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The critical factors that affected the distribution of aboveground biomass in the alpine steppe and meadow, Tibetan Plateau

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Abstract

Tibetan Plateau – the third pole of the world, with its extremly harsh and fragile ecological environment, is so sensitive to global change that it attracts many scientists' attention. Alpine grassland here is an important component of the global carbon cycle. Many studies have examined links between environmental factors and distribution of biomass, but little showed the critical environmental factors affecting the distribution of biomass. To document the general relationships between the habitat factors and aboveground biomass (AGB) in Tibetan Plateau, and to identify the critical factors for the distribution of AGB in the alpine steppe and meadow, the data of AGB and habitat factors from 110 field sites across the widely distributed alpine steppe and meadow of the plateau were compiled and analyzed with the classification and regression tree (CART) model, and the generalized additive model (GAM). The results showed that (1) the spatial pattern of AGB in alpine steppe was determined by six major environmental factors: soil organic carbon density of soil 0–30 cm depth (SOC1), longitude, mean annual precipitation (MAP), latitude, clay and soil moisture. As to the alpine meadow, the major factors were altitude, soil moisture, nitrogen, MAP and mean annual temperature (MAT). (2) As to the alpine steppe, increased SOC1, MAP and latitude were associated with increased AGB abundance, but increased longitude resulted in lower abundance of AGB. As to the alpine meadow, the distribution of AGB had strong negative relationships with altitude and soil moisture, but a positive correlation with soil nitrogen content across sites. The results suggested that the combined effects of meteorological factors, topographic factors, and soil factors were more significant for the spatial pattern of AGB in Tibetan Plateau. In addition, our work highlights the importance of further studies to seek effects of slope and aspect in alpine grassland.

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1 Introduction

Grasslands account for approximately 25 % of the land surface of the earth and 10 % of global C stocks (Hui and Jackson, 2006); furthermore, vegetation biomass or production significantly contributes to soil organic matters (Jobbágy and Sala, 2000; Ma et al., 2008); and aboveground biomass and belowground biomass are important components of terrestrial ecosystem carbon stocks (Mokany et al., 2006). They play important roles in the Earth's C cycle (Suter et al., 2002) and global change, while global change in turn has significantly affected the natural ecosystems in many regions of the world (Wang et al., 2011).

The Tibetan Plateau is known as the third pole of the world. Its peculiar geographical environment is particularly sensitive to global change (Chapin et al., 2008) compared to other regions because that the natural environment of this region is extremely harsh, and the soil is generally quite thin. Once the vegetation is disturbed or degraded, it is difficult to recover (Zhang et al., 1998). Furthermore, the environment and ecology system of the Tibetan Plateau recently has been detrimentally affected by excessive utilization, overgrazing, wood harvesting, collection of Chinese herbal medicines (Wang et al., 2000). As a result, the environment is severely damaged by climate change and human activities, so the region is of key importance to the ecological security of China. Moreover, grasslands are the most extensive vegetation type covering the Tibetan Plateau, which covers an area of more than 2.5 million km^2 (Shen et al., 2008). Alpine grassland is an important component of the global carbon cycle, and its response to environmental change will play a key role in determining future concentrations of atmospheric carbon dioxide. Therefore, accurate estimates of biomass and quantifying its relationships with environment at regional scales are essential to predict the consequences of global change. To better understand the dynamics of alpine grassland carbon cycles, it is critical to interpret the spatial pattern of biomass and to evaluate the controlling factors.

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Recently, the terrestrial biomass has been one of many hotspots in alpine environment issues. Most of the studies only focused on (1) relationship between plant species richness and biomass (Bhattarai et al., 2004; Thomas and Bowman, 1998; Namgail et al., 2012; Wang et al., 2008; Han et al., 2007; Grytnes, 2000), (2) aboveground and belowground biomass allocation from plant individual (Wang et al., 2010) to community level (Yang et al., 2009a) in Tibetan grasslands for verifying two important hypotheses in plant biomass allocation (Optimal partitioning and isometric allocation), or (3) the biomass spatial patterns (Wu et al., 2007; Luo et al., 2002), and the relationships between biomass and meteorological factors (Ma et al., 2010a; Yang et al., 2009b; Zhang et al., 2010), soil properties (Yang et al., 2009b; Lu et al., 2011; Gerdol et al., 2004), and topographical factors (Luo et al., 2004; Litaor et al., 2008; Fisk et al., 1998). There are many studies that have examined links between environmental factors and distribution of biomass (Li et al., 2011; Huang et al., 2011), but as far as we are concerned there are no attempt to screen the critical factors that affected the distribution of biomass.

Based generalities above, we hold that the environmental factors affecting the spatial pattern of biomass can be divided into three categories: meteorological factors (e.g. air temperature, relative humidity, precipitation, etc.), topographic factors(e.g. longitude, latitude, altitude, slope, aspect, etc.), and soil factors(e.g. soil moisture, soil temperature, soil nutrient, soil texture, soil organic matter, etc.).

In this paper, it should be noted that the inherent properties of vegetation will not be discussed. The objectives of the present study were to investigate the AGB (aboveground biomass) distribution pattern and its relationship with environmental factors on the Tibetan Plateau of China, and to examine the critical factors. Specifically, the study was aimed (1) to document the relationship between spatial pattern of aboveground biomass and the environmental factors in alpine steppe and meadow, (2) to screen the crucial factors that affect the distribution of above-ground biomass using CRT model, (3) to predict the trend of above-ground biomass changed with the main environmental factors by GAM, and (4) to identify the key environmental factors of the alpine steppe and meadow.

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2 Material and methods

2.1 Study area

The Tibetan Plateau is surrounded by massive mountain ranges. It is bordered to the north by the Kunlun Range which separates it from the Tarim Basin, and to the northeast by the Qilian Range. The plateau is a high-altitude arid steppe interspersed with mountain ranges and large brackish lakes. Within the region, alpine grassland is the most important ecosystem, mainly comprised of alpine meadow and alpine steppe (Wang et al., 2006). From west to east and from north to south of the Tibetan Plateau, Annual precipitation increases from 100 to 300 mm. Permafrost covers extensive parts of the plateau in the north and northwest; and the plateau becomes progressively higher, colder and drier, until reaching the remote Changthang region in the northwestern part of the plateau where average altitude exceeds 5000 m and winter temperatures can drop to −40 °C. For the extremely inhospitable environment, the Changthang-Kekexili region is the least populous region in Asia, and it is the third least populous area in the world after Antarctica and northern Greenland (http://en.wikipedia.org/wiki/Tibetan_Plateau). The unique climate and vegetation types, together with a low intensity of human disturbance, make the plateau an ideal region for identifying the responses of natural ecosystems to climate change (Yang et al., 2009).

This study was conducted in the alpine grasslands in Tibetan Plateau (Fig. 1). Vegetation types along the sampled sites included alpine steppe (dominated by cold-xerophytic, short, dense tussock grasses such as *Stipa purpurea* and *Festuca ovina*) and alpine meadows (dominated by perennial tussock grasses such as *Kobresia pygmaea* and *Kobresia tibetica*, usually mixed with alpine forbs, including *Polygonum viviparum* and species of Gentiana and Pedicularis) (Ma et al., 2010b; Zhang et al., 1988). The sampled region covers latitudes from 29.41 to 37.61° N and longitudes from 81.18 to 101.31° E.

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2.2 Data collection

We collected indexes (see Table 1) made in 110 sites (74 sites in alpine steppe and 36 sites in alpine meadow) from Yang' studies (Yang et al., 2008, 2009a, 2009b 2010), they harvested AGB at each site (10 m × 10 m) during the summers (July and August) of 2001–05. In addition, they collected soil samples to determine soil moisture, soil nitrogen, soil silt, soil clay, and soil organic carbon density at the depths of 30, 50, and 100 cm respectively. In the meanwhile, the meteorological factors of corresponding sites were also collected. In our views, we should take account of micro-geomorphy (e.g. slope and aspect), so the data of slope and aspect were extracted from Digital Elevation Model (DEM) via ARCgis 9.3 software, For verifying the accuracy of slope, aspect and altitude, the datum of slope and aspect were compiled from Feng' study (Feng et al., 2006), which were compared with the data from DEM, unfortunately, the low accuracy of data cannot be used as environmental factors. However, the very high correlation of altitude (Fig. 2a, $R^2 = 0.9885$) between observation (data from Yang' studies) and simulation (data from DEM). Even so, the micro-geomorphic factors should be considered when undertaking further research.

The Index of Aridity (Idm) was calculated using data of mean annual temperature (MAT) and mean annual precipitation (MAP), on account of the important indicator of evaluating the meteorological condition. In general, the Idm (de Martonne, 1926) was calculated in accordance with the following formulae:

$$\mathrm{Idm} = P/(T + 10) \quad (1)$$

where P is the average precipitation (mm) and T is the average temperature (°).

Special data package consists of meteorological factors (MAT, MAP and Idm), topological factors (longitude, latitude, altitude, slope and aspect), soil factors (moisture, clay, silt, nitrogen, soil organic carbon density in soil depth of 30 cm (SOC1), soil organic carbon density in soil depth of 50 cm (SOC2) and soil organic carbon density in soil depth of 100 cm(SOC3)), grassland types (alpine steppe and alpine meadow), and one target variable (AGB). The brief of datum is shown in Table 1.

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2.3 Data analysis

Data were processed by the following three steps.

Firstly, the relationships between AGB and environmental factors were studied by correlation analysis (CA). The apparent effects of environmental factors were found in the alpine steppe and meadow, but the critical factors were not identified.

Secondly, we performed classification and regression tree (CART) analysis to examine the relationships of AGB and the environmental factors across various sites. CART model was developed by Breiman (1984). The CART was a useful way to express knowledge that may be of help in decision-making, and it allowed for all possible interactions and adjustments (Toschke et al., 2005). In our study, we just used the CART to identify the critical variables having significant influence on the response variables. In CART analysis, the R package *rpart* was used, it contained *repart* function, *repart.control* function, *prune* function, and so forth. The special process of CART, see Supplement S1–S4.

Lastly, to explore the changed trend of AGB with the key environmental factors, the generalized additive models (GAM) analysis was used. The R package *mgcv* was used to fit generalized additive models, 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 *gam* function, *gam.fit* function and *family* function etc.

In the study, the statistical methodology and plots were made by R freedom software (version 2.15) (R Development Core Team, 2011).

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3 Results

3.1 The relationships between AGB and environmental factors in the alpine steppe and meadow

We explored the effect of environmental conditions on AGB. In Fig. 3 the correlations of topographic factors, soil factors and meteorological factors with aboveground biomass in the alpine steppe and alpine meadow were shown. The results showed that AGB was more sensitive to the topographic factors (longitude and latitude) and soil factors (SOC1, SOC2 and SOC3) across all sites in the alpine steppe, with the R^2 of 0.5914, 0.4614, 0.3624, 0.3897 and 0.4176, while the AGB of alpine meadow was more sensitive to the nitrogen, SOC1, SOC2, SOC3, moisture, longitude and altitude, with the R^2 of 0.4221, 0.2865, 0.246, 0.2028, 0.2777, 0.3396 and 0.2453 respectively.

3.2 Screening the critical factors by CART model in the alpine steppe and meadow

The AGB was closely related to its environmental conditions. For the purpose of distinguishing the major indicators from the environmental factors, we used the environmental factors containing topographic factors, soil factors, meteorological factors and AGB to carry out the CART analysis. CART works through splitting the data into mutually exclusive subgroups, called nodes, within which the objects have similar values for the response variable. The process starts from the root or parent node, which contains all objects of the data set. CART uses a repeated binary splitting procedure, which means that the parent node is split in two nodes, called child nodes. The process is repeated by treating each child node as a parent node (Put et al., 2003).

Initially, we set the CP value to be 0.005 in *R* procedure, which was parameter of the model' complexity (the lower CP value, the more complicated model). The thirteen predictive variables were used in the formula, and the result showed that the ten variables were used in the model. Nevertheless, the model was still very complex. Such trees

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often are difficult to interpret and their predictive ability for new observations is generally poor since they tend to match noise in the data. The selection of a smaller tree, derived from the maximal one, was then necessary for predictive purposes. Among other modeling techniques, one is looking for the best compromise between model fit and prediction properties. So we used the *prune* function to prune the tree, througth the *R* output, we noted that the xerror value decreased with the number of splitting before the No. 6, but the xerror value increased in the next splitting. To ascertain an appropriate tree, seeking the minimum of xerror value is a effective method. We found the minimum of xerror value was correspondent with a CP value (CP = 0.0497) in the output list, the new CP value was used to fit the model and the result was shown in Fig. 4.

In Fig. 4, the six major environmental factors (SOC1, longitude, MAP, Latitude, clay and mositure) were screened in alpine steppe, and the tree consists of a root node (SOC1), containing all samples ($n = 74$). The initial parent was splitted based on the value of the soil organic carbon density in 30 cm soil depth, and the best predictor was obtained. If SOC1 was greater than 9.38 kg m^{-2}, those samples were put in the first terminal node ($n = 3$), and all other AGB samlpes were placed in node 1 (SOC1is < 9.38 kg m^{-2}, $n = 71$). The group of samples in node 2 was initially assigned longitude, and it was also splitted into two children. Prediction was improved by further partitions. If longitude was less than 91.88°, the samples were put in the second terminal node ($n = 35$), and all other samples were placed in node 2 (longitude is > 91.88°, $n = 46$). It followed that, the MAP less than 299.4 mm were placed in the third terminal node ($n = 7$), and the preciptaion more than 299.4 mm were placed in node 3 ($n = 29$). The fourth, fifth and sixth subgroups were Latitude, clay and moisture, respectively. On the other hand, we also found that the sum of squares of deviations were decreased with the splitted parent in boxplots, and the criticlal factors were screened step by step.

In Fig. 5, the five major variables (altitude, moisture, nitrogen, MAP and MAT) were screened in alpine meadow, and the tree consists of a root node (altitude), containing all simples ($n = 36$). The initial parent was splitted based on the value of the altitude,

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and the best predictor was obtained. If altitude was greater than 4303 m, then those samples were put in the left children ($n = 16$), and all other samples were placed in right children (altitude is < 4303 m, $n = 20$). The group of AGB in left were initially assigned Moisture, it was also splitted into two children. Prediction was improved by further partitions. The right node was assigned nitrogen, If soil nitrogen content is less than 6.9 mg g^{-1}, then the samples were put in the left node ($n = 16$), and all other samples were placed in right node (soil nitrogen content is < 6.9 mg g^{-1}). The nodes were assigned MAP and MAT, respectively. It followed that, the samples that satisfied MAP ≥ 456.2 mm were placed the left children ($n = 12$), the other samples was placed the right ($n = 4$). The MAT also was splitted in two subgroups (Both left and right samples of children were $n = 2$). Also the sum of squares of deviations were decreased with the splitted parent in boxplots, and the optimal factors were screened.

3.3 Predicting the changed trend of AGB by GAM in the alpine steppe and meadow

For further exploring the relationships of environmental variables with the response variable (AGB), the distributed type of samples must be analyzed. The Fig. 6 showed that the samples were non-normal distribution in both alpine steppe and meadow. So we used the generalized additive models (GAM) to seek the relationships between environmental factors and AGB. Also the AGB exhibited large variations across all the sites, ranging from 9.80 to 347.50 g m^{-2} for alpine steppe, 31.80–255.90 g m^{-2} for alpine meadow. The median values were 45.20 g m^{-2} and 100.00 g m^{-2} for the alpine steppe and meadow, respectively. The STDEV of the alpine steppe and meadow were 58.33 ($n = 74$) and 56.30 ($n = 36$) (The information was provided by a summary of analysis process).

The GAM spline fits of individual environmental factors to AGB varied from simple linear functions to highly complex curves. We presented response curves for the critical factors including SOC1, longitude, MAP, MAT and soil moisture (Fig. 7) for the alpine steppe, and altitude, moisture and nitrogen for the alpine meadow (Fig. 8).

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Relationships of AGB abundance with critical factors showed two dominant patterns in the alpine steppe. The complicated curves increased in AGB with increasing in SOC1 and MAP, and the maximums of AGB were observed at approximately 10 kg m^{-2} SOC1 and 500 mm MAP. The second pattern, it is a linear decline in AGB with increasing longitude, and a linear increased with increasing latitude, and the maximums were observed at approximately 80° longitude and 37° latitude respectively. However, the relationship of AGB with moisture was not obvious due to the large errors. In other word, the relationship can not be fit by GAM. The shape of these response curves of critical environmental factors was highly variable, reflecting the spatial variability.

In alpine meadow, the relationships between AGB abundance and environmental factors showed a general decline with increased altitude and soil moisture. Within this generally negative trend, the maximums of AGB (Fig. 8) were observed at an altitude of approximately 3000 m and a 5 % of soil moisture. The other panel showed a generally positive relationship between abundance of AGB and the soil nitrogen, and the maximum was observed at approximately 10 mg g^{-1} soil nitrogen. Although the GAM told us an excellent means to seek the changed trend, it was difficult to compare models with the actual situation. Sometimes the fitting results would be contrary to common sense, but it does not prevent us from finding the most effective environmental factors, which is the essence of this method.

4 Discussion

The spatial pattern of abundance of AGB was significantly related to several environmental factors in the alpine grassland of Tibetan Plateau. The SOC1, longitude, MAP and latitude were the dominant variables for predicting the trend of AGB in the alpine steppe, and the altitude, moisture and nitrogen were the critical variables for predicting the trend of AGB in the alpine meadow.

As to the alpine steppe, increased SOC1 (soil organic carbon density of soil 0–30 cm depth), MAP (Mean annual precipitation) and latitude were associated with increased

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AGB abundance, but increased longitude resulted in lower abundance of AGB. Generally, soil organic matter constrains the supply of soil nutrients, which in turn may limit tundra production (Holzmann and Haselwandter, 1988). In alpine zone, the lower temperature might have resulted in restricted activity of microbial and reduced microbial decomposition of soil organic matter, and the slower and lower mineralisation of soil organic matter might have resulted in a higher proportion of soil organic matter (Wang et al., 2007). Therefore, the distribution of AGB was positively related to soil organic carbon in the 0–30 m depth in our study, and abundant soil organic could provide the more soil nutrient for plants growth.

Precipitation was also a critical factor controlling primary productivity for most of the alpine grassland ecosystems (Hu et al., 2010; Huxman et al., 2004; O'Connor et al., 2001), and it strongly influenced ecosystem net primary production through its effects on water availability (Epstein et al., 1997). Aboveground net primary production (ANPP) in the alpine steppe was positively related to mean annual precipitation (MAP), which was observed in our study. Our results were agreed with that of Lieth (Lieth et al., 1978; Xu et al., 2006; Bai et al., 2000).

Geographic position to determine the effect of climatic variation may play a stronger role on AGB in grassland (Briggs and Knapp, 1995). This was shown by Fisk (Fisk et al., 1998) who reported that topography controls snowpack accumulation and hence growing-season length, soil water availability, the distribution of plant communities and aboveground productivity. Different geographical responses of plants to topographic position had been reported in the literature. For instance, Bruun et al. (2006) had studied the species richness of vascular plants, bryophytes and lichens in alpine communities, and suggested that the topography may be an important and better predictor. In our study, the present analyses of the relationship between topographic factors (except for the slope and aspect) and the distribution of AGB revealed the negative effect of longitude and the positive effect of latitude on the abundance of AGB. The latitudinal characteristic of aboveground biomass of typha was studied by Asaeda (Asaeda et al., 2005). They indicated that typha grows in cold, temperate and tropical climates,

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and its productive and morphological characteristics vary accordingly. They also found that there was an inverse relationship between maximum aboveground biomass and latitude. The conclusion did not coincide with our finding. Overall, the longitude and latitude were likely to be much more important factors for the distribution of AGB. For Tibetan Plateau, special and complicated geographical environment and various climates lead to the longitude and latitude were the critical environmental factors controlling the distribution of AGB. Why? It can be partly attributed to longitudinal and latitudinal differences in soil conditions and micro-climates, and partly to differences in resource translocation and belowground organs.

As to the alpine meadow, generally, one would expect a negative linear relationship between AGB and altitude due to declining temperature and nutrients with increasing altitude (Rastetter et al., 2004). The argument was further bore out by our findings, which was agreed with the results of other studies (Roem and Berendse, 2000). However, Namgail (Namgail et al., 2012) found that the hump-shaped relationship between aboveground biomass and altitude was in contrary to our conclusion, and they held that it was possible that trampling and overgrazing by domestic livestock at the lower slopes deplete plant resources.

One interesting phenomenon of this study was that the strong negative relationships of distribution of AGB with soil moisture were found across sites in alpine meadow. So we concluded that soil moisture limits growth and production in alpine plants and soil moisture probably influence the spatial patterns of AGB. Oberbauer (Oberbauer and Billings, 1981) also held that the local distribution of plant species was largely determined by moisture within the alpine zone of a mountain range. The negative linear relationship between AGB and soil moisture could be the result of long-term plant adaptation to local habitant.

Indeed, soil nitrogen is the mineral nutrient that plants require in the greatest quantity and that most frequently limits growth in natural ecosystems (Chapin et al., 1987) because of its central role in the photosynthetic apparatus and its mobility in the soil system (Bowman et al., 1993). In the alpine meadow, the change of above-ground

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biomass depends on soil fertility (Han et al., 2007). Our finding also demonstrated that the soil nitrogen content was a major factor for distribution of AGB. It is likely that it was the lower soil mineralization rates of nutrient availability that caused the lower aboveground production in the cold, dry environment of alpine grassland in Tibetan Plateau. Therefore, a generally positive relationship between abundance of AGB in the alpine meadow was shown. A previous study (Han et al., 2007) reported that nitrogen was the major limiting element in the alpine meadow, and a nitrogen addition caused the changes of functional groups, especially the predominant grass. The result was agreed with that of Niklaus (Niklaus et al., 1998).

Yang et al. (2009b) suggested that moisture availability was a critical control of plant production, moreover, temperature and soil texture also affected vegetation growth in high-altitude regions. While, with the same document, we found that the SOC1, longitude, MAP and latitude were the dominant variables for predicting the trend of AGB in alpine steppe, and the altitude, moisture and nitrogen were the critical variables for predicting the trend of AGB in alpine meadow for the consideration to comprehensive environmental factors.

In conclusion, most research to date had focused on plant responses and adaptations to single features of the environment, but plants in nature often encounter multiple stresses (Chapin et al., 1987). So distribution of AGB varies with soil fertility, spatial pattern and meteorological condition in the alpine grassland. However, there are so great differences between the alpine steppe and the alpine meadow. In contrast to the alpine meadow, the key limiting factors of the alpine steppe were soil organic carbon, mean annual precipitation, and so forth, rather than soil moisture and nitrogen content. This should not be surprising since the soil water content and soil organic matter of the alpine meadow were more than those of the alpine steppe. Compared with soil moisture and soil nitrogen content, the soil organic matter and rainfall were more important in alpine steppe because soil organic matter content and rainfall were the preconditions for soil moisture and soil nitrogen content. However, why soil nitrogen content is still the limiting factor of alpine meadow under the higher soil organic matter? We considered

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that it is too cold climate and immature soil to accelerate the conversion of soil organic matter to soil nitrogen.

For the geographic location, we concluded that the meadow is not a zonal distribution, and the adequate water and lowlands maybe bring about the meadow, so the altitude was limiting factors, and the higher the altitude, the lower the atmospheric temperature, the more likely to limit the meadow growth. The steppe is zonal distribution under the sub-humid and semi-arid climatic conditions; the higher elevation was directly decisive power for alpine steppe, so the distribution of AGB was determined through the latitude and longitude.

Nevertheless, there were two unusual changed tendencies in our findings: one was the declined abundance of AGB with increasing latitude in the alpine grassland, and the other was the declined abundance of AGB with increasing soil moisture in alpine meadow. Despite the abnormal phenomenon requiring further study, the generalized additive model used to predict the trends of key variables change still produced meaningful results.

5 Conclusions

Our study illustrated that the distribution of AGB varied across sites with the critical environmental factors using the GAM. We also indicated that the SOC1, longitude, MAP and latitude were the dominant variables for predicting the trend of AGB in alpine steppe, and that the altitude, moisture and nitrogen were the critical variables for predicting the trend of AGB in alpine meadow using CART. Our findings verified that the environmental factors affecting the spatial pattern of AGB were meteorological factors, topographic factors, and soil factors. In addition, our work highlights the importance of further studies to find out mechanisms of slope and aspect in alpine grassland. The Tibetan plateau is the fiercest region respond to the climate change, and it was very

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important to develop a better understanding of the critical factors which affected distribution of AGB abundance for the ecological security of China.

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Table 1. Introduction of the datum was used in the study.

Index	Unit	Abbreviation	Source	Sample size	Category
Longitude	°	•	Yang et al. (2008, 2009a)	110	
Latitude	°	•	⋆	110	
Altitude	m	•	⋆	110	Topographic factors
Slope	°	•	Extracted from DEM	110	
Aspect	°	•	⋆	110	
Moisture	%	•	Yang et al. (2008, 2009b)	110	
Clay	%	•	⋆	110	
Silt	%	•	⋆	110	
Nitrogen	$mg\,g^{-1}$	•	⋆	110	Soil factors
Soil organic carbon density in the depth 30 cm	$kg\,m^{-2}$	SOC1	⋆	110	
Soil organic carbon density in the depth 50cm	$kg\,m^{-2}$	SOC2	⋆	110	
Soil organic carbon density in the depth 100 cm	$kg\,m^{-2}$	SOC3	⋆	110	
Mean annual temperature	°	MAT	Yang et al. (2008, 2009a)	110	
Mean annual precipitation	mm	MAP	⋆	110	Meteorological factor
Index of aridity	•	Idm		110	
Aboveground biomass	$g\,m^{-2}$	AGB	Yang et al. (2008, 2009a)	110	Target variable

Idm = $P/(T+10)$, P is the average precipitation(mm), T is the average temperature (°).

⋆ The same as above.

• Missing value or unit.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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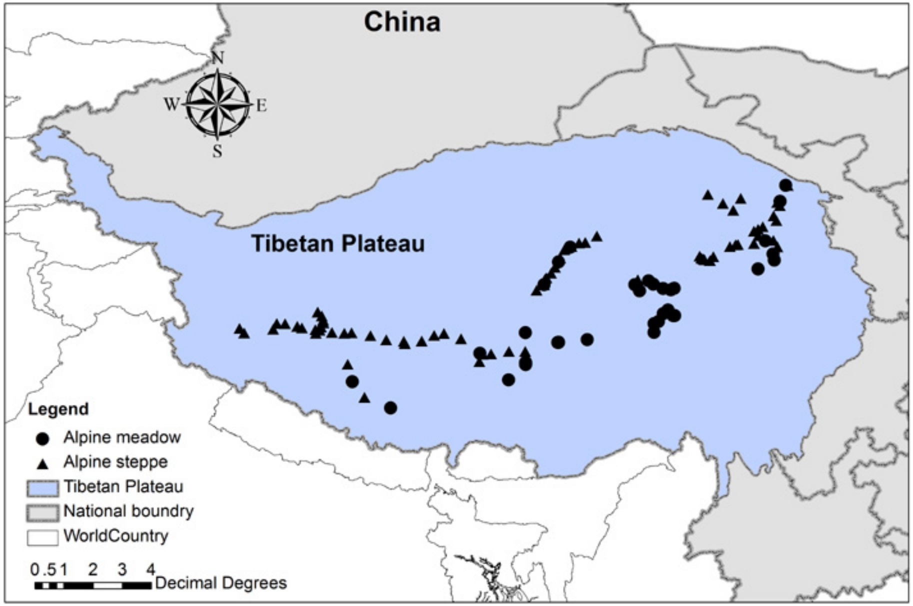

Fig. 1. Spatial distribution of sampling sites in alpine grasslands on the Tibetan Plateau, China. The black solid circles represent the samples collected in alpine steppe, and the black solid triangles represent the samples collected in alpine meadow. The locations of sampling sites surveyed during 2001–2005.

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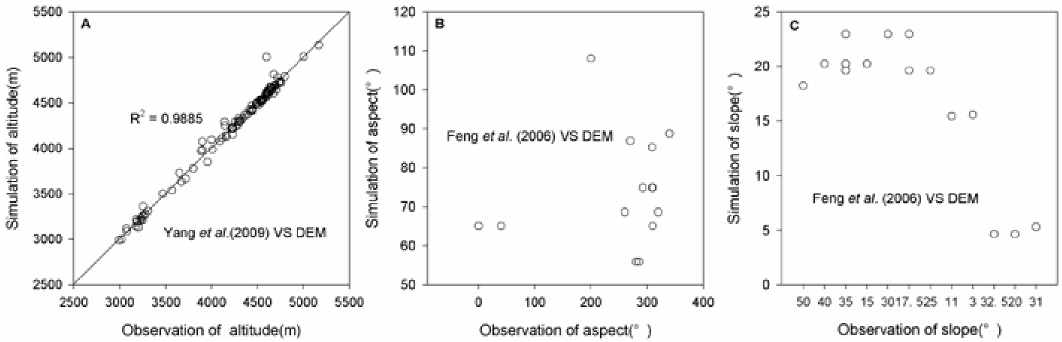

Fig. 2. The simulated results of altitude **(A)**, aspect **(B)** and slope **(C)** of the terrain parameters compared to observed values. In **(A)**, the fitting effect was very accurate ($R^2 = 0.9885$), so the datum of altitude was used in the paper. And we did not consider using the bad fitting effect of the aspect and slope for analyzing the relationship between AGB and the topographic factors.

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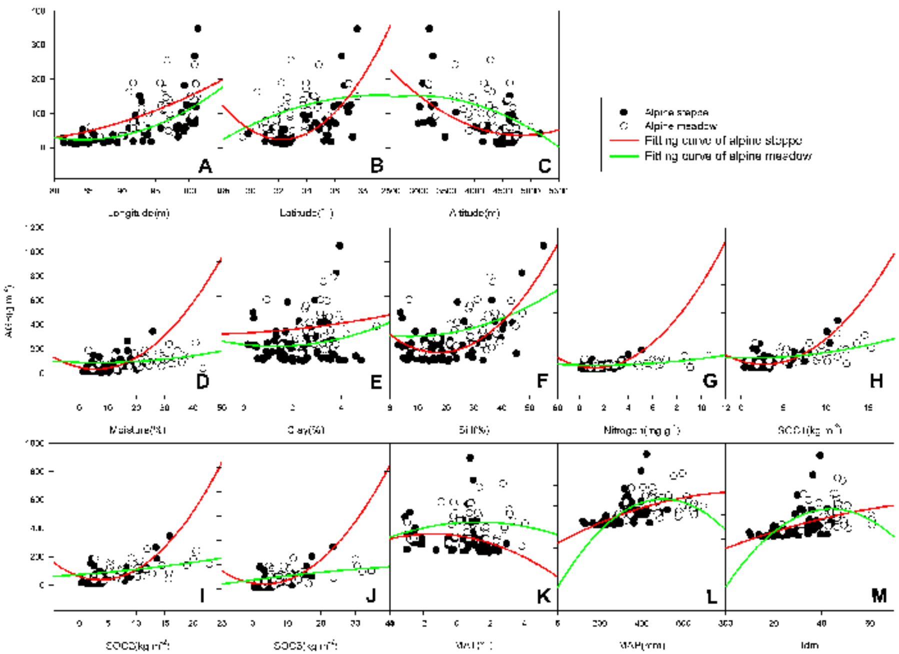

Fig. 3. The relationships between habitat factors and aboveground biomass in the Tibet Plateau were analyzed by correlation analyses (CA). The black solid circles represent the samples collected in alpine steppe, and the hollow circles represent the samples were collected in alpine meadow. The red and green curves represent the fitting curves of alpine steppe and alpine meadow, respectively. The panels **(A)**, **(B)**, **(C)**, **(D)**, **(E)**, **(F)**, **(G)**, **(H)**, **(I)**, **(J)**, **(K)**, **(L)** and **(M)** indicated the relationships of AGB (aboveground biomass) with Longitude, latitude, altitude, moisture, clay, silt, nitrogen, SOC1 (soil organic carbon density in the depth 30 cm), SOC2 (soil organic carbon density in the depth 50 cm), SOC3 (soil organic carbon density in the depth 100 cm), MAT (mean annual temperature), MAP (mean annual precipitation) and Idm respectively.

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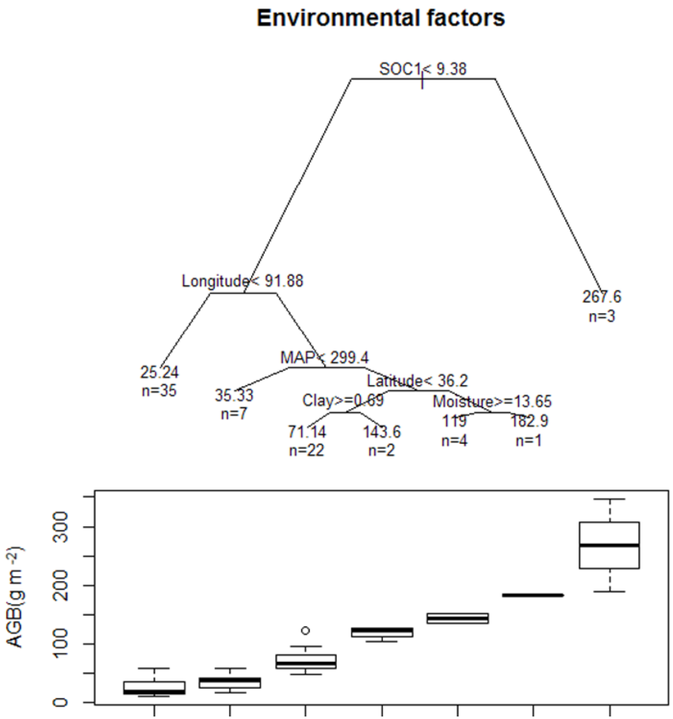

Fig. 4. The relationships between AGB (aboveground biomass) and environmental factors were analyzed via the CART (the classification and regression tree) analysis in the alpine steppe, and the critical factors were showed in the graph by screening. The y-axis represented the aboveground biomass, and the abbreviations of SOC1 and MAP were the soil organic carbon density in the depth 30 cm and the mean annual precipitation respectively.

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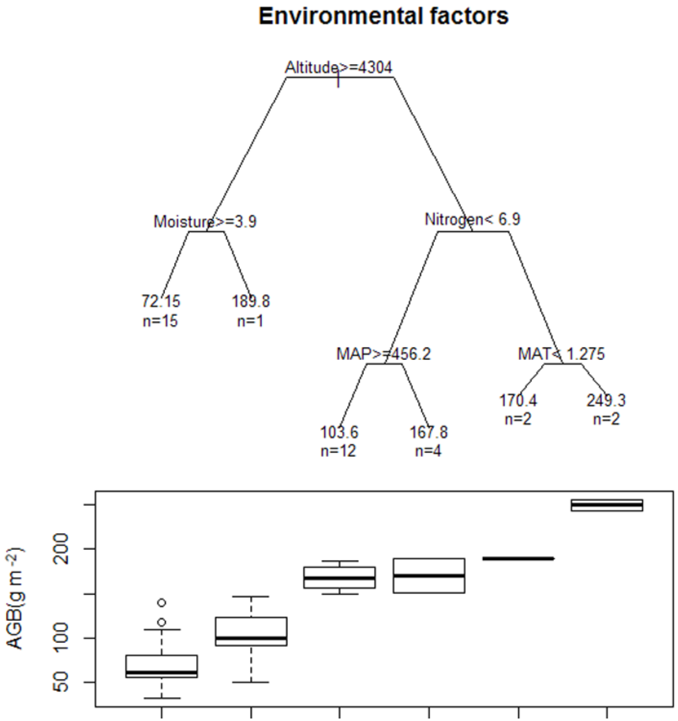

Fig. 5. The relationships between AGB (aboveground biomass) and environmental factors were analyzed via the CART (the classification and regression tree) analysis in the alpine meadow, and the critical factors were showed in the graph by screening. The y-axis represented the aboveground biomass, and the abbreviations of SOC1 and MAP were soil organic carbon density in the depth 30 cm and mean annual precipitation respectively.

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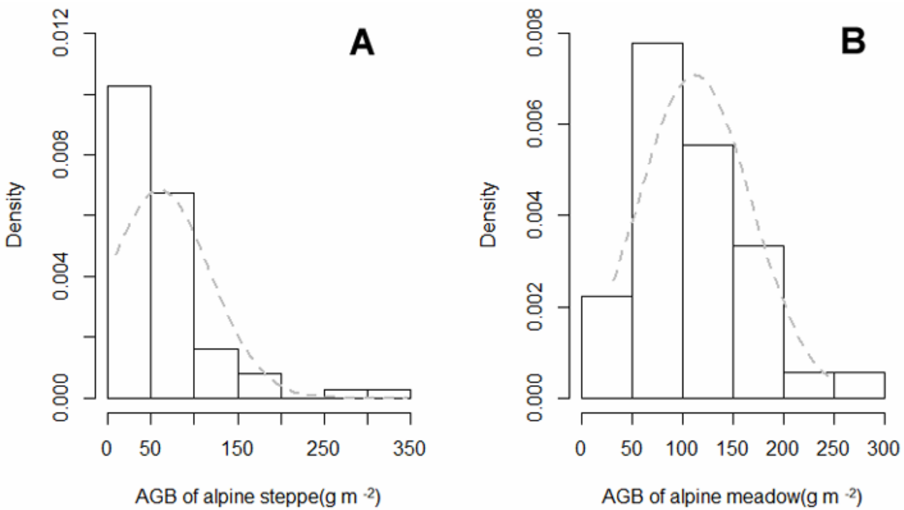

Fig. 6. The graphs show the density distribution curves of AGB (aboveground biomass) of samples collected in the alpine steppe **(A)** and alpine meadow **(B)** of Tibetan Plateau during 2001–2005.

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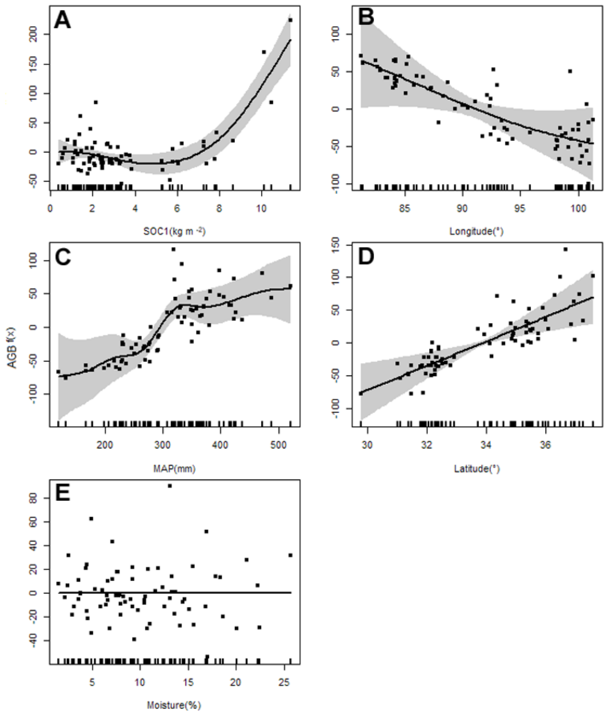

Fig. 7. Exploring and predicting the AGB (aboveground biomass) changed with the major environmental factors using GAM (the generalized additive models) analysis in the alpine steppe. Rugplot on the x-axis represents the number of observations, and the gray belts are the credible intervals. The y-axis label stands for the abundance of the aboveground biomass and the x-axis label of the panels **(A)**, **(B)**, **(C)**, **(D)** and **(E)** are SOC1 (soil organic carbon density in the depth 30 cm), longitude, MAP (mean annual precipitation), latitude, and moisture respectively.

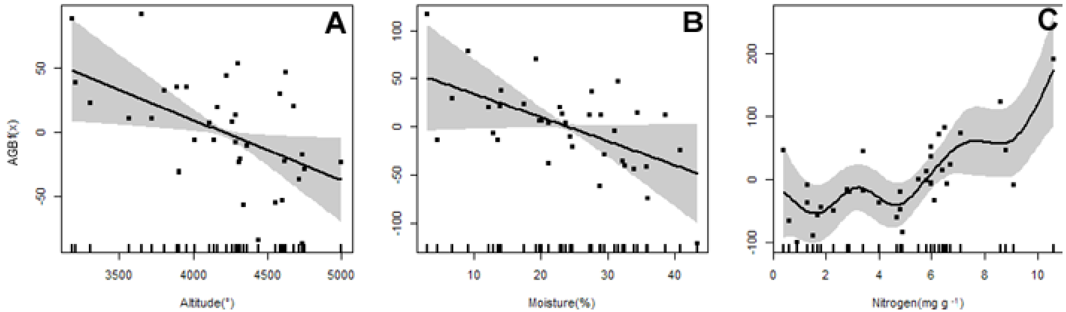

Fig. 8. Exploring and predicting the AGB (aboveground biomass) changed with the major environmental factors using GAM (the generalized additive models) analysis in the alpine meadow. Rugplot on the x-axis represents the number of observations, and the gray belts stand for the credible intervals. The y-axis label is the abundance of the aboveground biomass and the x-axis label of the panels **(A)**, **(B)** and **(C)** represent altitude, moisture and nitrogen respectively.

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