Environ Earth Sci (2011) 64:1911–1919
DOI 10.1007/s12665-011-1004-1

ORIGINAL ARTICLE

Root biomass distribution in alpine ecosystems of the northern Tibetan Plateau

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Received: 26 May 2010 / Accepted: 8 March 2011 / Published online: 29 March 2011

Abstract The root biomass distribution in alpine ecosystems (alpine meadow, alpine steppe, desert grassland and alpine desert) was investigated along a transect on the northern Tibetan Plateau in 2009. The results showed that roots were mainly concentrated in the 0–20 cm layer, and root biomass decreased exponentially with increasing soil depth. Root biomass was estimated to be 1,381.41 ± 245.29 g m^{-2} in the top 20 cm soil, accounting for 85% of the total root biomass. The distribution pattern of the root biomass proportion along the soil profile was similar in different alpine ecosystems. The root biomass density varied with different alpine ecosystems and the total average root biomass was 1,626.08 ± 301.76 g m^{-2}. Root biomass was significantly correlated with average relative humidity, annual precipitation and soil organic matter. This indicates that precipitation and soil organic matter might be crucial for plant growth in the study area, while temperature is not an important factor controlling root growth.

Keywords Alpine ecosystem · Environmental factors · Northern Tibetan Plateau · Root biomass

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Introduction

Plant root is a critical component of ecosystems (Norby and Jackson 2000). Root production represents the primary input source of organic carbon for soils and plant carbon stocks in terrestrial ecosystems can be measured based on root production (Eswaran et al. 1993; Jackson et al. 1996; Scurlock and Hall 1998; Mokany et al. 2006). For grassland ecosystems, the root systems represent a more important carbon storage mechanism than forests because root/shoot ratios are higher for grasslands (Jackson et al. 1996). The proportion of root biomass can be greater than 80% of the total plant biomass in some grassland ecosystems (Caldwell and Richards 1986; Mokany et al. 2006). In Tibet Plateau, the proportion of root/shoot can reach up to 5.8 (Yang et al. 2009b). Moreover, root biomass constitutes the core portion of a plant's total primary productivity in grassland ecosystem (Yan et al. 2005). The primary productivity of roots often accounts for 60–80% of total net primary production in grassland ecosystem (Coleman 1976; Agren et al. 1980). Thus, it is vitally important to study the distribution of root biomass in grasslands.

Relative to the aboveground biomass, investigation of root biomass distribution and belowground processes are much more challenging due to the high requirement of intensive labor and high cost (Vogt et al. 1995; Hu et al. 2005; Hendricks et al. 2006; Metcalfe et al. 2007). In addition, environmental factors, including climate, soil physical, chemical and biological characteristics, and plant properties can all affect the distribution of root biomass (Zhang et al. 1996; Rodríguez et al. 2007a; Macinnis-Ng et al. 2010). It is important to understand the effects of environmental factors on root biomass distribution in various regions.

Current studies about root system in Chinese grasslands have been mainly carried out on temperate grasslands in Inner Mongolia (Ma et al. 2008), alpine grasslands in the Tianshan Mountains (Wang et al. 2008; Li et al. 2008), and alpine meadows on the Tibetan Plateau (Wang et al. 2007a). Studies on the vast northern Tibetan grassland are still limited. Field data about root biomass has been collected along the south–north transect transiting from forest to alpine grassland in the eastern Tibetan Plateau (Luo et al. 2005). Yang et al. (2009a) reported the root biomass distribution around Beiluhe station (34°51.236′N, 92°56.395′E, 4,628 m asl) of Tibetan Plateau. Wu et al. (2011) studied root biomass and root turnover rate in a *Kobresia humilis* meadow (37°29–45′N, 101°12–23′E) at Haibei alpine meadow ecosystem research station at the northeast edge of Tibetan Plateau. These studies involved only a small portion of the northern Tibetan Plateau.

The Tibetan Plateau is known as the third pole of the world, and the grassland ecosystem occupies approximately 2.5×10^6 km^2 of area. The alpine ecosystems of the northern Tibetan Plateau, southwest China, are in the central part of Tibetan Plateau (Li 2000). With its unique geographical environment, the northern Tibetan Plateau is a region particularly sensitive to global change, especially warming. It has been reported that global warming has been more severe on northern Tibetan Plateau than other region in northern hemisphere (IPCC 2007). Due to the combined effects of global change and anthropogenic activities (i.e., grazing), the ecological conditions have deteriorated in the past decades (Zhou et al. 2005; Duan et al. 2006). A clear understanding of grassland root distribution in northern Tibet is critical to reserving and recovering grassland of northern Tibet. In addition, the northern Tibetan Plateau is an ideal place to study root biomass distribution and the relationships between root biomass and environmental factors due to the low population density and relatively less frequent human activities in the region.

The objectives of the present study were to investigate the root distribution pattern and its relationship with environmental factors on the northern Tibetan Plateau of China. Specifically, the study was aimed (1) to analyze the vertical distribution of root biomass density in four alpine ecosystems and (2) to measure total soil nitrogen, total soil phosphorus, pH and soil organic matter to analyze their potential influence on root biomass. In this study, the hypothesis that root distribution may be limited by precipitation or temperature was tested. It was hoped that this study would provide a scientific reference for the restoration of degraded alpine grassland ecosystems.

Materials and methods

Study area

The study was carried out on northern Tibetan Plateau, where the mean elevation is 4,500 m above sea level, being high in the north and south and low in the middle. The plateau's surface is characterized by quite integrated, hummocky uneven terrain. The strath and basin are widely distributed. It features a typical continental highland climate, being cold, dry and arid or semi-arid in most regions of the Plateau and has low annual precipitation and high annual evaporation. There are large annual and daily changes in air temperature. The mean air temperature is 6–10°C in the warmest month and below −10°C in the coldest month. Annual precipitation ranges from 100 to 300 mm and decreases from southeast to northwest (Yang and Zheng 2002). It exhibits no obvious four seasons, and it has only a cold season (long, cold and dry) and a warm season (short, wet and cool). The growing season is only 90–150 days. This area has strong winds in winter and spring, and the annual wind velocity averages 3.4 m s^{-1}. The representative vegetation types are alpine meadow mainly consisting of *S. subsessiliflora* var. *basiplumosa* or *Festuca ovina*, alpine steppe typically composed of *Stipa purpurea, Carex moorcroftii* and compact ceratoides, and desert grassland principally consisting of *Stipa glareosa* and alpine desert predominated by *Ceratoides laten*. The soil layer is thin with a high gravel content. The most widely distributed soil type is cold frozen calcium (alpine steppe soil) under the alpine steppe, followed by alpine desert grassland soil and alpine desert soil, which developed under plants of the alpine semi-desert and desert (Li 2000).

Sampling

Thirty-seven sampling sites were set up along a transect from Anduo County of Naqu district (31°36.432 N′, 91°42.297′E) in the east to Risong county of Ali district (33°21.055′N, 79°42.644′E) in the west (Fig. 1). The transect covers latitudes from 30°N to 34°N and longitudes from 79°E to 92°E across an area approximately 1,200 km long and 400 km wide. The transect traversed four vegetation zones, including an alpine meadow zone, alpine steppe zone, desert grassland zone and alpine desert zone, from east to west on the northern Tibetan Plateau.

Soil data were collected using soil core in May 2009 (Table 1). A global positioning system was used to locate longitude, latitude and altitude. Belowground biomass was measured on each sampling site to the visible root depth, with the deepest measurements being 1.3 m (depth intervals of 0–5, 5–10, 10–20, 20–30, 30–50, 50–70, 70–100

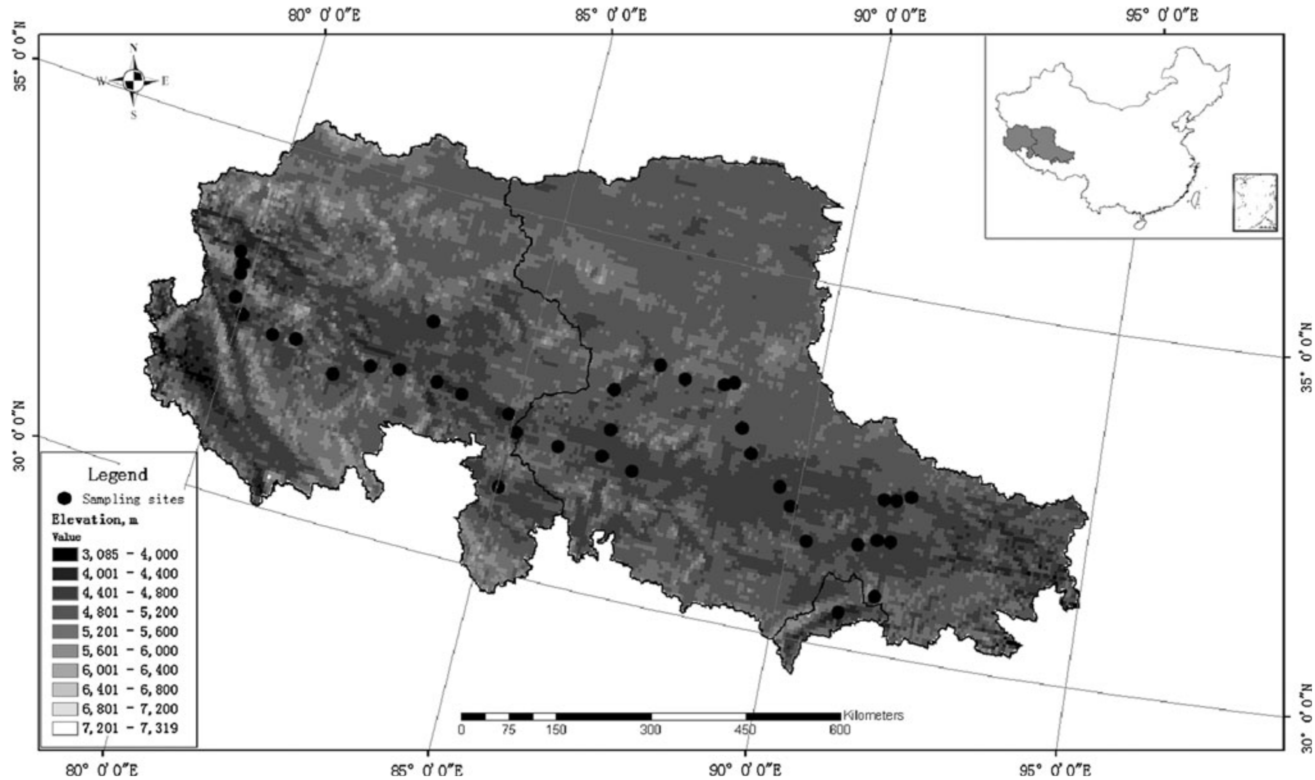

Fig. 1 Location of study area and sampling sites on the northern Tibetan Plateau of China

and 100–130 cm). A soil core (5 cm inner diameter) was utilized to sample roots. Three soil samples were collected from each soil layer in each site and then washed through a sieve to obtain roots. All root samples were oven-dried in a forced-air oven at 85°C for 48 h to a constant weight, and their weights were recorded. Soil samples were collected in each soil layer from three randomly selected points at each site, mixed into one sample and then air-dried for analysis of soil physico-chemical properties, including soil organic matter (SOM g kg^{-1}), soil pH, total N (g kg^{-1}) and total P (k kg^{-1}).

Results

Root distribution among soil profiles

There was a great amount of vertical variation in root biomass density. The root biomass in the different alpine ecosystems was mainly concentrated in the surface layer (0–20 cm), with a density of 1,381.41 ± 245.29 g m^{-2} on average, accounting for 85% of the total root biomass. The average root biomass in each layer decreased exponentially with increasing soil depth (Fig. 2). The proportion of root biomass in each layer to the total was approximately 40% in the 0–5 cm soil layer, 60% in the top 10 cm and 80% in the top 20 cm. The proportion of root biomass to the total root biomass decreased exponentially with increasing soil depth. The exponentially fit equation between the root biomass proportion in each layer to the total and the soil depth in all alpine ecosystems was:

$$y = 5.63 + 46.20 \times \exp(-0.09 \times x) \quad \left(R^2 = 0.72,\ P < 0.01\right)$$

where y is the proportion of root biomass to the total root biomass and x is soil depth.

The distribution pattern of the root biomass proportion in alpine meadow was most similar to that in alpine steppe. The patterns in desert grassland and in alpine desert were highly similar (Fig. 3). The exponential decreasing trends in alpine meadow and in desert grassland were significant at the 0.01 level ($R^2_{\text{alpine meadow}} = 0.91$, $R^2_{\text{desert grassland}} = 0.76$). In alpine steppe and alpine desert, they were significant at the 0.05 level ($R^2_{\text{alpine steppe}} = 0.82$, $R^2_{\text{alpine desert}} = 0.69$).

The average root depth in all sites was 49.74 cm, reflecting the shallow plant root depths on the northern Tibetan Plateau. The average maximum root depth was 48.57 cm for alpine meadow, 56.88 cm for alpine steppe, 47.50 cm for desert grassland and 46 cm for alpine desert. The root biomass density decreased with increasing root depth (Fig. 4). The maximum root depths explained 12% of the variation in root biomass density ($P < 0.025$) for the 37 sampling sites in the sampling transect of the northern Tibetan Plateau.

Table 1 Description of the sampling sites located in the transect of northern Tibetan Plateau

Site name	Longitude (E) (°)	Latitude (N) (°)	Altitude (m)	MAT (°C)	MAP (mm)	Vegetation type
East Namaqie	91.92	32.27	4,594	−1.09	493.19	AM
Anduo	91.70	31.61	4,629	−2.96	456.49	AM
Gulu	91.68	32.19	4,694	−0.94	476.92	AM
Namaqie	91.62	30.81	4,568	−0.95	479.89	AM
Cuoma	91.48	31.59	4,612	−1.80	469.10	AM
West Namaqie	91.48	32.17	4,750	−1.60	440.58	AM
Dangxiong	91.18	31.49	4,325	1.57	498.59	AM
East Naqu	91.07	30.50	4,630	−0.31	408.80	AS
East Maqian	90.31	31.39	4,578	−0.56	386.66	AS
East Duoma	89.93	31.83	4,642	−1.15	364.59	AS
Duoma	89.69	32.06	4,789	−2.16	317.50	AS
East Shuanghu	89.08	32.44	4,896	− 2.79	299.25	AS
East Gacuo	88.85	32.76	5,135	−4.04	270.44	AS
Gacuo	88.56	33.35	4,859	−3.06	280.63	AS
West Gacuo	88.40	33.30	4,921	−3.12	249.12	AS
Beicuo	87.71	33.25	4,817	−2.87	234.35	AS
Nima	87.25	33.36	4,659	−0.40	257.70	AS
Egiu	87.17	31.83	4,538	−0.75	237.19	AS
West Nima	86.66	32.32	4,615	−0.53	234.28	AS
Rongma	86.62	31.94	4,730	−2.24	213.67	AS
Asuo	86.56	32.88	4,948	−1.71	185.54	AS
Zhongcang	85.85	31.93	4,587	−0.51	179.38	AS
Cuoqin	85.11	31.97	5,032	−1.18	159.92	AS
Dongcuo	85.05	31.17	4,425	0.09	185.30	AS
Gaize	84.91	32.19	4,447	−0.12	153.96	DG
Wuma	84.05	32.29	4,437	−0.41	137.29	DG
Xianqian	83.59	32.37	4,706	−1.88	115.32	DG
Wenbu	83.25	33.17	4,460	−0.08	122.23	DG
Yanhu	82.91	32.39	4,667	−1.55	91.20	DG
Xiongba	82.42	32.33	4,611	−0.32	89.24	DG
Geji	81.83	32.07	4,506	0.04	77.07	DG
Zuozuo	81.06	32.40	4,775	−1.63	53.64	DG
Shiquanhe	80.65	32.37	4,350	0.83	63.66	AD
Lameila	80.06	32.52	4,796	−2.20	37.34	AD
Risong	79.86	32.72	4,352	−0.10	54.72	AD
South Risong	79.82	33.20	4,390	−0.25	52.82	AD
North Risong	79.82	33.05	4,288	−0.70	48.53	AD

Site description with longitude, latitude, altitude, mean annual temperature for 30 years (MAT), mean annual precipitation for 30 years (MAP) and vegetation type of each site. Climate data for the sample sites were obtained from spatial interpolation values in ANUSPLIN (Hutchinson 2004) using mean annual precipitation and temperature derived from weather stations data recorded from 1978 to 2008 on the northern Tibetan Plateau

Vegetation type: *AM* alpine meadow, *AS* alpine steppe, *DG* desert grassland, *AD* alpine desert

Effects of grassland type on root distribution

The root biomass density decreased from east to west along the transect and varied with different vegetation types as follows: 3,799.14 ± 1,131.62 g m^{-2} for alpine meadow, 1,412.77 ± 200.75 g m^{-2} for alpine steppe, 919.07 ± 321.93 g m^{-2} for desert grassland and 397.64 ± 85.67 g m^{-2} for alpine desert. The root biomass density in alpine meadow was 2.69, 4.13 and 9.55 times greater than that in alpine steppe, desert grassland and alpine desert,

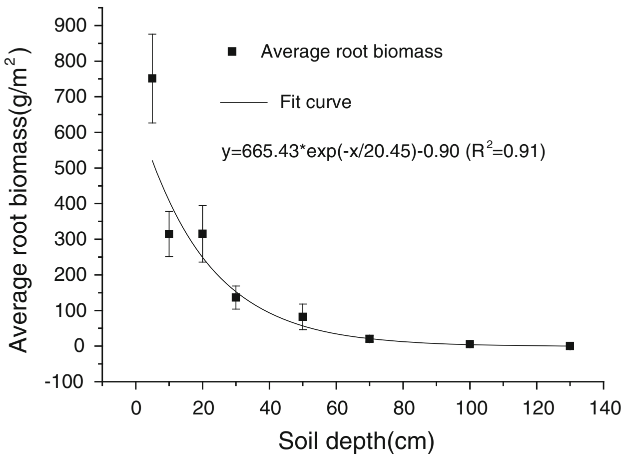

Fig. 2 Distribution of average root biomass through soil depth. *Error bars* indicate standard error of the mean

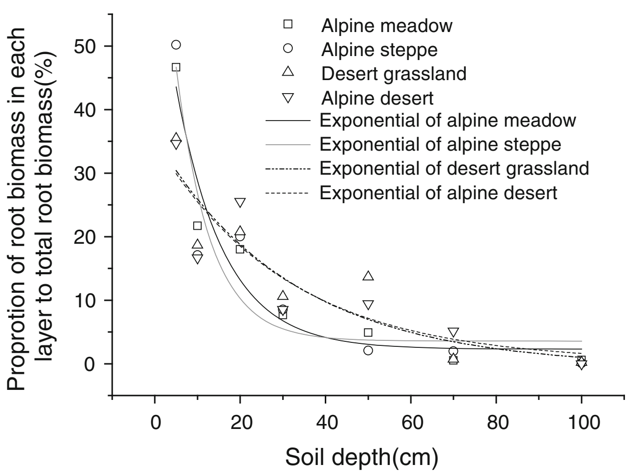

Fig. 3 The change of the proportion of root biomass in each soil layer to total root biomass with soil depths

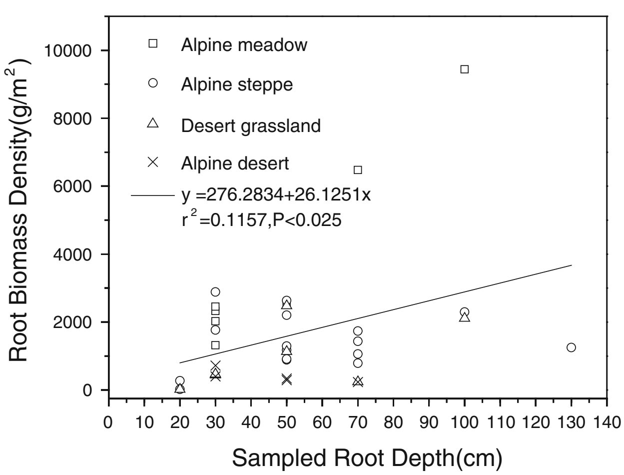

Fig. 4 Relationship between sampled maximum root depth and root biomass density

respectively. The analysis of variance indicated that the root biomass density in alpine meadow was higher than for the other vegetation types (statistically significant at the 0.05 level), but the root biomass density compared among the other vegetation types was not statistically significant. The average root biomass for the entire depth at all sampling points was 1,626.08 ± 301.76 g m^{-2}. The change of root biomass in different vegetation types varied with different soil depths (Fig. 5), and the curves for root biomass were able to fit by exponential equations. Root biomass exhibited significant differences among the four vegetation types ($F = 6.966$, $P = 0.001$, $df = 3$). In conclusion, the highest root biomass appeared in alpine meadow and alpine grassland, and it varied greatly with soil depth. The lowest root biomass occurred in desert grassland and alpine desert, where the variation among sites was small.

Relationships between root biomass and environmental factors

The total root biomass (TRB) at each sampling point showed a highly significant positive correlation with the mean annual relative humidity (RH) ($R = 0.472$, $P < 0.01$) and mean annual precipitation (MAP) ($R = 0.528$, $P < 0.01$) on the Northern Tibetan Plateau, whereas there was no significant correlation with mean annual temperature (MAT) ($R = -0.298$, $P > 0.05$) (Table 2). The total root biomass was significantly correlated with the average content of soil organic matter (SOM) ($R = 0.390$, $P < 0.02$) and soil pH ($R = -0.545$, $P < 0.01$), whereas it had no significant correlation with TN and TP (Table 2).

Discussion

Root distribution among soil profiles

The root distribution differed with soil depths (Snyman 2006; Rodríguez et al. 2007b). The root biomass exhibited a pattern of being concentrated in the surface soil layer, similar to findings in previous studies (Yan et al. 2005; Li et al. 2006). The root biomass in the top soil (0–10 cm) represented 65.57% of the root biomass in Tibet Plateau, which is higher than the 47% in a temperate grassland of inner Mongolia (Ma et al. 2008) and 44% in temperate zone grasslands globally (Jackson et al. 1996). The higher concentration in top soil layer might be due to special environmental conditions that are obstructive to root growth (such as permafrost and high soil rigidity). Root biomass below the surface layer (0–20 cm) changed very little, particularly below 30 cm, partly because of the root growth-limiting factors of the arid climate, strong fragmental soil and low vegetation coverage on the northern

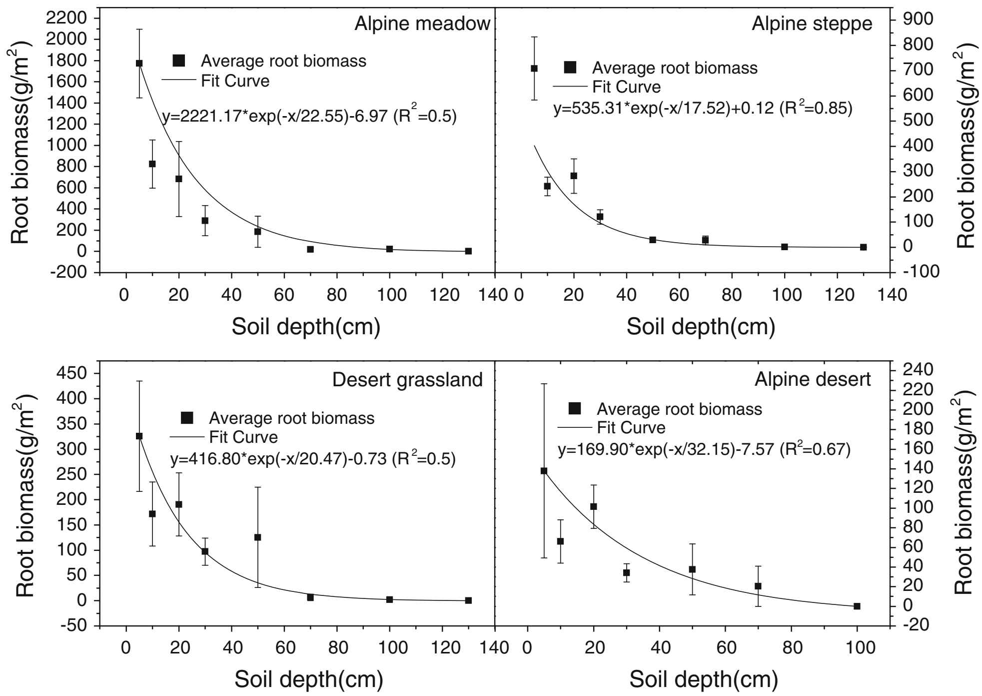

Fig. 5 Distribution of average root biomass in different vegetation types through soil depth

Tibetan Plateau. The pattern of decreasing root biomass with increasing soil depth was in accordance with the results of previous studies (Ma et al. 2008), which might be caused by an increase in soil grain size and decrease in soil nutrient levels with depth (Yang et al. 2009a).

The proportion of root biomass in the surface soil (0–20 cm) compared to the total root biomass was large (74.85–87.29%), as it may mainly be affected by hydrothermal conditions. The proportion of root biomass in each layer compared to total root biomass was similar in different vegetation types. This could partially be explained by the fact that the same limiting factors influenced root growth in the different vegetation types. Gravel content or coarse sand content increased sharply below 30 cm, and poor soil nutrient conditions in deep soil could limit root growth.

Effect of grassland type on root distribution

The variation pattern of root biomass density found in different vegetation types was basically consistent with that reported by Yang et al. (2009b). The spatial variation pattern may be closely related to climatic conditions, vegetation coverage and soil environmental factors. The median root biomass found in the alpine steppe ecosystem of Tibet Plateau over the root distribution depth was 1,270.83 g m^{-2}, which was considerably different compared to what was found in other studies (Yan et al. 2005; Yang et al. 2009b). In the present study, the average root biomass found in desert grassland was 919.07 ± 321.93 g m^{-2}, which was higher than the average of 855.0 g m^{-2} found across desert grasslands of terrestrial ecosystems in China, based on the ratio of root/shoot (Fang et al. 1996) and lower than that of 301.0 g m^{-2} found in a desert grassland of Inner Mongolia in China (Ma et al. 2008). This might be caused by the different sampling depths, sample size, calculation methods, different sampling timing and positions in these studies (Ping et al. 2010). In addition, it might be related to the different research regions, and environmental conditions were also an important factor. Therefore, the study of root biomass in alpine ecosystems requires longer study periods and larger-scale surveys.

Relationships between root biomass and environmental factors

Root biomass was affected by environmental factors (Pechackova et al. 1999). Temperature and precipitation affect the dynamics of alpine grassland biomass on the Tibetan Plateau (Wang et al. 2007b). Temperature and precipitation take on spatial variation patterns and may have an indirect effect on the spatial changes of root biomass. However, the relationships between root biomass and climate factors have been difficult to infer due to the interactive effects of temperature, moisture and soil nutrients on root biomass (Snyman 2009). In the long term, temperature and precipitation are considered to be the limiting factors for the growth and distribution of vegetation. The present study found that root distribution is solely limited by precipitation on the northern Tibetan Plateau.

Table 2 Correlation coefficients and significant levels of the relations between root biomass and environmental factors

	TRB	MAP	RH	MAT	TN	TP	SOM	PH
TRB								
Pearson correlation	1	0.528**	0.472**	−0.298	0.104	0.138	0.390*	−0.545**
Sig. (2-tailed)		0.001	0.003	0.073	0.538	0.415	0.017	0.000
N	37	37	37	37	37	37	37	37
MAP								
Pearson correlation	0.528**	1	0.974**	−0.143	0.535**	−0.455**	0.547**	−0.500**
Sig. (2-tailed)	0.001		0.000	0.399	0.001	0.005	0.000	0.002
N	37	37	37	37	37	37	37	37
RH								
Pearson correlation	0.472**	0.974**	1	−0.145	0.514**	−0.500**	0.497**	−0.487**
Sig. (2-tailed)	0.003	0.000		0.391	0.001	0.002	0.002	0.002
N	37	37	37	37	37	37	37	37
MAT								
Pearson correlation	−0.298	−0.143	−0.145	1	0.051	0.050	−0.079	0.301
Sig. (2-tailed)	0.073	0.399	0.391		0.762	0.769	0.643	0.070
N	37	37	37	37	37	37	37	37
TN								
Pearson correlation	0.104	0.535**	0.514**	0.051	1	−0.384*	0.696**	−0.314
Sig. (2-tailed)	0.538	0.001	0.001	0.762		0.019	0.000	0.059
N	37	37	37	37	37	37	37	37
TP								
Pearson correlation	0.138	−0.455**	−0.500**	0.050	−0.384*	1	0.071	−.045
Sig. (2-tailed)	0.415	0.005	0.002	0.769	0.019		0.676	0.793
N	37	37	37	37	37	37	37	37
SOM								
Pearson correlation	0.390*	0.547**	0.497**	−0.079	0.696**	0.071	1	−0.395*
Sig. (2-tailed)	0.017	0.000	0.002	0.643	0.000	0.676		0.016
N	37	37	37	37	37	37	37	37
PH								
Pearson correlation	−0.545**	−0.500**	−0.487**	0.301	−0.314	−0.045	−0.395*	1
Sig. (2-tailed)	0.000	002	0.002	0.070	0.059	0.793	0.016	
N	37	37	37	37	37	37	37	37

** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed)

The vegetation type changes along the investigated transect from alpine meadow to alpine steppe and further to desert grassland and alpine desert were mainly determined by precipitation. With the moisture gradient decreasing from the southeast to the northwest on the northern Tibetan Plateau, the root biomass exhibited the same variation trend. Precipitation explained 22.9% of the spatial distribution of root biomass, and temperature only explained 4% on the northern Tibetan Plateau. Therefore, the main factor affecting root biomass on the northern Tibetan Plateau was not temperature, but precipitation.

Soil properties, including soil organic matter and pH, could also be important factors affecting root biomass. At the same time, the wide distribution of permafrost, the degradation of permafrost and undetermined environmental variables may impact root biomass. Future research on the factors affecting root biomass will be helpful in establishing the relationship between root biomass and limiting factors and to estimate regional root biomass.

Conclusions

Root biomass density was concentrated in the top 20 cm soil layer and exhibited a sharp decrease with soil depth as an exponential function of soil depth. Furthermore, root biomass differed among regions with different vegetation types. The amount of root biomass in alpine meadow and alpine steppe was far greater than the root biomass in desert grassland and alpine desert. The growth and distribution pattern of root biomass in alpine ecosystems were closely correlated with hydrothermal factors. Root biomass was negatively correlated with soil pH and positively correlated with average relative humidity, average annual precipitation and the content of soil organic matter. Overall, soil properties and climate factors may contribute in concert to determine differences in the root biomass distribution in alpine ecosystems.

Acknowledgments This research was supported by the National Key Basic Research Development Program of China (Grant No. 2010CB951704) and the National Science and Technology Support Program of China (Grant No. 2007BAC06B01). We are grateful to Guohui Zhong and his team for conducting indoor soil experiments and to our colleagues for collecting samples. We also thank Junxi Wu and Yuqiang Tian for their suggestions and comments.

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