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Distribution and Estimation of Aboveground Biomass of Alpine Shrubs along an Altitudinal Gradient in a Small Watershed of the Qilian Mountains, China

LIU Zhang-wen[1,2] http://orcid.org/0000-0002-2791-9653; e-mail: zwliu@lzb.ac.cn
CHEN Ren-sheng[1] http://orcid.org/0000-0002-2073-3098; e-mail: crs2008@lzb.ac.cn
SONG Yao-xuan[1] http://orcid.org/0000-0002-8913-9580; e-mail: yxsdesert@163.com
HAN Chun-tan[1] http://orcid.org/0000-0002-8412-6692; e-mail: hancht@lzb.ac.cn

1 Qilian Alpine Ecology & Hydrology Research Station, Key Laboratory of Ecohydrology of Inland Basin, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

2 University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract: Shrublands serve as an important component of terrestrial ecosystems, and play an important role in structure and functions of alpine ecosystem. Accurate estimation of biomass is critical to examination of the productivity of alpine ecosystems, due to shrubification under climate change in past decades. In this study, 14 experimental plots and 42 quadrates of the shrubs *Potentilla fruticosa* and *Caragana jubata* were selected along altitudes gradients from 3220 to 3650 m a.s.l. (above sea level) on semi-sunny and semi-shady slope in Hulu watershed of Qilian Mountains, China. The foliage, woody component and total aboveground biomass per quadrate were examined using a selective destructive method, then the biomass were estimated via allometric equations based on measured parameters for two shrub species. The results showed that *C. jubata* accounted for 1–3 times more biomass (480.98 g/m^2) than *P. fruticosa* (191.21 g/m^2). The aboveground biomass of both the shrubs varied significantly with altitudinal gradient ($P<0.05$). Woody component accounted for the larger proportion than foliage component in the total aboveground biomass. The biomass on semi-sunny slopes (200.27 g/m^2 and 509.07 g/m^2) was greater than on semi-shady slopes (182.14 g/m^2 and 452. 89 g/m^2) at the same altitude band for *P. fruticosa* and *C. jubata*. In contrast, the foliage biomass on semi-shady slopes (30.50 g/m^2) was greater than on semi-sunny slopes (27.51 g/m^2) for two shrubs. Biomass deceased with increasing altitude for *P. fruticosa,* whereas *C. jubata* showed a hump-shaped pattern with altitude. Allometric equations were obtained from the easily descriptive parameters of height (H), basal diameter (D) and crown area (C) for biomass of *C. jubata* and *P. fruticosa*. Although the equations type and variables comprising of the best model varied among the species, all equations related to biomass were significant (P < 0.005), with determination coefficients (R^2) ranging from 0.81 to 0.96. The allometric equations satisfied the requirements of the model, and can be used to estimate the regional scale biomass of *P. fruticosa* and C. *jubata* in alpine ecosystems of the Qilian Mountains.

Keywords: Aboveground biomass; Allometric equations; Alpine shrub; Altitudinal gradient; Qilian Mountains

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Introduction

Shrublands is an important component of terrestrial ecosystems, and play a significant role in researching biodiversity and ecosystem functions in high latitude and alpine regions (Wang et al. 2002; Liu et al. 2012). Some studies indicated that biomass, cover and abundance of deciduous shrub have been increased (shrubification) in the Arctic, high latitude and alpine ecosystems over the past several decades (Sturm et al. 2001; Tape et al. 2006). Rapid climatic warming has allowed the increasing of shrublands in China over the past decades (Fang et al. 2007; Piao et al. 2009), Shrub cover in alpine ecosystems has increased quickly in the Qilian Mountains of northwestern China over the past decades (Liu et al. 2012). The space connection length between shrub and forest patches increased 3867 km, and the cover and average patch size of shrub increased by 6.8% and 49% in the Qilian Mountains in the past 20 years (Liu et al. 2012). Piao et al. (2009) identified shrub increasing was the most uncertain factor contributing to carbon sinks of forest ecosystems in China. Moreover, alpine shrub also influenced the water allocation and re-distribution of rainfall in Qilian Mountains (Liu et al. 2012; Chen et al. 2014). Therefore, alpine shrubs have been an essential theme in the ecological, hydrological research and management policy in the alpine region of the Qilian Mountains (Liu et al. 2015).

The term biomass refers to the organic matter assimilated by plant as a result of its photosynthetic activity, and is the most important determinant factor of an ecosystem's productivity (Porté et al. 2002). Aboveground biomass can provide important biological information of net primary productivity, nutrient cycling, wood production, carbon and water partitioning coefficients recently (Nelson et al. 1999; Houghton 2007; Liu et al. 2015). Compared with arbor, shrub is often neglected in biomass research. Shrubs come in a wide variety of forms, both single and multiple stem. Thus, accurate estimation of shrub biomass is relatively difficult owing to the mixture of species typically present in some shrubland ecosystems (Liu et al. 2015). The allometric equation offers a useful tool for estimating the biomass of shrubs in the terrestrial ecosystems, as it is a non-destructive and time-efficient method (Uso et al. 1997; Murray et al. 1982; Návar et al. 2004; Frank et al. 2005; Radloff and Mucina 2007). Different types of variables and functions have been used to establish predictive models (Návar et al. 2004; Elzein et al. 2011). The mathematical prediction model is normally tested by simple linear or multiple regression equations (Murray and Jacobson 1982). The considerable researches have performed the estimation of biomass using allometric equations for individual shrub species in different temperate and tropical regions (Murray and Jacobson 1982; Hierro et al. 2000; Paton et al. 2002; Návar et al. 2004; Zeng et al. 2010). However, the prediction equation of biomass in alpine shrub ecosystems has received little attention (Elzein et al. 2011; Liu et al. 2015). There is an increasing need to improve the estimation accuracy of biomass of alpine shrub. The estimation will provide useful information in deciphering the functional role of this ecosystem compartment, as well as the carbon and hydrological balance in the alpine region of China.

Previous studies for alpine shrubs in Qilian Mountains focused mainly on species richness and diversity (Wang et al. 2002; Ding and Su 2010), formation patterns of below-ground biomass (Zhou et al. 2006), annual turnover (Li et al. 2006), pastoral activities (Zhou et al. 2004), and CO_2 flux change of shrubs (Zhao et al. 2010). More detailed studies have focused on a general description of aboveground biomass and change patterns with the altitude and environmental factors on the northern slopes of the Qilian Mountains (Lei et al. 2011; Jin et al. 2012; Liang et al. 2013). However, little studies have explored distribution patterns of foliage, woody component and total aboveground biomass with altitude and slope, as well as the estimation of biomass estimation by allometric equations for individual shrub species in the southern slopes of the Qilian Mountains.

In this paper, *Potentilla fruticosa* and *Caragana jubata* shrubs, which largely distribute in the high altitudes of the Qilian Mountains, were selected along altitudes gradients on semi-sunny and semi-shady slopes in Hulu watershed of Qilian Mountains, China. This study primarily deals with the quantitative distribution characteristics of the component and total aboveground shrub biomass, and analyzes the impact of altitude and slope factors on shrub biomass at the watershed scale. It also attempts to develop allometric equations of the components and total aboveground biomass of the two shrubs based on descriptive parameters in the Qilian Mountains.

1 Materials and Methods

1.1 Study area

The Qilian Mountains lies on the northeastern margin of the Tibetan Plateau, and three rivers, namely Heihe, Shule and Shiyang, originate from the entire drainage area, producing the Hexi Oasis (He et al. 2012). This region has always aroused the interest of scientists due to its ecological and economic significance (Jin et al. 2003; Cheng et al. 2006). There is a very wide altitudinal gradient ranging from 1450 to 5500 m a.s.l. of the Qilian Mountains (Wang et al. 2002; Jin et al. 2003). Accordingly, vegetation along this gradient shows a remarkable zonal distribution pattern from 1700 to 3900 m a.s.l.. The forests mainly distributed below 3300 m a.s.l. on shady slopes (Jin et al. 2003). As a dominant plant life-form in the alpine region, shrubs mainly distributed from 3300 to 3900 m a.s.l. on semi-sunny and semi- shady slope in the Qilian Mountains (Wang et al. 2002).

The study area located at the Hulu watershed of the Qilian Alpine Ecology and Hydrology Research Station in the south slope of Qilian Mountains of China. The watershed lies within 38°12' N and 38°17' N latitude and 99°49' E and 99°54' E longitude. The Hulu watershed has a total area of 23.1 km^2 (38°12'-38°17' N, 99°49'-99°54' E), and varies from 2960 to 4800 m a.s.l.. This large altitudinal gradient provides a good condition to discuss the change characteristics of shrub biomass in a relatively small area. The average annual temperature of the watershed is approximately 0.2°C, with the lowest mean temperature reaching -18.4°C in January and the highest reaching 19.0°C in August. The mean annual relative humidity is 54.2%. The mean annual precipitation is 495.1 mm, with 85% concentrated in the period of June to October, based on 4 years of manual and electronic rain gauge data collected from 2008 to 2012 (Liu et al. 2015).

The vegetation in the watershed includes arbor *Picea crassifolia* and *Sabina przewalskii*, dwarf alpine shrubs and alpine meadows. Shrubs are distributed mainly on shady, semi-shady and semi-sunny slopes. There are at least eight species of shrubs in the watershed according to field measurements. *P. fruticosa* and *C. jubata* shrubs are mainly distributed from 3000 to 3700 m a.s.l. (Wang et al. 2002; Jin et al. 2003), covering from the lower to upper parts of the watershed. *P. fruticosa* generally distributed from 3000m to 3900 m, and *C. jubata* distributed from 3200 m to 3700 m. The dominant herb species are *Polygonum viviparum*, *Poa pratensis*, *Stipa capillata*, and *Stellera chamaejasm*. Most of the Hulu watershed was covered by mountain drab soil, chestnut soil, and subalpine shrub meadow soil (Liu et al. 2015). Distribution of soil was consistent with the vegetation's distributions in Hulu watershed. Mountain drab soil mainly distributes from 3100 m to 3300 m a.s.l. in the arbor type, such as *P. crassifolia* and *S. przewalskii*. Chestnut soil mainly covers from 3000 m to 3300 m a.s.l. in the alpine grassland, and subalpine shrub meadow soil mainly allocates from 3000 m to 3700 m a.s.l. in the alpine shrub and meadow. Alpine cold desert soil distribute from 3800 m to 4500 m a.s.l. above the vegetation belt and below the glacier (Chen et al. 2014).

1.2 Sampling design

In order to analyze the distribution trend of biomass along altitudinal gradient, the elevation from 3200 m to 3700 m was divided into 7 altitudinal belts in Hulu watershed. In this study, we definite the semi-sunny slope as orienting from NE to SE (from 45° to 135°), and the semi-shady slope from SW to NW (from 225° to 315°) (Table 1). Then, one plot was chosen at each altitude belt per slope aspect (semi-sunny and semi-shady slope) to analyze the impact of slope on shrubs aboveground biomass. There were a total of 14 plots along seven 7 altitudinal belts on two slopes. The information concerning the altitude, aspect and slope angle of the plots as well as shrub coverage are shown in Table 1. Three 5 m × 5 m quadrates were established at per plot along the altitude gradient, and a total of 42 quadrates were chosen. The shrubs were monitored in mid-September 2012 during the peak season of increasing biomass, when biophysical parameters such as foliage

Table 1 Survey of sample plots of alpine shrubs in the Hulu watershed

Code	Alt. (m a.s.l.)	Long. (°)	Lat. (°)	Aspect (°)	Slope angle (°)	Coverage (%)
S1	3655	99°53′29.0″	38°14´03.1″	270	38	65
S2	3654	99°53′25.9″	38°14′03.5″	78	32	50
S3	3593	99°53′23.6″	38°14′09.6″	68	32	50
S4	3583	99°53′25.1″	38°14′13.5″	263	32	60
S5	3528	99°53′19.7″	38°14′21.2″	70	27	50
S6	3531	99°53′07.7″	38°14′43.4″	293	29	30
S8	3410	99°52′02.9″	38°15′12.6″	52	26	50
S9	3407	99°51′48.8″	38°15′17.1″	280	19	65
S10	3371	99°51′54.2″	38°15′19.7″	78	23	60
S11	3369	99°52′05.0″	38°15′18.2″	291	29	60
S7	3323	99°53′02.0″	38°14′45.1″	285	33	75
S12	3315	99°52′12.6″	38°15′19.9″	50	30	50
S13	3220	99°52′05.0″	38°15′18.2″	275	15	45
S14	3223	99°52′12.6″	38°15′19.9″	61	16	40

biomass and canopy cover are relatively stable. The eight shrubs were sampled per quadrate using by the selective destructive technique (Lodhiyal and Lodhiyal 1997). Before the harvest, all shrubs were measured for the following data: 1) basal diameter (*D*: diameter at 10 cm above ground, cm) using a digital caliper; 2) height (*H*: height from ground level to the tallest canopy, cm; and 3) crown area (*C*: crown width multiplied by crown length at right angles, cm^2). The shrubs were then cut at the soil surface/ground level, placed in separate bags. Because of the symbiosis relationship of the two shrubs in the research regions, measurements of parameters were conducted in the same quadrate for two shrubs.

In the laboratory, each shrub was subdivided into foliage and woody fractions at the whole-shrub level. The foliage and woody fractions of each segment were separated. Then, the samples were placed in envelopes and dried for 48 hours in an oven at 80°C until reaching constant weight. Finally, at room temperature, the dry weights of the samples were recorded using nearest 0.01g balance as the biomass.

1.3 Data Analysis

First, scatter plots between the dependent and independent variables were used to determine whether the relationships were linear. Then, it was determined whether or not good relationships existing between shrub biomass and each of the measured and calculated variables. Next, the best fit allometric equations between the independent and dependent variables were tested and established based on the data collected for the *P. fruticosa* and *C. jubata* shrubs. The independent variables represented by *D*, *H*, D^2H and *C*, and the components and total aboveground biomass of shrubs was the dependent variable. Because there is heteroscedasticity correlation between the data exhibited heteroscedasticity, the power function was an inappropriate model in this study. Therefore, the data for linear regression was transformed by a natural logarithm. The transformation equalizes the variance over the entire range of biomass values, and satisfies the prerequisite of linear regression (Sokal and Rohlf 1995). However, this transformation introduced a higher systematic bias when back-transforming the calculation into biomass (Sah et al. 2004). Therefore, in this study, we mainly use linear regression model to estimate the shrubs biomass. The independent variables was represented by *X*, included *D*, H, D^2H, and *C*. Aboveground shrub biomass was the dependent variable (*W*), included components and total biomass of shrubs. The five models are used as follows in the present work: 1) W=a+bX; 2) W=a+bX_1+cX_2; 3) W=a+bln$X$; 4) W=a+bX+cX^2 and 5) W=aX^b. The regression analysis was performed with linear correlation between independantsindependents and biomass of shrubs, for components and total biomass. Stepwise regression is carried out by an automatic procedure. Stepwise regression can be achieved either by trying out one independent variable at a time and including it in the regression model if it is statistically significant, or by including all potential independent variables in the model and eliminating those that are not statistically significant, or by a combination of both methods. As a result, the final models can have the fewest parameters with high values of determination R^2, as well as low values of root mean square error (*RMSE*) (Davison and Hinkley 1997).

Statistical analysis is conducted by SPSS16.0 software (SPSS Statistics 16, 2007), and data were presented as mean ± standard deviation (SD). One-way ANOVA (Duncan) was used to calculate the statistically significant differences between the biomass and altitudinal gradient and slopes. Correlation and regression analyses were conducted to examine the relationship between the total aboveground biomass and each component (D, H, D^2H, and C). The best models for each species were selected with the maximum values of the determination coefficients (R^2) and their prediction error (root mean square error, *RMSE*). When more than one model presented a similarly good fit with the data, the regression equation with the fewest parameters was chosen as the best model.

2 Results

2.1 Distribution of shrub biomass

Aboveground biomass exhibited large variations between the two shrubs species, . This suggested that shrub species strongly influences the difference of biomass (F = 120.13, $P < 0.01$). Compared with the aboveground biomass, *C. jubata* was significantly higher than *P. fruticosa* in all 14 plots along the altitude (F = 83.56, $P < 0.05$). The *C. jubata* shrubs (480.98 ± 60.45 g/m^2) stored from 1 to 3 times more biomass than *P. fruticosa* (191.21 ± 14.37 g/m^2). *C. jubata* had a major contribution to the total biomass (62.32% – 75.51%, average 71.16%) in the symbiotic community of *C. jubata* and *P. fruticosa* in the Hulu watershed.

The aboveground biomass of the shrubs varied significantly with altitude change (F = 86.32, $P < 0.05$). Aboveground biomass decreased with increasing altitude for *P. fruticosa* in the Hulu watershed. Compared to the high altitude areas, biomass was significantly higher in low altitude plots (F = 98.23, $P < 0.05$) The minimum biomass (134.68 ± 15.47 g/m^2) and maximum biomass (241.80 ± 25.29 g/m^2) was at 3650 m and 3315 m a.s.l. for *P. fruticosa*. For *P. fruticosa* shrub significant differences were shown between the altitudes below and above 3370 m a.s.l. (F = 78.76, $P < 0.0.5$), but differences were not significantly shown in adjacent belts (e.g. 3220, 3315 and 3370 m a.s.l.; 3410 and 3530 m a.s.l.; 3590 and 3650 m a.s.l.) ($P > 0.05$) (Figure 1). By contrast, the biomass of *C. jubata* shown a hump-shaped pattern with altitude, and peaked at around 3370 m a.s.l. (730.80 ± 91.02) (Figure 1). The minimum biomass (302.76 ± 45.21 g/m^2) was at 3650 m a.s.l.. Biomass with altitude showed significant differences between below and above 3370 m a.s.l. (F = 86.54, $P < 0.05$), and differences in biomass between adjacent altitudinal belts of *C. jubata* was not significant (F = 43.28, $P > 0.05$) (Figure 1).

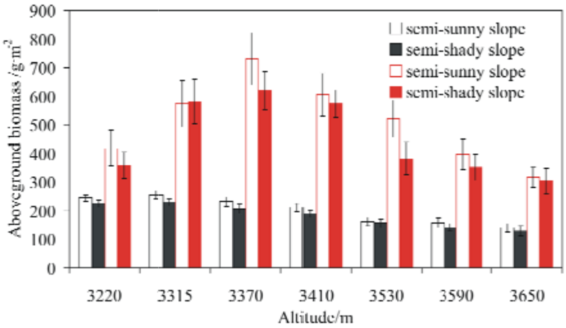

Figure 1 Aboveground biomass of shrubs at different altitudes and slopes. Black bars: *P. fruticosa*, red bars: *C. jubata*.

The variations in biomass for each component along the altitudinal gradient were shown in Figures 2 and 3. The trends of the woody fraction biomass resembled with the trend of total biomass of *P. fruticosa* shrub, excepted at 3315 m a.s.l. (Figure 2). The relations between altitude and foliage biomass was not significant. The biomass of foliage and woody fraction represented a hump-shaped pattern along the altitudinal gradient for *C. jubata*. have the maximum biomass of *C. jubata* ranged between 3315 and 3410 m a.s.l.. Similarly, the woody fraction biomass with altitude was consistent with the total aboveground biomass for two shrubs. However, the distribution pattern of foliage biomass was irregular with altitude change (Figures 2 and 3). The woody fraction contributed the largest portion to the total aboveground biomass. The woody fraction accounted for 85.8% and 93.8% of the total biomass in *P. fruticosa* and in *C. jubata*, respectively.

Compared with the significant differences of biomass between altitudinal gradient, there were no significant differences between slope aspects (F

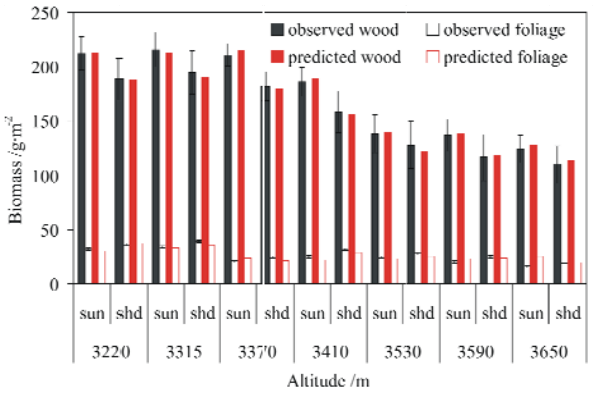

Figure 2 Variations of biomass of woody fraction and foliage for *P. fruticosa* shrubs. “Sun” and “shd” respectively referred to semi-sunny and semi-shady slopes.

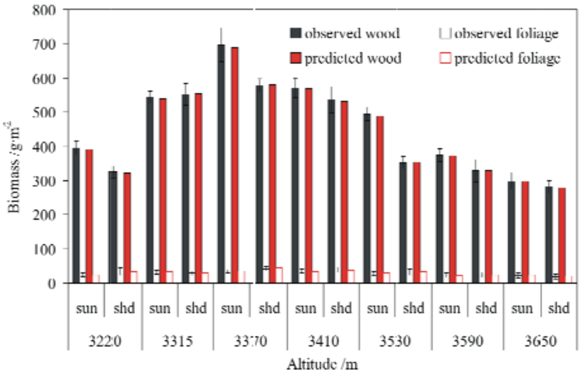

Figure 3 Variations of biomass of woody fraction and foliage for *C. jubata* shrubs. “Sun” and “shd” respectively referred to semi-sunny and semi-shady slopes.

= 40.15, $P > 0.05$). Although the aboveground biomass did not vary significantly with the slopes, it showed differences in biomass on different slopes in the same altitudinal belts. In general, biomass on semi-sunny slope (354.67 ± 40.46) was higher than those on semi-shady slopes (317.52 ± 34.41) for both shrubs at the same altitudinal band, except for *C. jubata* at 3315 m a.s.l. (Figure 3). The biomass showed little difference between different aspects for *P. fruticosa*, and showed a great difference at 3370 and 3530 m a.s.l. for *C. jubata*. In contrast to the total biomass, the foliage biomass on the semi-shady slope was higher than on the semi-sunny slopes for *P. fruticosa* in the same plot. The variation across the slope types of foliage biomass of *C. jubata* was regular (Figures 2 and 3).

The proportion of foliage biomass represented the ratio leaf biomass accounting for the wood biomass. The proportion of foliage biomass of *P. fruticosa* (average 16.54%) was greater than that of *C. jubata* (6.63%). The proportion increased slightly at altitudes below 3370 and reached its minimum from 3370 to 3410 m a.s.l.. Then, the proportion increased sharply and reached the summit at 3530 m, and showed little change above 3530 m for *P. fruticosa* (Figure 4). The foliage biomass above 3530 m a.s.l. was lower than below the altitude for *P. fruticosa*. But the proportion of leaf biomass was higher above 3530 m a.s.l. due to the relatively low total biomass below 3530 m ($P < 0.05$). The changing trend of foliage proportion was different with distribution pattern. the proportion showed little change with the altitude for *C. jubata*. *P. fruticosa* showed a higher proportion in leaf biomass on the semi-shady slopes than the semi-sunny slopes in the same plot, but the difference was not significant difference ($F = 8.23$, $P > 0.05$). The slope aspect had no effect on the proportion of foliage biomass for *C. jubata* (Figure 4).

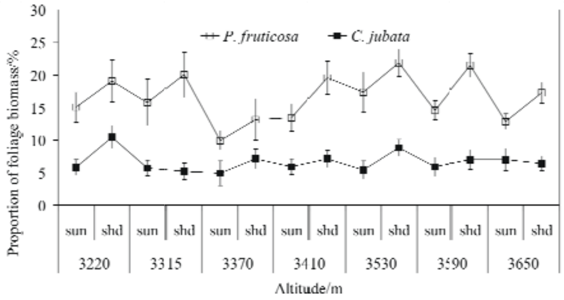

Figure 4 Changes of foliage/wood biomass ratio (%) with altitudinal gradient for *P. fruticosa* and *C. jubata*.

2.2 Allometric equations of shrub biomass

The correlations between the biomass and basal diameter (*D*), height (*H*), D^2H and crown area (*C*) for *P. fruticosa* and *C. jubata* were analyzed. There was a strong positive linear correlation between all the independents and dependent variables (data were not shown). These showed that measure parameters had very strong explanatory power for estimating the shrub biomass. Therefore, these parameters can use to establish the estimating model of the biomass of shrubs.

The coefficient of determination (R^2) can determine the percentage of the variation in the dependent variables explained by the independent variables. The regression model is considered more accurate if it gives a lower value of root mean square error (*RMSE*) and a higher R^2 value. In this case, when developed the model using all measured independent variables (D, H, D^2H and C), all equations had a determination coefficient higher than 0.80. The R^2 values ranged from a low of 0.81 for foliage biomass to a high of 0.96 (Table 2). R^2 of allometric equation of leaf component biomass was 0.81 and 0.89 for *P. fruticosa* and *C. jubata* shrub, respectively. R^2 values of foliage component model were lower than the woody component and total biomass model. The allometric equation of woody components biomass showed 0.95 and 0.96 of R^2 values. R^2 of allometric equation of total biomass was 0.96 and 0.95 for *P. fruticosa* and *C. jubata* shrub, respectively. Based on measured variables in the field, the biomass equations provided excellent fits for the estimated total and components biomass. These species-specific regression equations were statistically significant ($P<0.005$) (Table 2). The equations satisfied the requirement of the equations for each shrub. No autocorrelation or heteroscedasticity was observed in the distribution of the residues. Therefore, these equations can been used to estimate biomass the two alpine shrubs in this regions. These models type could model aboveground biomass other shrub species when re-estimating the parameter values in allometric equations.

Due to the difference in the morphological features, the best equation types differed among the shrub species and components. For the foliar biomass of *C. jubata* and woody biomass of *P. fruticosa*, the quadratic equation was the most ideal models, as they showed the highest R^2 and lowest *RMSE*. Power equation was chosen as the most ideal models for the foliar biomass of *P. fruticosa* and total biomass of *C. jubata*. Linear model showed the best fit for the total biomass for *P. fruticosa*, whereas linear equation had the highest R^2 for the woody biomass of *C. jubata* (Table 2).

Species-specific allometric equations included the different variables and combinations of the variables. Equations with D^2H as the sole independent variable had the highest R^2 for the woody biomass of all species and the total biomass of *C. jubata*. However, equations with H as the independent variable were the best for estimating the foliar biomass of *C. jubata*. The independent variable C provided the most ideal fit for the foliar biomass of *P. fruticosa*. For the total biomass of *P. fruticosa*, C and H were the best independent variables ($R^2 = 0.96$, $RMSE = 2.08$) (Table 2).

3 Discussions

3.1 Biomass change with altitude and slopes

Previous studies (Wang et al. 2002; Liang et al. 2013) showed that shrubs were the important composition of subalpine ecosystem productivity of the Qilian Mountains. The maximum biomass was found at 3960 and 4012 m a.s.l., in a three-river source region (Sa et al. 2012). In the research watershed, shrubs are the dominant vegetation type and the trees distributed lower than in Pailugou watershed (He et al. 2012; Liu. 2015). Alpine shrubs have lower photosynthetic rates and leaf turnover time (1.0 year) than meadow (Sternberg and Shoshany 2001; Zhou et al. 2006). The interception of light in the study watershed is relatively seldom, thus more solar energy could be converted to biomass via photosynthetic activity

Table 2 The best-fit allometric equations of foliage, wood and total aboveground biomass for *P. fruticosa* and *C. jubata* shrubs

Shrub and component		**Equations**	**a**	**b**	**c**	R^2	***P*-value**	***RMSE***
P. fruticosa	Foliage	$W = aC^b$	0.49	0.84		0.81	0.005	3.29
	Wood	$W = a+b(D^2H)+c(D^2H)^2$	-71.95	31.77	-0.90	0.95	0.002	7.55
	Total	$W = a+bC+cH$	-20.4	0.18	0.38	0.96	0.002	2.08
C. jubata	Foliage	$W = a+bH+cH^2$	16.53	-0.09	0.003	0.89	0.001	2.39
	Wood	$W = a+b(D^2H)$	198.05	1.12		0.96	0.001	24.38
	Total	$W = a(D^2H)^b$	10.07	0.54		0.95	0.001	13.3

Notes: R^2 is the coefficient of determination for allometric equation, *RMSE* is the root mean square error, a, b and c are the equation coefficients.

(Haase et al. 2000; Sternberg and Shoshany 2001). The leaves may serve as key media for photosynthesis activity, and have a great influence on the biomass formation. The proportion of foliage biomass was considered a critical factor that influence formation of aboveground biomass (Sternberg and Shoshany 2001; Liu et al. 2009). The proportion of foliage biomass also served as a strong indicator of the growth potential of individual shrub (Zhao et al. 2010). Therefore, the foliage biomass on the semi-shady slope was greater than on the semi-sunny slopes for *P. fruticosa* in the same plot.

Aboveground biomass of shrubs decreased with increasing altitude in the Pailugou watershed on the north slope of Qilian Mountains. The biomass were significantly higher in low altitude plots, and relationship between biomass and altitude was a negative correlation ($R^2 = 0.8987$, $P < 0.01$) (Lei et al. 2011; Jin et al. 2012). These results were consistent with our findings. The foliar biomass in the Pailugou watershed showed the same pattern of the total biomass with Hulu watershed (Lei et al. 2011; Jin et al. 2012). There was a hump-shaped pattern of the foliage and woody biomass along the gradient for *C. jubata*. The total biomass in different altitudinal belts was similar with this study. This is mainly due to that higher rainfall and lower temperatures with the increasing altitude. At 3200 m a.s.l., hydrothermal conditions was suitable to the growth of shrubs, and resulted in high species diversity. The maximum total biomass were found between 3315 and 3410 m a.s.l. in the Pailugou watershed, the maximum wood biomass was at 3300, 3500 and 3700 m a.s.l. (Lei et al. 2011). The proportion of foliage in the Pailugou watershed was higher than in this study. The Pailugou study distributed mainly four shrubs, namely *P. fruticosa*, *C. jubata, Salix gilashanica* and *Spiraea alpine*, the latter two of which were larger in height and leaf area than the former two (Wang et al. 2002). Therefore, the greater amount of foliage in *S. gilashanica* and *S. alpine* resulted in higher total foliar percentages above ground than Hulu watershed.

The productivity among the different vegetation communities and altitudinal gradients could be influenced by the characteristics of individual species and environmental conditions (Lei et al. 2011). Colder temperatures determined the pool of species which are potentially able to withstand the increasingly severe conditions in the alpine zone (Gaston 2000). The uncertainty of precipitation is also high in the alpine region. The micro-climate change, as well as soil condition (Bai et al. 2012), water allocation (Liu et al. 2012) and human disturbance (grazing intensity) (Zhou et al. 2004), should acquire a better understanding of the effects of the environmental factors.

3.2 Allometric equations of shrub biomass

Direct harvesting techniques for the estimation of biomass are labor intensive and time consuming. The allometric equation is a commonly used and nondestructive alternative, in which biomass is estimated based on the easily measured attributes of shrubs (Návar et al. 2004; Zhang and Han 2008; Elzein et al. 2011). Mathematical forecasting models for the biomass productivity and carbon cycling in forest ecosystem research provide a useful tool and data support in large scale models. Allometric equations were obtained for the total and component biomass of *C. jubata* and *P. fruticosa,* which are the most common dwarf shrubs of alpine ecosystems in the Qilian Mountains (Wang et al. 2002).

The plotting scatter diagrams of correlation between each independent variable and dependent variable notifies what sign should be expected on the coefficient of that particular variable in the regression model. In spite of the obvious correlation relationship, an effective model could not employ all measured variables at the same time (Návar et al. 2004). There is the multicollinearity between the independent (measured) variables. Models including all measured variables may result in an unexpected negative sign on the coefficient, and produce high values of *RMSE.* In order to avoid this problem, the stepwise regression method was used to establish the allometric equations of biomass of alpine shrubs.

The types of allometric equations were different among different species and studied areas. In this study, the power and quadratic model were the most appropriate equations. The proposed models of shrubs were consistent with those previously reported in the Gannan grasslands (Zhang and Han 2008). They estimated biomass by linear regression models between the biomass of shrub and crown area (*C*) and height (*H*). In comparison with other regions, the quadratic, power and linear equations are common for modeling the biomass of shrub in the subtropical regions (Cai et al. 2006; Zeng et al. 2010; Ketterings et al. 2001), Jinggang Mountain (Lin et al. 2010) and Balangshan Mountain (Liu et al. 2006) of China, as well as western Spain (Oñatibia et al. 2010) and northeastern Mexico (Návar et al. 2004). Although there were different between the species and regions, these equations had the similar type with ours. The power, quadratic and linear equations could be applied to estimate biomass of shrubs. Compared with previous results, the foliage and woody biomass also were estimated by the quadratic, power and linear equations in this study (Table 2). However, some studies estimated the shrub biomass by the other equation type. The logarithmic equation was the best model for estimating the biomass in the western Alps (Elzein et al. 2011). Therefore, the presented allometric equations of our study can be applied to the *C. jubata* and *P. fruticosa* in Qilian Mountains and other alpine region of China.

The variables were important factors to establish the allometric equations. Generally, the variables crown area (*C*), shrub height (*H*) and D^2H were the ideal parameters in equations for alpine shrubs (Elzein et al. 2011). The allometric equations of studied species shrub biomass were estimated using variables *D*, D^2H, *C* and *H*, which were consistent with the previous studies (Paton et al. 2002; Návar et al. 2004; Elzein et al. 2011). The model inclusion *H* is more familiar for trees than shrubs (Peek 1970; Murray and Jacobson 1982), However, this study revealed that *H* was an important variable for estimating the total and component biomass for shrubs. It was also found that D^2H was more suitable than the sole *D* variable. In particular, the best-fit allometric equations with D^2H as the sole variable showed the best regresses in the woody fraction biomass of both shrubs and the total biomass of *C. jubata*. This result was consistent with the equations presented in the western Alps by Elzein et al. (2011). These observations suggest that the D^2H variable was suitable variable for estimating the biomass of shrub species, especially in shrubs in which wood contributes to large portion of the total biomass (Cai et al. 2006; Zeng et al. 2010). The *C* variable was also used in some allometric equations biomass (Zhang and Han 2008; Zeng et al. 2010; Salis et al. 2006).

Due to the variation in morphological features, the best variable factor for estimating biomass differed among the shrub species and components. The canopy of *P. fruticosa* is conical and the foliage mainly concentrated in up 30 cm of crown (Zhao et al. 2010). Therefore, biomass in the foliage was more than biomass in the woody fraction in the upper 30 cm of the *P. fruticosa* canopy (Li et al. 2006). The variable *C* is an important factor affected the quantity of foliage, and it could serve as variable to accurately estimate the foliar biomass for *P. fruticosa*. However, the crown of *C. jubata* was cylindrical and the foliage distributed from the tip to 50 cm of the canopy, and *H* served as the best interpret factor for the model of foliar biomass. For the total biomass of the *P. fruticosa* shrub, *C* and *H* as independent variables provided the best estimation. Therefore, the equations between the biomass and measured variables not only showed being positive in quantity, but also presented clear ecological significance in shrub ecosystems.

4 Conclusions

The distribution of biomass along altitudinal gradient and slope in Qilian Mountains was discussed. The aboveground biomass of both the shrubs varied significantly with altitude change ($P < 0.05$). Woody component accounted for the larger portion than foliage component in the total aboveground biomass. The biomass on semi-sunny slope was greater than on semi-shady slopes at the same altitudinal belt, but the difference was not significantly. The foliage biomass on semi-shady slopes was greater than on semi-sunny slopes in the same plot. A decrease trend in biomass was observed with increasing altitude for *P. fruticosa,* whereas *C. jubata* showed a hump-shaped pattern with altitude.and peaked at around 3370 m a.s.l..

This study represented an effective and flexible method, which may be used for the determination of aboveground biomass in alpine shrub ecosystems. These equations used simple and time efficient procedures to estimate the total or component biomass for two species that are the most abundant dwarf shrubs without total plant destruction. The related researches should continue to deal with the different formations or specific communities of biomass in the alpine environment in the future. Ideally, all these equations should be tested with larger data sets that do not presently taken into account, such as gradients in soil moisture and nutrient etc. Such equations will provide useful information for ecological research and environmental protection in alpine areas, as well as valid parameters and empirical formulas for eco-hydrological models for plots and watershed scales.

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