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Meta-analysis of relationships between environmental factors and aboveground biomass in the alpine grassland on the Tibetan Plateau

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Abstract. The Tibetan Plateau, known as the "world's third pole" for its extremely harsh and fragile ecological environment, has attracted great attention because of its sensitivity to global changes. Alpine grassland on the Tibetan Plateau has an important function in the global carbon cycle. Many studies have examined the effects of various environmental factors on biomass distribution. In this study, the relationships between the habitat parameters and the aboveground biomass (AGB) abundance on the Tibetan Plateau were examined through a meta-analysis of 110 field sites across the widely distributed alpine steppe and meadow. The obtained data were then analysed using the classification and regression tree model and the generalized additive model. The results showed that the AGB abundance in alpine steppe was positively correlated with six environmental factors, namely, soil organic carbon density of the top soil layer from 0 cm to 30 cm (SOC30 cm), longitude, mean annual precipitation (MAP), latitude, clay, and soil moisture. For the alpine meadow, five main factors were detected, namely, altitude, soil moisture, nitrogen, MAP, and mean annual temperature. The increased AGB abundance in the alpine steppe was associated with the increased SOC30 cm, MAP, and latitude, and the increased longitude resulted in decreased AGB abundance. For the alpine meadow, altitude and soil moisture showed strongly negative effects on AGB abundance, and soil nitrogen content was positively related to the AGB distribution across all examined sites. Our results suggest the combined effects of meteorological, topographic, and soil factors on the spatial patterns of AGB on the Tibetan Plateau.

1 Introduction

Grasslands, covering approximately 25 % of the land surface on earth, account for 10 % of the global soil carbon stocks (Hui and Jackson, 2006). Vegetation biomass and production are of vital importance (Jobbágy and Sala, 2000; Ma et al., 2008) because both aboveground biomass (AGB) and belowground biomass are the major contributors to soil organic matter, which can affect greenhouse gas emissions in terrestrial ecosystem; thus, vegetation biomass has a particular function in the global carbon cycle (Mokany et al., 2006; Wang et al., 2011). The Tibetan Plateau is well known for its extremely harsh environment and high sensitivity to climate changes (Chapin et al., 2008). Vegetation on the Tibetan Plateau is difficult to recover once disturbed or degraded because of its thin soil layer (Zhang et al., 1998). The Tibetan Plateau has faced environmental degradation in recent years because of intensified human activities in the area such as overgrazing, wood harvesting, and collecting specific herbs for the production of Chinese medicine (Wang et al., 2000). Therefore, the severely affected environment is more fragile and sensitive to climate changes, resulting in increasing attention to the issue of ecological security in China. Alpine grasslands are the most extensive vegetation on the Tibetan Plateau and cover an area of more than 2.5 million km^2 (Shen et al., 2008). The spatial patterns of biomass shape the dynamics of the alpine grassland's carbon cycles. Therefore, elucidating the mechanisms that determine the alpine grassland biomass along different ecological gradients is fundamental to understanding ecosystem responses to global changes in ecologically fragile regions.

The relationship between biomass and plant species richness has been extensively investigated (Bhattarai et al., 2004; Thomas and Bowman, 1998; Namgail et al., 2012; Wang et al., 2008; Han et al., 2007; Grytnes, 2000). Recent studies further implicate the optimal portioning and isometric mechanisms for AGB and belowground biomass allocation from individual plant to the community levels. The spatial pattern of biomass is considered to depend largely on meteorological conditions, topographic variables, and soil characteristics. For instance, biomass spatial patterns have been shown to be severely affected by environmental variables, including meteorological factors (Ma et al., 2010a; Yang et al., 2009; Zhang et al., 2010), soil properties (Yang et al., 2009b; Lu et al., 2011; Gerdol et al., 2004), and topographical factors (Bruun et al., 2006; Luo et al., 2004; Litaor et al., 2008; Fisk et al., 1998). Many studies have examined the relationship between AGB distribution and environmental factors. However, the relative contributions of different environmental variables to the spatial patterns of alpine grassland biomass remain unclear when all aforementioned environmental factors are included for analysis. The integrative effects of environmental factors (i.e. precipitation, temperature, soil silt, and sand) on the AGB of the alpine grassland were analysed (Yang et al., 2009b) on the Tibetan Plateau; temperature and soil texture were found to be determinants of AGB in alpine grasslands. Generally, the environmental factors that affect the spatial pattern of biomass can be divided into three categories: meteorological factors (i.e. air temperature, relative humidity, and precipitation), topographic factors (i.e. longitude, latitude, altitude, slope, and aspect), and soil factors (i.e. soil moisture, soil temperature, soil nutrient, soil texture, and soil organic matter). However, only a limited number of environmental factors have been analysed in previous studies, and the effect of vegetation type has been considered. The vegetation type of the alpine steppe is highly different from that of the alpine meadow. The alpine steppe is dominated by cold-xerophytic, short, and dense tussock grasses such as *Stipa purpurea* and *Festuca ovina*, and the alpine meadow is dominated by perennial tussock grasses such as *Kobresia pygmaea* and *Kobresia tibetica* (Ma et al., 2010b; Zhang et al., 1988).

The objectives of the present study were to investigate the distribution pattern of AGB abundance on the Tibetan Plateau and its relationship with the environmental factors in the alpine steppe and meadow, respectively, and to identify the main factors using the classification and regression tree (CART) model. We also predicted the evolutions of AGB with the major environmental factors using the generalized additive model (GAM).

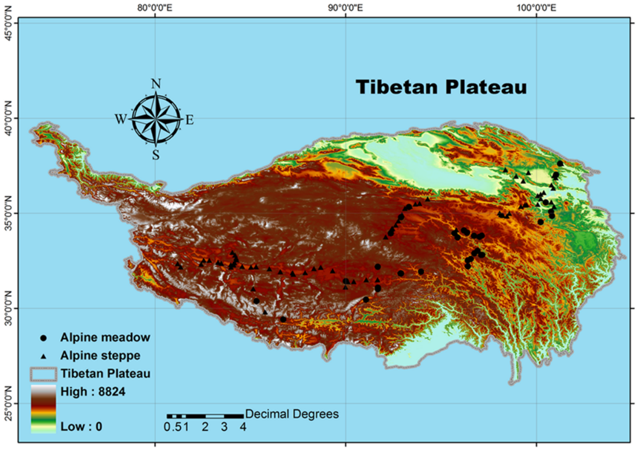

Fig. 1. Spatial distribution of the sampling sites in the alpine grasslands on the Tibetan Plateau, China. Samples were collected in the alpine meadow (circles) and alpine steppe (triangles) from 2001 to 2005.

2 Material and methods

2.1 Study area

The Tibetan plateau is high altitude grassland interspersed with mountain ranges (bordered to the north by the Kunlun Range and to the northeast by the Qilian Range) and large brackish lakes. In the region, the grassland mainly consists of alpine meadow and alpine steppe (Wang et al., 2006). The annual precipitation is increasing in the Tibetan Plateau. Permafrost covers extensive parts of the northern and northwestern plateau. In the Changthang region, the average altitude exceeds 5000 m (Zhang et al., 2002; Cheng et al., 2011). The unique climate, vegetation types, and relatively low intensity of human disturbance make the plateau an ideal region to investigate the natural ecosystem response to climate change (Yang et al., 2008). The examined alpine grassland area (latitude from 29.41 to 37.61° N and longitude from 81.18 to 101.31° E) and the sampling sites chosen in this study are presented in Fig. 1.

2.2 Data collection

The data package required in this study include meteorological factors (i.e. mean annual temperature (MAT), mean annual precipitation (MAP), and aridity index (Idm)), topological factors (i.e. longitude, latitude, altitude, slope, and aspect), soil factors (i.e. moisture, clay, silt, nitrogen, and organic carbon density at the depth of 30 cm (SOC30 cm), 50 cm (SOC50 cm), and 100 cm (SOC100 cm)), grassland types (i.e. alpine steppe and alpine meadow), and one target variable of AGB abundance (Table 1). Table 1 and Fig. 1 show the data we adopted from previous studies (Yang et al., 2009a, 2008), in which the samples were collected from 110 sites (74 in the alpine steppe and 36 in the alpine meadow;

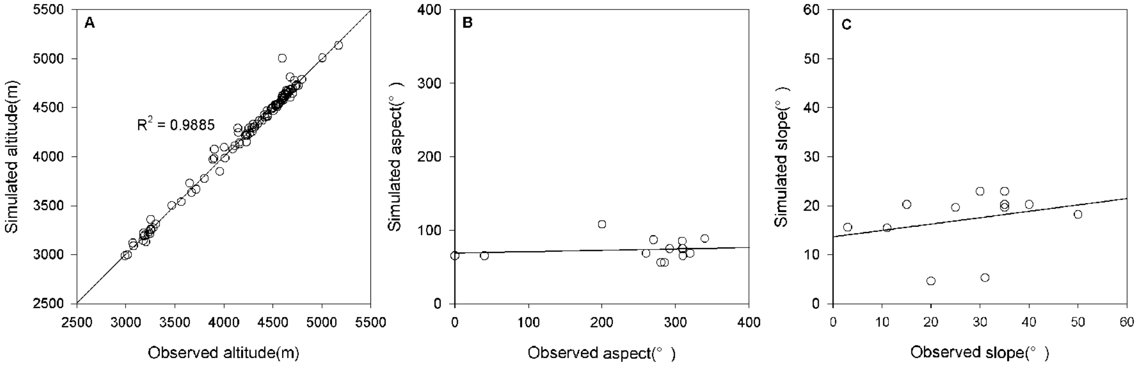

Fig. 2. Comparison of the simulated results of the topographic factors: altitude **(A)**, aspect **(B)**, and slope **(C)** with the observed values (with good fittings, $R^2 = 0.9885$) obtained only for altitude.

Table 1. Descriptive statistics of the environmental factors and AGB.

Alpine ecosystem	Descriptive statistics	Topographic factors					Soil factors								Meteorological factors			Target variable
		Longitude (°)	Latitude (°)	Altitude (m)	Slope (°)	Aspect (°)	Moisture (%)	Clay (%)	Silt (%)	Nitrogen ($\mathrm{mg\,g^{-1}}$)	SOC30 cm ($\mathrm{kg\,m^{-2}}$)	SOC50 cm ($\mathrm{kg\,m^{-2}}$)	SOC100 cm ($\mathrm{kg\,m^{-2}}$)	MAT (°C)	MAP (mm)	Idm	AGB ($\mathrm{g\,m^{-2}}$)
Alpine steppe ($n = 72$)	Maximum	101.31	37.61	5168	–	–	25.7	4.82	54.92	5.1	11.38	15.82	23.41	2.96	521.3	46.72	347.5
	Minimum	81.18	29.81	2990	–	–	1.5	0.17	2.93	0.1	0.39	0.39	0.39	−3.09	119.6	9.72	9.8
	Mean	91.84	33.88	4237.66	–	–	10.09	2.19	19.07	1.37	3.28	4.3	5.52	0.32	309.1	30.96	60.07
Alpine meadow ($n = 36$)	Maximum	101.24	37.61	5004	–	–	43.4	5.46	47.47	10.6	15.32	22.79	34.64	4.05	694	60.85	255.9
	Minimum	85.32	29.41	3179	–	–	3.2	0.94	6.86	0.4	0.93	1.26	1.32	−2.96	288.6	23.27	31.8
	Mean	95.02	33.08	4201.8	–	–	24	3	29.41	4.77	7.71	9.47	11.42	1.01	500.13	45.73	111.81

Note: Soil organic carbon density in the depth of 30 cm (SOC30 cm); Soil organic carbon density in the depth of 50 cm (SOC50cm); Soil organic carbon density in the depth of 100 cm (SOC100cm), Mean annual temperature (MAT), Mean annual precipitation (MAP), Index of aridity (Idm), and Aboveground biomass (AGB). The sample size is 110.

each site area is 10 m × 10 m) in July and August of each year between 2001 and 2005. Moisture, nitrogen, silt, clay, and organic carbon density (at depths of 30, 50, and 100 cm, respectively) of the soil were determined at each site. Meteorological factors were also examined using spatially interpolated methods from the records of 43 climatic stations (Piao et al., 2003; Yang et al., 2008). The data of altitude, slope, and aspect were extracted by digital elevation model (DEM) using the ArcGIS 9.3 software and compared with the results of previous studies (Feng et al., 2006; Yang et al., 2008) (Fig. 2). A good fit was observed only for the factor of altitude (Fig. 2a, $R^2 = 0.9885$) between previous observations (Yang et al., 2008) and the simulated DEM results in this study. However, the poor fitting effects of aspect and slope were not used for the correlation analysis (CA) between AGB and the topographic factors. As an important meteorological factor, Idm was calculated using the data of MAT and MAP by the formula (De Martonne, 1926): $\mathrm{Idm} = P/(T + 10)$, where P is the average precipitation (mm) and T is the average temperature (°C).

2.3 Data analysis

The apparent effects of each environmental factor on AGB abundance were studied by CA using the data collected across various studied sites. The CART model was used as previously described (Breiman, 1984). CART enables the possible interactions and adjustments for making decisions (Toschke et al., 2005), as it can identify the critical variables that significantly influence the response variables. In the analysis, the R-package repart containing the repart function, repart. control function, and prune function was used. The method works by splitting the data into mutually exclusive subgroups (nodes), within which all the objects have similar values for the response variable. Using a repeated binary splitting procedure, the process starts from the split of the root (or parent node) containing all the objects in the data set into two nodes (or child nodes), and the process continues by treating each obtained child node as a new parent node (Put et al., 2003). We used the x-error as a criterion to determine the critical factors. When x-error reaches a minimum, the optimal tree is obtained, and the main environmental factors of the optimal tree are simultaneously screened. CP is a complexity parameter; any split that does not decrease the overall lack of fit by a factor of CP is not attempted. For instance, with ANOVA (analysis of variance) splitting, the overall R-squared must increase by CP at each step. The main function of this parameter is to save computing time by pruning off splits that are not important. The user informs the program that any split that does not improve the fit by CP will likely be pruned off by cross-validation so the program need not pursue this split (R Development Core

Table 2. Correlations between AGB and environmental factors.

AGB	Items	Longitude	Latitude	Altitude	MAT	MAP	Moisture	Clay	Silt	Nitrogen	SOC30 cm	SOC50 cm	SOC100 cm	Idm
Alpine steppe	Pearson Correlation	0.620^{b}	0.645^{b}	-0.616^{b}	-0.177	0.504^{b}	0.555^{b}	0.121	0.519^{b}	0.583^{b}	0.683^{b}	0.696^{b}	0.720^{b}	0.465^{b}
	Sig. (2-tailed)	0.000	0.000	0.000	0.131	0.000	0.000	0.302	0.000	0.000	0.000	0.000	0.000	0.000
	N	74	74	74	74	74	74	74	74	74	74	74	74	74
Alpine meadow	Pearson Correlation	0.503^{b}	0.389^{a}	-0.418^{a}	0.071	0.092	0.303	0.132	0.342^{a}	0.502^{b}	0.433^{b}	0.432^{b}	0.417^{a}	0.022
	Sig. (2-tailed)	0.002	0.019	0.011	0.679	0.594	0.072	0.443	0.041	0.002	0.008	0.009	0.011	0.900
	N	36	36	36	36	36	36	36	36	36	36	36	36	36

Note: [a] correlation is significant at the 0.05 level (2-tailed). [b] Correlation is significant at the 0.01 level (2-tailed). All designations are the same as those in the footnotes below Table 1.

Team, 2011). Initially, we set the CP value to 0.001 in the R-procedure. All the predictive variables were included in the formula, and the results showed that some variables were finally adopted in the model. Nevertheless, the model was still highly complex. Such trees are often difficult to interpret, and their predictive ability for new observations is generally poor because they tend to match noise in the data. The establishment of a smaller tree, derived from the maximal one, was then generated for predictive purposes. Therefore, we used the prune function to prune the tree. Through the R-output, we noted that the x-error value decreased with the number of splitting, but the x-error value increased in the next splitting. An effective method to develop an appropriate tree is to seek the minimum of x-error value. We found that the minimum of x-error value was associated with a CP value in the output list. This new CP value was used to fit the model. Details of the CART process can be found in Supplement S1 to S4 in the supporting information. Finally, GAM analysis was conducted to explore the evolutionary trend of AGB abundance with respect to the critical environmental factors. The R-package mgcv was used to fit GAMs specified by giving a symbolic description of the additive predictor and a description of the error distribution. The gam used the backfitting algorithm to combine different smoothing or fitting methods (R Development Core Team, 2011; Qian, 2008). The mgcv package contained the gam function, gam. fit. function, and family function. In the study, statistical analysis and plotting were performed using the R-freedom software (version 2.15) (R Development Core Team, 2011).

3 Results

3.1 Effects of environmental factors on AGB abundance

The effects of environmental factors (i.e. topographic, soil, and meteorological factors) on AGB abundance were examined by Pearson CA (Table 2). The results showed that AGB abundance was positively related to the topographic factors (i.e. longitude and latitude) and soil factors (i.e. SOC30 cm, SOC50 cm, and SOC100 cm) across all sites in the alpine steppe, with the corresponding R^2 values of 0.620, 0.645, 0.683, 0.696, and 0.720, respectively. By contrast, the AGB abundance of the alpine meadow was statistically or negatively or positively related to soil nitrogen, SOC30 cm, SOC50 cm, SOC100 cm, moisture, longitude, and altitude, with the corresponding R^2 values of 0.502, 0.433, 0.432,0.417, 0.303, 0.503, and 0.389, respectively.

3.2 Identification of critical factors by CART model

The effects of all kinds of environmental conditions on AGB abundance were observed. The minimum of x-error was 0.4151, with a CP value of 0.0114 in the output list (Fig. S2 in the Supplement), and the optimal tree was obtained. As shown in Fig. 3a, six critical environmental factors (i.e. SOC30 cm, longitude, MAP, latitude, clay, and moisture) were obtained for the alpine steppe; the tree consists of a root node (SOC30 cm) containing all samples ($n = 74$). For the alpine meadow, the minimum x-error of 1.0202 was obtained, with a CP value of 0.5424 in the output list, for the construction of the optimal tree. Only one root node in the tree did not meet the minimum standard of five nodes required for CART analysis; thus, the CP value of 0.0437 and x-error value of 1.928 were used to generate a new tree (S4 in the supporting information). As shown in Fig. 3b, five critical environmental factors (i.e. altitude, moisture, nitrogen, MAP, and MAT) were obtained; the tree consists of a root node (altitude) containing all samples ($n = 36$).

3.3 Prediction of the changing trend of AGB abundance by GAM

To further explore the relationships of environmental variables with AGB, the distribution type of samples should be analysed. Figure 4 shows that the samples were from non-normal distributions for both alpine steppe and meadow. GAM was used to understand this relationship. AGB abundance exhibited large variations across all sites, ranging from 10 to 348 $\mathrm{g\,m^{-2}}$ for the alpine steppe and from 32 to 256 $\mathrm{g\,m^{-2}}$ for the alpine meadow. The average values were

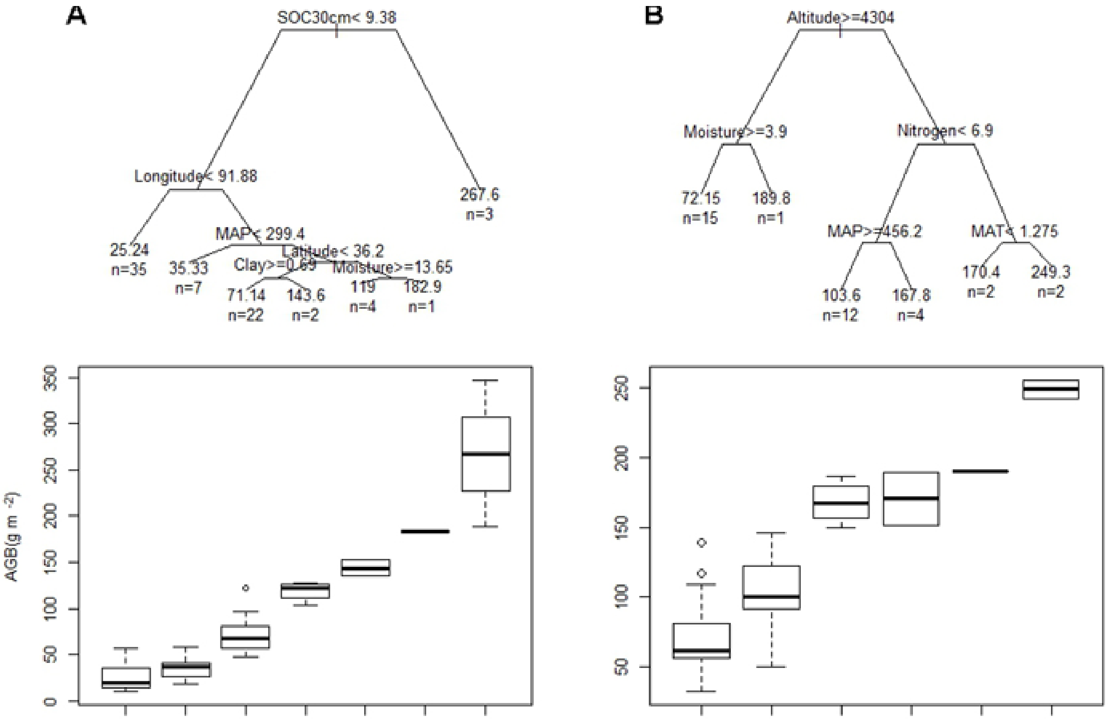

Fig. 3. CART analyses of the relationships between AGB abundance and environmental factors in the alpine steppe **(A)** and the alpine meadow **(B)**. The environmental factors are indicated in the graph by the screening in the higher panel. In the lower panel, the box-plots represent the deviation of AGB under the corresponding environmental factors in the children nodes. All designations are the same as those in the footnotes below Table 1.

60 and 118 $\mathrm{g\,m^{-2}}$ for the alpine steppe and meadow (Table 1), respectively.

The results of the GAM spline fittings regarding each individual environmental factor to AGB abundance varied from simple linear functions to highly complex curves. The response curves of the critical factors for the alpine steppe (i.e. SOC30 cm, longitude, MAP, MAT, and soil moisture) and the alpine meadow (i.e. altitude, soil moisture, and nitrogen) are shown in Fig. 5.

The relationships of AGB abundance with the critical factors showed two dominant patterns in the alpine steppe. The first pattern is that the AGB curves increased with the increasing SOC30 cm and MAP values, with the maxima AGB observed at the corresponding values of approximately 10 $\mathrm{kg\,m^{-2}}$ for SOC30 cm and 500 mm for MAP, respectively (Fig. 5a, c). The second pattern is a linear decline in AGB with increasing longitude and a linear increase with increasing latitude, with the maxima AGB observed at the longitude of 80° E and latitude of 37° N, respectively (Fig. 5b, d). However, the relationship of AGB with soil moisture was not apparent because of the large value of errors (Fig. 5e). This relationship cannot be obtained by GAM. Overall, the shapes of these response curves of critical environmental factors were highly variable, indicating their spatial variability.

For the alpine meadow, the relationships between AGB abundance and the critical environmental factors showed a general decline with increasing altitude and soil moisture (Fig. 5f, g). In this trend, the maxima of AGB were observed at an altitude of approximately 3000 m and soil moisture of 5 %. The other trend we observed was a generally positive relationship between AGB abundance and soil nitrogen, with the maxima AGB observed at a soil nitrogen level of approximately 10 $\mathrm{mg\,g^{-1}}$ (Fig. 5h).

4 Discussion

4.1 Soil properties

For the alpine steppe, the increase in SOC30 cm led to increased AGB, but increased longitude resulted in decreased AGB abundance. Soil organic matter generally constrains the supply of soil nutrients, resulting in limited tundra production (Holzmann and Haselwandter, 1988). In alpine zones, low temperature results in the restricted activity of microbes in the topsoil (0 to 30 cm depth), thus reducing microbial decomposition of soil organic matters and leading to relatively higher soil organic carbon density (Wang et al., 2007). Therefore, soil carbon density at SOC30 cm showed a positive effect on AGB abundance, with nutrient supply most likely coming from soil organic matters for plant growth. The strongly negative relationship between AGB abundance

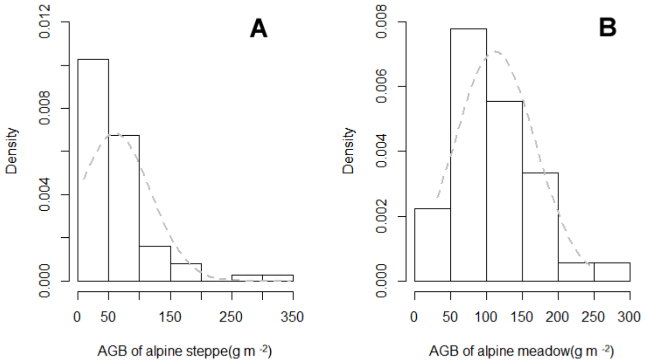

Fig. 4. Density distribution curves of the AGB of samples collected in the alpine steppe **(A)** and the alpine meadow **(B)** of the Tibetan Plateau from 2001 to 2005. All designations are the same as those in the footnotes below Table 1.

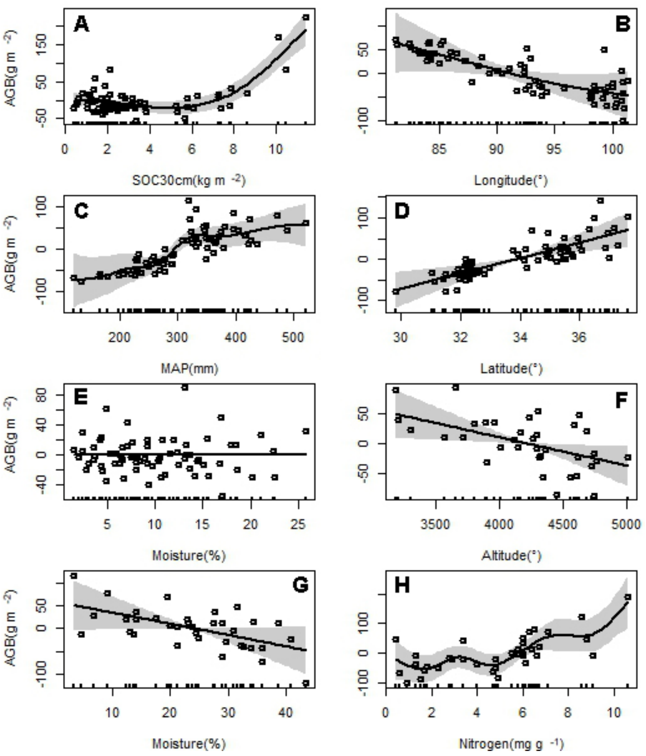

Fig. 5. Predicted changes in the alpine steppe AGB along with the major environmental factors by GAM analysis. Rugplot on the x-axis represents the observed value, and the gray belts indicate the credible intervals. Panels **(A)**, **(B)**, **(C)**, **(D)**, and **(E)** represent the variations of AGB with SOC30 cm, longitude, MAP, latitude, and moisture, respectively, in the alpine steppe. Panels **(F)**, **(G)**, and **(H)** represent the variations of AGB with altitude, moisture, and nitrogen, respectively, in the alpine meadow. All designations are the same as those in the footnotes below Table 1.

and soil moisture across the alpine meadow sites is an interesting finding. We argue that soil moisture is a limiting factor for alpine plant growth and production and can influence AGB abundance. Similar observations were obtained by Oberbauer and Billings (1981) and Yang (2009b), who reported that the local distribution of plant species is largely determined by moisture within the alpine zone of a mountain range. This relationship can reflect the result of long-term plant adaptation to local habitats in these studied areas. For soil nitrogen, nitrogen is the mineral nutrient that plants require in the greatest quantity (Chapin et al., 1987) and that reportedly often limits plant growth in natural ecosystems because of its central function in the photosynthetic apparatus and high mobility in the soil system (Bowman et al., 1993). Therefore, nitrogen content is a major soil factor affecting AGB abundance in the alpine meadow because AGB abundance strongly depends on soil fertility (Han et al., 2007). The relatively low soil mineralization rates and low nutrient availability likely resulted in the relatively low aboveground production in the cold, dry environment of alpine grassland of the Tibetan Plateau. This result is in agreement with previous findings that nitrogen is a key constraint in the alpine meadow. Nitrogen addition leads to community shifts of the dominant grass species (Han et al., 2007; Niklaus et al., 1998). Other soil factors, such as silt soil and sandy soil, appeared to have less important effects on the distribution of AGB. The results were contrary to previous observations (Yang et al., 2009b), and the discrepancy likely resulted from the difference in the data volume of environmental variables used for analysis.

4.2 Topographic conditions

The geographic position that determines the effect of climatic variation significantly influences AGB abundance in grasslands (Briggs and Knapp, 1995). Fisk et al. (1998) reported that topography controls snowpack accumulation and growing-season length, affecting soil water availability, distribution of plant communities, and aboveground productivity. Different geographical responses of plants to topographic positions have been reported in the literature, confirming the significant function of topography in assessing plant species richness. For instance, Bruun et al. (2006) studied the species richness of vascular plants, bryophytes, and lichens in alpine communities, and suggested that topography is an important and better predictor. In this study, a negative effect was observed between longitude and AGB abundance, but latitude showed a positive correlation with AGB abundance in the alpine steppe. This finding disagrees with the previously reported inverse relationship between maximum AGB and latitude (Asaeda et al., 2005). The following statements do not provide a reasonable explanation for the discrepancy between this study and that by Asaeda et al. (2005). Longitude and latitude are likely to be the most primary topographic factors affecting AGB abundance because of the differences in soil conditions and micro-climates in different longitudinal and latitudinal positions. Differences in resource translocation and belowground organs can help explain our findings on the functions of longitude and latitude. In the alpine meadow, a clearly negative linear relationship between AGB abundance and altitude was observed because temperature and soil nutrients decrease with increasing altitude (Rastetter et al., 2004). This result is consistent with previous findings (Roem and Berendse, 2000). However, a hump-shaped relationship is also possible in the case of trampling and overgrazing by domestic livestock at the lower slopes, which depletes plant resources (Namgail et al., 2012). From a geographic perspective, the meadow does not exhibit a zonal distribution. The adequate water and lowlands may be adequate for the meadow, and thus the altitude becomes a limiting factor. The higher the altitude is, the lower the atmospheric temperature, which is more likely to limit meadow growth. By contrast, the steppe exhibits a zonal distribution under sub-humid and semi-arid climatic conditions. Elevation becomes a directly decisive parameter for alpine steppe, with AGB abundance determined mainly by latitude and longitude.

4.3 Meteorological parameters

Precipitation is considered one of the critical factors controlling primary productivity in most alpine steppes (Hu et al., 2010; Huxman et al., 2004; O'Connor et al., 2001) that is strongly influenced by water availability (Epstein et al., 1997). Our results are consistent with those in previous studies showing that aboveground net primary production in alpine steppe is positively related to MAP (Lieth et al., 1978; Xu et al., 2006; Bai et al., 2000). Yang et al. (2009b) also found that AGB in alpine grasslands appears to increase with growing season precipitation, but temperature has a minor function in shaping spatial patterns of AGB.

4.4 Integrative effects of environmental factors

A number of studies have investigated the response and adaptation of plants to various environmental conditions, but meta-analysis has rarely been performed by including a wide variety of environmental factors (Chapin et al., 1987). AGB abundance in the alpine grassland is known to be influenced by soil fertility, spatial pattern, and meteorological conditions of the alpine grassland. However, in this study, significant differences were observed between the alpine steppe and the alpine meadow. The previous limiting factors in the alpine steppe were SOC30 cm and MAP, but soil moisture and nitrogen content had more important functions in the alpine meadow. This difference can be largely explained by the relatively higher soil water content and organic matter in the alpine meadow than those in the steppe. Soil organic matter and rainfall appear to be the primary factors in the alpine steppe because they are the preconditions for soil nitrogen content and moisture. However, because of the cold temperature and soil immaturity, the conversion of soil organic matter into nitrogen nutrient was limited. Therefore, soil nitrogen was found to be a critical factor affecting AGB abundance in the alpine meadow even though relatively high soil organic contents were present in soil. Furthermore, AGB abundance decreased with increasing latitude in the alpine steppe and with increasing soil moisture in the alpine meadow. Further study using more complicated and comprehensive models is required.

5 Conclusions

AGB abundance and the environmental parameters across 110 sites were analysed. GAM was used to investigate the underlying mechanisms that determine the spatial patterns of AGB abundance in the alpine steppe and meadow on the Tibetan Plateau. Based on the CART model, soil organic carbon density of the top soil 30 cm (SOC30 cm), longitude, MAP, and latitude were the critical environmental factors for alpine steppe, and the governing environmental factors for the alpine meadow were altitude, moisture, and nitrogen. The results of this study suggest that the spatial patterns of alpine grassland biomass cannot be explained by a single set of environmental variables and highlight the importance of including key parameters for the predictive understanding of alpine carbon cycles.

Supplementary material related to this article is available online at: http://www.biogeosciences.net/10/1707/2013/bg-10-1707-2013-supplement.pdf.

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