistics of environmental factors and belowground biomass (soil depths of 0–30 cm) at all sampling sites

No.	Altitude (m)	AMT (°C)	MAP (mm)	SOC	TN	TP	BGB (kg/m ²)
				(g/kg)			
H1	4,267	−2.3	516	26.24±14.28	1.95±0.90	0.50±0.05	3.34±1.50
H2	4,526	−1.6	501	52.58±23.57	3.63±0.74	0.81±0.02	3.24±1.62
H3	4,415	−1.0	474	117.68±53.59	8.30±2.80	1.08±0.15	11.00±4.48
H4	4,476	−1.7	477	71.64±26.59	5.88±2.59	1.10±0.03	3.54±1.71
H5	4,421	−2.1	428	15.51±9.16	1.53±0.64	0.62±0.04	1.75±0.73
H6	4,421	−2.1	428	140.18±48.44	9.22±2.66	0.76±0.13	16.76±4.22
H7	4,577	−3.1	421	52.72±37.93	3.19±1.34	0.51±0.10	8.77±4.10
H8	4,813	—	—	—	—	—	16.00±2.30
H9	4,706	−4.7	421	26.86±9.52	1.91±0.33	0.57±0.04	4.55±1.51
H10	4,681	−4.2	412	59.20±29.04	3.83±0.56	0.70±0.07	4.96±2.25
H11	4,278	−4.2	412	161.80±18.09	10.15±2.02	0.76±0.08	14.47±1.32
H12	4,279	−2.8	342	19.45±4.95	2.24±0.62	0.54±0.05	2.70±0.97
H13	4,278	−3.0	339	18.47±0.68	1.76±0.28	0.55±0.02	1.99±0.61
H14	4,259	−3.1	330	8.30±0.85	0.95±0.24	0.37±0.02	2.55±0.71
H15	4,230	−2.1	325	19.96±6.67	1.41±0.25	0.35±0.04	4.63±1.94
H16	4,218	−2.7	329	8.00±0.44	0.93±0.10	0.28±0.01	2.20±0.21
H17	4,407	−2.8	333	8.53±0.73	0.83±0.06	0.36±0.04	2.30±0.52
H18	4,516	−4.0	356	26.02±6.63	1.95±0.27	0.57±0.02	4.58±1.36
H19	4,316	−4.8	367	119.76±13.4	7.84±0.31	0.76±0.03	18.91±0.20
H20	4,526	−3.8	361	39.40±16.72	2.91±1.36	0.55±0.07	10.80±2.15
H21	4,527	−4.7	403	116.87±28.00	8.87±2.39	0.62±0.06	15.48±0.52
H22	4,527	−4.6	423	81.68±5.06	6.18±0.50	0.70±0.04	5.94±2.05

Note: AMT, annual mean temperature; MAP, mean annual precipitation; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorous; BGB, belowground biomass. Mean±SD. “—” means no data available.

2.2 Effects of soil nutrients and climatic factors on belowground biomass

SOC, TN and TP were the main factors influencing on belowground biomass (Fig. 2). The contribution of SOC, TN and TP on belowground biomass varied from 47.87% to 72.06% at soil depths of 0–30 cm. Moreover, the contribution of AMT and MAP on belowground biomass ranged from 0.92% to 4.10% at these depths.

2.3 Relationships of soil nutrients with belowground biomass and climate factors, and inter-correlations between soil nutrients

There was a positive relationship between belowground biomass and SOC at 0–10, 10–20 and 20–30 cm soil depths (Fig. 3a). Similar relationship was also found between belowground biomass and TN at these soil depths (Fig. 3b). Importantly, the effects of soil nutrients on belowground biomass weakened with increasing soil depth. However, positive relationship between belowground biomass and TP was only observed at the 0–10 cm soil depth (Fig. 3c).

Significant correlations were observed between MAP and SOC and TN at the 0–10 cm soil depth, and clear effects of MAP on TP were identified at all soil depths (Table 2). Moreover, the

linear relationships and power functions were found between SOC and TN and between SOC and TP, respectively across all sampling sites at 0–10, 10–20 and 20–30 cm soil depths (Fig. 4).

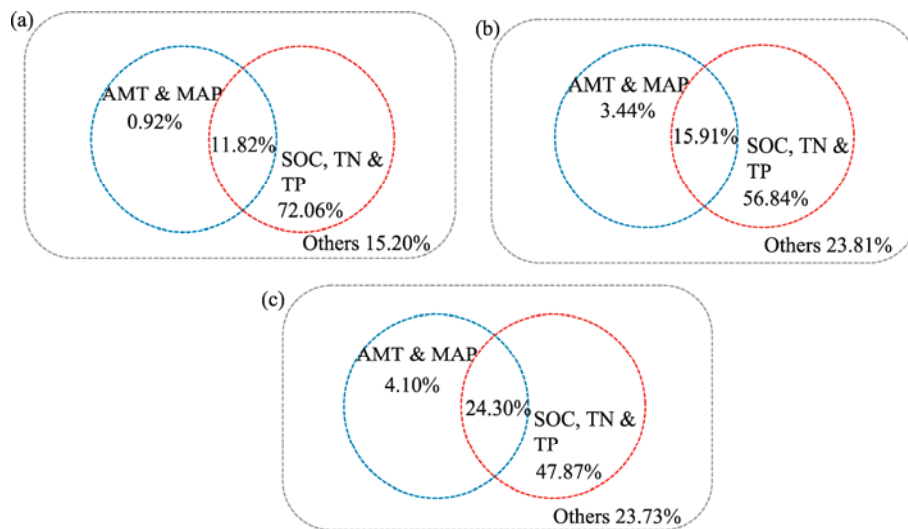


Fig. 2 Venn diagrams of the contributions of environmental factors to belowground biomass at 0–10 (a), 10–20 (b) and 20–30 (c) cm soil depths. AMT, annual mean temperature; MAP, mean annual precipitation; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus.

Table 2 Pearson correlations of soil nutrients at depths of 0–30 cm and climate factors

Soil depth (cm)	Soil nutrient	AMT	MAP
0–10	SOC	−0.03	0.49*
	TN	−0.05	0.47*
	TP	0.22	0.67**
10–20	SOC	−0.22	0.30
	TN	−0.16	0.33
	TP	0.24	0.65**
20–30	SOC	−0.32	0.27
	TN	−0.32	0.29
	TP	0.16	0.66**

Note: * and ** mean significance at $P < 0.05$ and $P < 0.01$ levels (2-tailed), respectively. $n = 22$.

3 Discussion

3.1 Effects of soil nutrients and climatic factors on belowground biomass

In this study, most of the variations in belowground biomass could be attributed to soil nutrients, while temperature and precipitation only had little effect on belowground biomass. The temperature ranged from -4.8°C to -1.0°C in the study area (Table 1) and the small spatial difference of the temperature in this region may result in low effect on belowground biomass. Moreover, the same results were also documented in other areas of China (Yang et al., 2010). It is noted that precipitation is not a limited factor on belowground biomass in the alpine meadow (Geng et al., 2012), particularly in the Yangtze–Yellow rivers source region, because precipitation and soil moisture are relatively high in this region. Therefore, precipitation plays a minor role in regulating the distributions of belowground biomass in the alpine meadow in this region. Meanwhile, low temperature may restrain the biogeochemical cycles in the alpine meadow, and then reduce soil nutrients supply for plant growth, and further limit the response of vegetation production of alpine meadow to precipitation (Yang et al., 2010). Thus, we concluded that temperature and precipitation

have little influence on belowground biomass in the alpine meadow in the source region of the Yangtze-Yellow rivers.

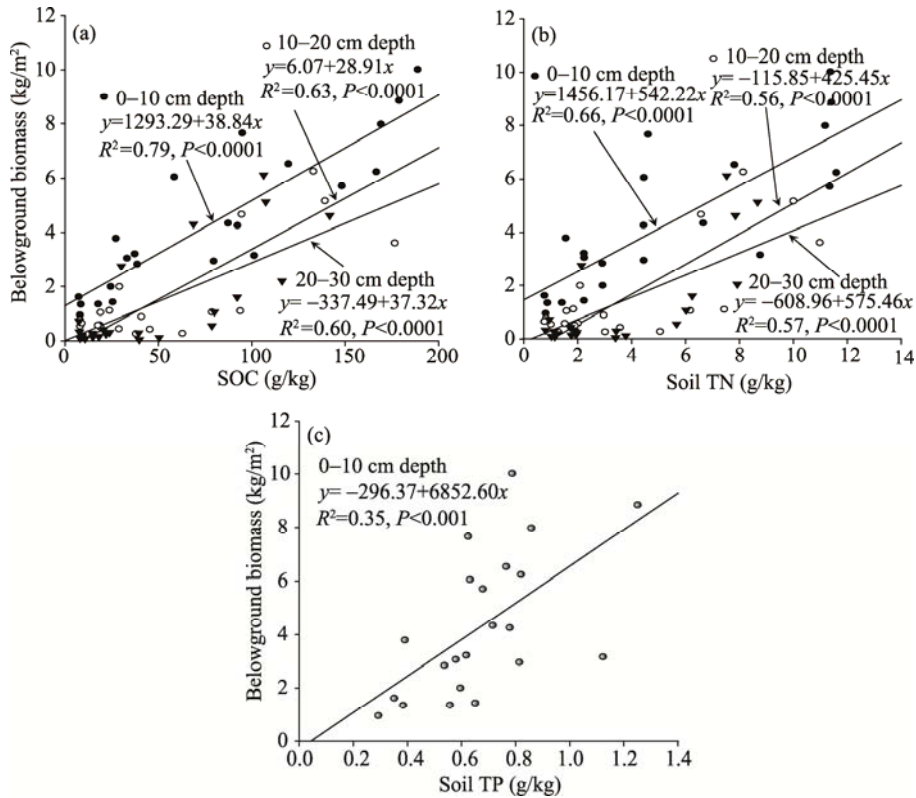


Fig. 3 Relationships of belowground biomass with soil organic carbon (SOC; a) and total nitrogen (TN; b) at 0–10, 10–20 and 20–30 cm soil depths, and with total phosphorous (TP) at the 0–10 cm soil depth (c)

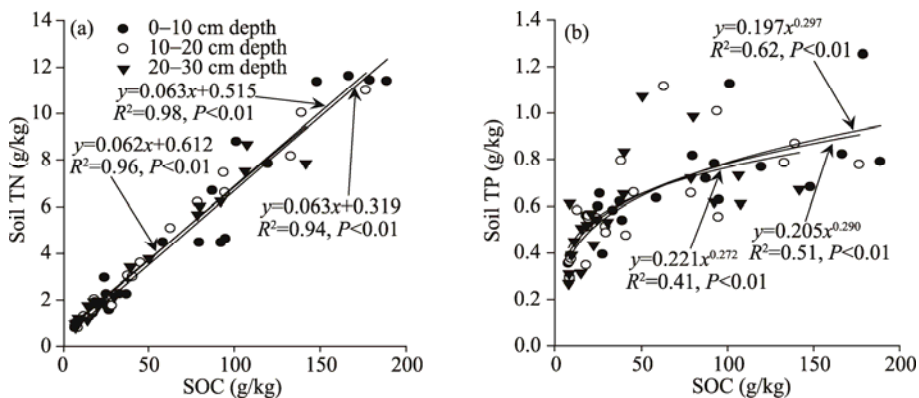


Fig. 4 Relationships of SOC with TN (a) and TP (b) at 0–10, 10–20 and 20–30 cm soil depths

In a steppe ecosystem, SOC inputs mainly come from the senescing plant tops and the exudation of organic compounds from plant roots (He et al., 2009). In this study, soil nutrients influenced the belowground biomass at different soil depths, with the contributions of 72.06%, 56.86% and 47.87% on belowground biomass at depths of 0–10, 10–20 and 20–30 cm, respectively. Primary production in ecosystems is dependent on soil nutrient availability (Blue et al., 2011). Soil nitrogen is an especially limiting factor for belowground production in most terrestrial ecosystems (Verburg et al., 2013). These findings are consistent with our results that SOC and TN had a significant positive effect on belowground biomass. The important roles of

SOC, TN and TP on belowground biomass in this study are in good accordance with the results of a previous study on the Tibetan Plateau (Yang et al., 2009). A study on degraded grasslands in Dawu village, Qinghai province of China showed that soil carbon and nitrogen pools are strongly correlated with belowground biomass (Li et al., 2014). Thus, the results documented that soil nutrients are the critical factors in determining the belowground biomass at different soil depths in the alpine meadow on the Tibetan Plateau.

3.2 Relationships between SOC, TN and TP

In this study, linear relationships were found between SOC and TN while power functions were observed between SOC and TP at all soil depths. Previous studies indicated that plant composition, application of manure and reseeded could affect the stability of soil carbon and nitrogen as well as their decomposition rates (Meng et al., 2014; Shang et al., 2014). Moreover, the closed coupling of TN and TP with SOC levels was observed as increasing temperature and precipitation in a temperate grassland (Bai et al., 2010) and a degraded and restored alpine grassland (Dong et al., 2012; Li et al., 2014). On a broad geographical scale, Yang et al. (2014) reported the stability of soil carbon and nitrogen stoichiometry across the alpine grasslands, Tibetan Plateau.

3.3 Effects of annual precipitation and temperature on soil nutrients

The relationships between precipitation, temperature and accumulation of soil organic matter have been well documented (Ambebe and Dang, 2009; Copeland et al., 2012; He et al., 2012; Chang et al., 2014). Our results suggested that SOC varied significantly with changes of MAP. Increased precipitation might promote the microbial and enzymatic activities in soils (Zhou et al., 2013), and thereby will alter the availability of soil nutrients. In addition, NPP (Klopfenstein et al., 2015) and litter input have a significant impact on soil carbon and nitrogen dynamics (Chen et al., 2015). Along a precipitation gradient, SOC and vegetation production maintain a stable trend in temperate grasslands (Liu et al., 2014) and alpine grasslands (Li et al., 2014), and soil carbon stocks are mainly driven by the inputs from vegetation (Gabarrón-Galeore et al., 2015). Notably, the present study revealed that variations in soil nitrogen and phosphorous were coupled with changes in SOC, and soil nitrogen and phosphorous increased significantly with increasing MAP.

Interestingly, some previous studies suggested that temperature has a significant effect on SOC, TN and TP (Dessureault-Rompré et al., 2010; de Dios et al., 2013; Sanaullah et al., 2014; Zhang et al., 2015). However, we did not find a significant relationship of temperature with SOC, TN and TP (Table 2). Actually, there is still no consensus regarding the effects of temperature on soil carbon stocks currently (Hassan et al., 2015). The effect of low temperature and soil types on the diffusibility of enzymes could be an important mechanism affecting the decomposition rate of SOC (Frøseth and Bleken, 2015). In the alpine meadow, poor soil condition and extremely short plant growing seasons may result in a slower turnover of soil carbon. Our study found that temperature has no effect on TN and TP. This result is consistent with the finding of Figueiredo et al. (2015), who found that increased temperature has no effect on TN content.

4 Conclusions

Temperature and precipitation can affect vegetation production. The differences in geographical conditions result in different relationships among belowground biomass and environmental factors. Poor soil condition and extremely short plant growing season may be important limiting factors on belowground biomass of vegetation in the alpine meadow on the Tibetan Plateau. Our results suggested that most of the variation in belowground biomass could attribute to soil nutrients, with only a small proportion could be explained by temperature and precipitation. MAP had a significant and direct effect on SOC, TN and NP, while it had an indirect effect on belowground biomass via soil nutrients. SOC, TN and TP were tightly coupled with various climate factors in the alpine meadow. Our results will be of value for assessing the consequences of carbon storage in alpine meadows.

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