#### **RESEARCH ARTICLE**

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# Aboveground and belowground biomass and its' allometry for Salsola passerina shrub in degraded steppe desert in Northwestern China

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#### Abstract

Knowledge of the biomass allometry and partitioning is essential for understanding shrub adaptive strategies to degraded habitats as well as for estimating organic carbon storage. We studied biomass accumulation, allocation patterns, and allometric models of Salsola passerina shrub in the Alxa Desert steppe, Northwestern China. We measured aboveground and belowground biomass accumulation across different ages (0-50 years) by destructive sampling. The biomass allocation patterns between aboveground biomass, leaves, branches, and roots were studied by fitting allometric functions for both pooled and age-classed data. Allometric biomass models were developed by regressing on single-input variable of basal diameter, crown area, height, and age alone or on the pairwise variables of above four parameters. Biomass accumulation increased with age, aboveground components represented 86-89% of the total biomass, root to shoot biomass ratios increased with shrub age. Allometry patterns of S. passerina were relatively constant, and the growth rate of root was faster than that of aboveground components. Allometric models with two-input variables were obviously better than single variable models. Crown area and basal diameter were the best predictors for biomass of S. passerina shrub.

#### KEYWORDS

allocation pattern, allometric model, Alxa, biomass partitioning, desertification

#### INTRODUCTION 1

Biomass allocation of plant plays an important role in resource acquisition and survival competition (Hermans, Hammond, White, & Verbruggen, 2006; Poorter et al., 2012). It is frequently used to evaluate plants' response to environmental changes and experimental manipulation (Peng et al., 2019; Sun, Ma, & Lu, 2017). There are two prevalent hypotheses on biomass allocation: optimal partitioning and allometric partitioning (Ma & Wang, 2020). Optimal partitioning theory suggests that plants preferentially partition more biomass to the tissue that acquires limited resources (Gargaglione, Peri, & Rubio, 2010). This means that if light becomes more limited, plants will partition more biomass to leaves and branches, and if water or

nutrients become limited, plants will partition more biomass to roots (Mokany, Raison, & Prokushkin, 2006; Ryser & Eek, 2000). Allometric theory suggests that the allocation of plant biomass is restricted only by the size of the individual. The accumulation of biomass in different organs has an allometric relationship which is determined by a power function  $Y_1 = \beta Y_2^{\alpha}$ , where  $Y_1$  and  $Y_2$  are interdependent variables (e.g., above ground and below ground biomass);  $\alpha$  and  $\beta$  are allometric coefficient and allometric constant, respectively. When  $\alpha$  = 1 it becomes a linear equation describing the isometric relation, when  $\alpha \neq 1$  it expresses the allometric relationship. One recent study indicated that the allometric theory and optimal partitioning theory may be complementary to each other instead of independent in explaining plant biomass allocation (Chen, Zhao, He, & Fu, 2016).

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Land degradation will cause drastic changes of the ecosystems, especially in photosynthetic uptake of C and biomass (Peng et al., 2019; Poorter et al., 2012; Wang, Wang, & Wang, 2006). Different biomass components have different functions, and they may also react differently to land degradation (Peng et al., 2019; Sun et al., 2017). Peng et al. (2019) reported that the degradation of alpine grassland on the Qinghai-Tibet Plateau resulted in the increase of belowground biomass and the decrease of aboveground biomass. Sun et al. (2017) found that plants adapted to land degradation by adjusting their morphological structure and biomass allocation patterns. The species that responds quickly and effectively to environmental changes will have higher tolerance, and can occupy a wider ecological range and more diverse habitats (Geng et al., 2006). Biomass allocation in degraded land reflects the response strategy of plants to environmental constraints, and affects the survival, growth, and reproduction of individual plants and the energy and material flow of degraded ecosystems (Peng et al., 2019; Sun et al., 2017; Wu, Ren, Dong, Shi, & Wang, 2012). Research of dominant plants in degraded habitats can help us to understand the plasticity of biomass allocation and the mechanism of resource trade-off for improving resource utilization efficiency (Yang, Zhang, Li, Li, & Sun, 2008). These species are also the preferred species for the restoration of degraded land.

The Alxa steppe desert ecosystems have degraded sharply over the past 50 years (Wan, Yan, Xiao, Xie, & Qian, 2018). Biodiversity and vegetation cover decreased with deterioration on soil and hydrological conditions (Wan et al., 2018). Overgrazing is generally considered to be one of the main ecological factors leading to these results (Peng et al., 2019; Wan et al., 2018). In this unstable ecosystem, native species may show distinctive strategies to adapt to the deteriorating environment, which is reflected in the phenotypic plasticity of individuals, especially in biomass allocation (Peng et al., 2019). We hypothesized that the response mechanism of dominant species to overgrazing may be revealed by the biomass allocation.

Salsola passerina, a perennial species of the family Chenopodiaceae, is a dominant species in Alxa steppe desert of Northern China (Jin et al., 2018a; Shan et al., 2018). This species is typical xerophytes, featured by strong resistance to salinity, drought, and cold (Shan et al., 2018). The growing season spans from April to October (Jin et al., 2018a). Root distribution (Shan et al., 2018), water use efficiency (Jin, Wang, Zhang, Pan, Xu, et al., 2018), photosynthesis activities (Jin et al., 2018b) of the S. passerina shrub have been studied extensively. There are few studies on biomass allocation and environmental adaptation mechanism. In addition, shrub age is an important factor determining biomass allocation (Fonseca, Alice, & Rey-Benayas, 2012). Studies in even-aged plantation showed that biomass allocation changed greatly with age (Köhl, Neupane, & Lotfiomran, 2017; Peichl & Arain, 2007). And old shrubs have been affected by land degradation for a longer time in our study. In the context of desertification, the multiple interaction of shrub age and habitat degradation on biomass allocation needs further study to understand its adaptive strategies, and to accurately quantify biomass of S. passerina communities at regional scale (Buras et al., 2012; Jenkins, Birdsey, & Pan, 2001; Lambert, Ung, & Raulier, 2005; Wang, Schaffer, Yang, & RodriguezIturbe, 2017). Therefore, we studied allometry and partitioning of aboveground and belowground biomass of *S. passerina* shrub typically to answer three main questions: (a) How is the biomass of *S. passerina* allocated in overgrazing habitats? (b) Does *S. passerina* follow allometric patterns of biomass allocation in degraded steppe desert? (c) What is the best biomass predictor of *S. passerina* shrub in degraded desert steppe?

#### 2 | METHODS

#### 2.1 | Study site

The study area is located in the southwestern margin of the Alxa Plateau ( $101^{\circ}34'E$ ,  $38^{\circ}46'N$ ). Mean annual air temperature is  $9.4^{\circ}C$  and annual precipitation is 119.5 mm for the reference period 1999–2018 (Ma & Wang, 2020). The groundwater level is greater than 40 m below ground (according to the local well waterlevel). For a more detailed site description see Ma and Wang (2020).

#### 2.2 | Field measurement and biomass sampling

Vegetation investigation was carried out in three square plots of 100 m<sup>2</sup>. In each plot, the total number of *S. passerina* shrubs was counted, and the shrub density was  $1,070 \pm 750$  plants ha<sup>-1</sup>, basal diameter (D), height (H), and crown area (C) of each S. passerina shrub were measured, and were  $14.1 \pm 0.5$  mm,  $12.4 \pm 0.5$  cm, and 389.3 $\pm$  42.2 cm<sup>2</sup>, respectively. In the adjacent area of the above mentioned three vegetation investigation plots, a total of 143 individuals of S. passerina were randomly selected and excavated in two growing seasons of 2018 and 2019. Basal diameter, height, and crown area of the harvested shrubs were measured. Basal diameter was the mean of two perpendicular diameters of stem base, height was the vertical distance from the highest point of the canopy to the groundsurface, and crown area was calculated by taking the longest and shortest diameters through the centre of the fullest part of the canopy. Cut shrubs up to the ground with pruning shears and all aboveground components (branches and leaves) were placed in individual paper bags for transport and drying. Roots of individual shrubs were completely excavated with a shovel on a circular plot centered on stump until no roots were found (approximate maximum rooting depth 0.4 m for the study area). Special personnel were assigned to collect broken roots during excavation to minimize the loss of fine roots. In the laboratory, branch-leaf components were allowed to air-dry for several days to facilitate hand separation. The main stem of S. passerina was classified as branch biomass. Roots were sorted into fine roots (≤2 mm in diameter, with a main function to absorb water and nutrients from soil) and coarse roots (>2 mm in diameter), and excavated roots were cleaned manually with a brush. All component materials were ovendried at 65°C to constant weight, allowed to cool for 4-6 hr, and weighed by an electronic balance (0.01 g) for biomass calculation. For 56 individuals harvested in 2019, high definition photos of rings were

taken for analyzing age on computer, and their ages varied from 0 to 50 years, dividing them into three age classes, 0–20, 21–30, and 31–50 years according to growth stage and sample size. Basic characteristics of each group are shown in Table 1.

#### 2.3 | Biomass scaling relations

Biomass partitioning patterns were studied by logarithmically transformed allometric function with  $log_{10}$  transformed data. The analyses for allometric scaling of aboveground biomass (hereafter aboveground) versus root biomass (hereafter roots), branch biomass (hereafter branches), and leaf biomass (hereafter leaves) were conducted on classified and pooled biomass data.

Data from 143 harvested shrubs were used to develop biomass equations. Different biomass components (i.e., foliage, branches, total aboveground, coarse roots, fine root, total belowground, and total shrub biomass) were regressed on single shrub variable, crown area (C), basal diameter (D), height (H) and age (A), to obtain biomass equations. Total above- and belowground biomass and total shrub biomass were also regressed on the pairwise variables of above four parameters to obtain the better biomass equations. Since the samples harvested in 2018 did not determine age, the age-related equation only used biomass data harvested in 2019. The allometric equation of the form  $Y = c \cdot X^a$  was used for single variable modeling, where Y is shrub biomass component (e.g., leaf, branch, coarse root, fine root), X is a predictor (i.e., crown area, basal diameter, height, and age), a and c are allometric coefficients. The equation was logarithmically transformed into a linear equivalent,  $ln(Y) = ln(c) + a \cdot ln(X)$ . The equation with two input variables was described by  $Y = c \cdot X_1^a \cdot X_2^b$ , with logarithmically transformed form  $\ln(Y) = \ln(c) + a \cdot \ln(X_1) + b \cdot \ln(X_2)$ ,

Where: Y is shrub biomass component,  $X_1$  and  $X_2$  are predictors (i.e., crown area, basal diameter, height, and age), *a*, *b*, and *c* are model parameters. When including the second variable did not improve the fit and significance, we presented biomass estimates using singleinput variable equation only.

Models with one parameter were assessed by coefficient of determination ( $R^2$ ), while models with multiple input variables were assessed by adjusted coefficient of determination ( $R^2_{adj}$ ). The relative error (RE) defined as the error of predicted biomass ( $B_P$ ) relative to measured biomass ( $B_M$ ), RE = ( $B_P - B_M$ )/ $B_M$  (Chave et al., 2005).  $R^2$ ,  $R^2_{adj}$ , RE, and Akaike information criterion (AIC) (Akaike, 1974) were used to select the most suitable model. The best single variable equation

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had the highest  $R^2$  and lowest RE. The most suitable two variable model had the highest  $R^2_{adi}$ , and lowest RE and AIC values.

### 3 | RESULTS

#### 3.1 | Biomass partitioning

The average biomass of each shrub component increased with age, most of the biomass was pooled in aboveground components (Table 2). Branches were the main aboveground biomass pool, and coarse roots were the main underground biomass pool (Table 2). The relative portion of aboveground biomass dropped with age, and the portion of belowground biomass increased with age (Figure 1, Table 2).

The mean root to shoot biomass ratios were 0.12, 0.13, and 0.18 in three age classes. The root to shoot biomass ratio for all pooled data (including data of undetermined age) was 0.20. The aboveground and belowground biomass of 143 harvested shrubs was analyzed by linear regression, it exhibits a fairly stable relationship with a regression slope corresponding to 0.20 (Figure 2).

#### 3.2 | Allometric relations for biomass partitioning

The linear relationship of biomass  $\log_{10}$ -transformed data was used to represent biomass partition pattern among shrub components. For pooled data,  $R^2$  varied from 0.42 to 0.73 (Figure 3). The allometric scaling for aboveground vs. roots, branches vs. roots, leaves vs. roots, and leaves vs. branches and its 95% Cl are shown in Figure 3. The allometric scaling for age-specific data (from harvested shrubs in 2019) is shown in Figure 4. There was no significant difference in allometry coefficient of three age classes for all allometric relationships.

#### 3.3 | Allometric biomass models

Empirical allometric coefficients for estimating biomass of different components based on crown area, basal diameter, height, and age are presented in Table 3. C and D were good at estimating aboveground biomass components and belowground biomass components, respectively (Table 3). H and A, by contrast, showed a less viable estimation for almost all components (Table 3).

**TABLE 1** Basic characteristics of *S. passerina* stands in the Alxa Steppe Desert (mean ± SE)

Age class	Crown areas (cm <sup>2</sup> )	Basal diameters (mm)	Heights (cm)	Ages (years)	Sample size
0-20	513.0 ± 147.7	9.0 ± 0.9	17.3 ± 0.6	16.7 ± 1.5	12
21-30	1,134.1 ± 95.2	12.6 ± 0.6	21.3 ± 0.9	24.8 ± 0.5	31
31-50	1,520.8 ± 233.3	21.3 ± 1.7	23.0 ± 2.3	40.2 ± 1.5	13
Total (0–50)	1,090.8 ± 92.4	12.5 ± 0.5	20.7 ± 0.8	26.8 ± 1.2	56

TABLE 2	Biomass of S. passerina components (g shrub <sup>-1</sup> )
according to	age class

	Biomass (g shrub <sup>-1</sup> )						
Shrub component	0–20 years	21–30 years	31–50 years				
Branch	23.8 ± 7.6	53.4 ± 5.5	89.0 ± 16.7				
Leaf	15.3 ± 3.1	26.4 ± 2.6	35.5 ± 5.4				
Total aboveground	39.1 ± 10.3	79.8 ± 7.4	124.5 ± 20.7				
Fine root	0.6 ± 0.1	1.5 ± 0.2	$2.3 \pm 0.4$				
Coarse root	4.2 ± 1.3	8.5 ± 0.9	$16.8 \pm 2.5$				
Total belowground	4.8 ± 1.3	10.0 ± 1.0	18.9 ± 2.7				
Total shrub	43.9 ± 11.6	89.8 ± 8.3	143.4 ± 23.1				

Note: Mean  $\pm$  SE; n = 12, 31, and 13 individuals for age class 0–20, 21–30, and 31–50 years, respectively.



**FIGURE 1** Partitioning of biomass among different shrub components in age class 0-20, 21-30, and 31-50 years, respectively. n = 12, 31, and 13 individuals for age class 0-20, 21-30, and 31-50 years, respectively



FIGURE 2 Relationship between aboveground and belowground biomass

When including two input variables, model fits were sharply improved (Table 4). Equation with input variables of C and D was good at estimating aboveground-, belowground and total biomass (Table 4). Other combinations of input variables were less good, except for the combination of D and H, which was good at estimating belowground biomass (Table 4). AIC values supported the above results (Table 4).

#### 4 | DISCUSSION

In our field study, we found a clear gradient in biomass accumulation (either in total or in aboveground and belowground components alone) in terms of age classes. The proportion of root increased with age. Root to shoot biomass ratios varied with environmental constraints and individual shrub size. Allometry patterns of *S. passerina* were relatively constant, and the growth rate of root was faster than that of aboveground components. We developed biomass equations for *S. passerina* to accurately predict biomass and carbon storage in Alxa Steppe Desert.

Roots of young shrubs held a smaller proportion than old shrubs in our study. This is not consistent with previous studies by Peichl and Arain (2007) and Weiner (2004). It may be caused by extreme drought in our study area. As the shrubs grow, the water demand continues to increase, and water restriction here causes plants to invest more biomass into the root system to absorb more water to maintain its growth and reproduction, which has led to a continuous increase of root during the life cycle. This is supported by Ryser and Eek (2000) and Hartmann (2011), they reported that plants partitioned more biomass to their roots when water was the limiting factor. This situation may be common in our study area. For example, a recent study on Reaumuria soongorica showed that the ratio of root to total biomass increased from 21.8 to 27.1% with age (Ma & Wang, 2020). Although the collection of fine roots was incomplete, missing fine roots only accounted for a small fraction of total root biomass (e.g., Peichl & Arain, 2007), thus, the effect on calculations of total root biomass can be neglected.

The root to shoot ratios of S. passerina ranged from 0.08 to 0.47, which met other arid land shrubs (0.07-1.55) in northern China (Wang, Su, Yang, & Yang, 2013). Our overall mean value was lower than that reported for the same species by Yang et al. (2013). The differences may be caused by site-specific climatic and hydrogeological conditions. Affected by extreme arid environment, plants can only use a small amount of precipitation and soil condensation water in our study area (Pan, Wang, Zhang, & Hu, 2018). Additionally, poorer desertified soil also limits root development. The southeastern edge of the Tengger Desert, in contrast, has more annual precipitation (186 mm), and more fertile soil. The root to shoot biomass ratios increased with age in our study, although not much. This indicates that biomass partitioning of S. passerina changes with shrub size. The ability to alter biomass allocation according to environmental constraints and individual size may contribute to the distribution of S. passerina over a wide range of site-specific conditions.



FIGURE 3 Biomass partitioning of S. passerina log<sub>10</sub>-transformed data. Each circle on the graph represents one shrub



**FIGURE 4** Scaling exponents of different biomass partitioning relations for three age classes.  $M_A$ , aboveground biomass;  $M_B$ , branch biomass;  $M_L$ , foliage biomass;  $M_R$ , root biomass. Lowercase letters indicate significant difference among age class (p < .05). The error bars indicate the standard errors of the scaling exponent per age class

Regression analysis of log<sub>10</sub>-transformed biomass data indicated that biomass partitioning of *S. passerina* follows allometric rules.

Enquist and Niklas (2002) suggested that the allometric scaling of the leaves relative to stem (including branches) or root was 0.75, and that of stem to root was 1. Our results showed that allometric scaling for pooled data was significantly different from predictions by Enquist and Niklas (2002), while that for age-classified data was not different from their predictions. Given the larger sample size and smaller confidence interval, we think the allometric scaling for pooled data seemed to stand for actual values. Age factor had no significant effect on any scaling exponents, which indicates that the allometry relationship of *S. passerina* is relatively constant.

The scaling exponents of aboveground biomass components relative to roots were all less than 1, indicating that the growth rate of root is faster than that of branches, leaves and the sum of them. In fact, the relative proportion of root to total shrub biomass in 31–50 years is 1.2 times that in 0–20 years in our study. This meets the optimal partitioning theory, and verifies that plants tend to increase root biomass under drought conditions (Bogeat-Triboulot et al., 2007; Mokany et al., 2006). The results suggest that the biomass allocation of *S. passerina* can be well explained by the complementary optimal allocation theory and allometric theory under overgrazing conditions (Chen et al., 2016; Gargaglione et al., 2010).

We found that aboveground and belowground biomass components had good correlation with C and D, respectively. These results

	х	ln(c)	SE[ln(c)]	а	SE (a)	R <sup>2</sup>	p-value	RE
Branch	Crown area	-2.87	0.37	1.00	0.06	.69	<.001	-0.09
Leaf	Crown area	-2.09	0.37	0.78	0.06	.57	<.001	-0.10
Aboveground	Crown area	-1.84	0.28	0.91	0.04	.76	<.001	-0.06
Fine-root	Crown area	-5.86	0.84	0.88	0.13	.25	<.001	-0.37
Coarse-root	Crown area	-2.66	0.55	0.76	0.08	.37	<.001	-0.20
Belowground	Crown area	-2.56	0.50	0.76	0.08	.42	<.001	-0.17
Total	Crown area	-1.47	0.30	0.88	0.05	.72	<.001	-0.07
Branch	Basal diameter	-1.05	0.29	1.83	0.11	.65	<.001	-0.09
Leaf	Basal diameter	0.00	0.34	1.16	0.13	.36	<.001	-0.14
Aboveground	Basal diameter	-0.01	0.25	1.60	0.10	.66	<.001	-0.07
Fine-root	Basal diameter	-3.96	0.65	1.48	0.25	.20	<.001	-0.39
Coarse-root	Basal diameter	-2.99	0.25	2.05	0.09	.77	<.001	-0.06
Belowground	Basal diameter	-2.71	0.21	2.00	0.08	.81	<.001	-0.04
Total	Basal diameter	0.03	0.23	1.66	0.09	.72	<.001	-0.05
Branch	Height	-0.32	0.65	1.34	0.22	.21	<.001	-0.23
Leaf	Height	-0.54	0.55	1.19	0.18	.23	<.001	-0.17
Aboveground	Height	0.33	0.55	1.27	0.18	.25	<.001	-0.17
Fine-root	Height	-4.96	0.98	1.62	0.33	.15	<.001	-0.42
Coarse-root	Height	-0.77	0.71	1.03	0.24	.12	<.001	-0.28
Belowground	Height	-0.60	0.67	1.02	0.22	.13	<.001	-0.25
Total	Height	0.66	0.55	1.23	0.18	.24	<.001	-0.18
Branch	Age	-1.52	0.95	1.62	0.29	.36	<.001	-0.16
Leaf	Age	-0.37	0.84	1.06	0.26	.24	<.001	-0.14
Aboveground	Age	-0.39	0.84	1.40	0.26	.35	<.001	-0.13
Fine-root	Age	-5.51	1.55	1.68	0.48	.19	<.001	-0.30
Coarse-root	Age	-4.05	0.79	1.86	0.24	.52	<.001	-0.11
Belowground	Age	-3.62	0.77	1.78	0.24	.51	<.001	-0.10
Total	Age	-0.44	0.81	1.46	0.25	.39	<.001	-0.12

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Notes: Form of single input variable equation is  $\ln(Y) = \ln(c) + a \cdot \ln(X)$ , where Y is dry mass (g) of shrub component: ln(c) is a constant with the standard error SE (ln(c)); a is power exponent with the standard error SE (a); X is crown area, basal diameter, height, or age; n = 143 except for age-related equation (n = 56);  $R^2$  is determination coefficient; p-value is the significance of regression; RE is the relative error.

have been corroborated by many previous studies (Kuyah, Dietz, Muthuri, van Noordwijk, & Neufeldt, 2013; Liu, Bi, & Zhao, 2009; Peichl & Arain, 2007; Yang, Wang, Tan, & Gao, 2017; Zhang, Cui, Shen, & Liu, 2016). We speculate that equal distribution of shrub branches and leaves in horizontal direction and connection between the stem base and root collar help C and D to more accurately estimate the aboveground and belowground biomass, respectively. Although C and D were both the best variables for estimating biomass of S. passerina, there were still some deviations. This may be due to the difficulties in quantifying crown area and basal diameter. The basal cross sections are always irregular shape which is difficult to measure its diameter accurately, and the crown area can only be measured roughly based on the major and minor axes of canopy. However, we did not find more suitable single predictors.

We found the addition of age or height as second variable in crown area or basal diameter based equations had a slight improvement for the equations of few biomass components. In agreement with this result, Peichl and Arain (2007) and Kuyah et al. (2013) reported that plant age and height were inefficient variables because of their marginal improvement for diameter-based equations. Our results suggest that crown area and basal diameter were the best two input variables for biomass estimation of S. passerina. This may be due to the complementation of the two variables that C and D were the best predictors for aboveground and belowground biomass, respectively. The model developed by Yang et al. (2017) for the same species in the southeastern edge of the Tengger Desert was used in our study, and it showed a difference of 13% for all pooled biomass estimate, indicating that site-specific models are necessary.

**TABLE 3** Biomass equations with single variable for shrub components: foliage, branches, total aboveground, coarse roots, fine root, total belowground, and total shrub biomass

TABLE 4 Biomass equations with two-input variables for shrub components: total aboveground, total belowground, and total shrub biomass

	х	ln(c)	SE(ln(c))	а	SE(a)	b	SE(b)	R <sup>2</sup> (adj)	p-value	AIC	RE%
Aboveground	C-H	-1.88	0.34	0.91	0.05	0.03	0.13	.76	<.001	-278.46	-0.06
	C-D	-2.13	0.21	0.62	0.04	0.85	0.08	.87	<.001	-364.16	-0.02
	C-A	-2.51	0.46	0.80	0.06	0.40	0.15	.83	<.001	-133.58	-0.04
	D-H	-1.81	0.35	1.44	0.09	0.75	0.11	.74	<.001	-269.83	-0.04
	D-A	-0.92	0.70	1.44	0.28	0.47	0.28	.56	<.001	-78.84	-0.09
	H-A	-2.53	0.85	1.04	0.22	1.11	0.23	.53	<.001	-75.22	-0.09
Belowground	C-H	-2.49	0.59	0.77	0.09	-0.04	0.22	.41	<.001	-117.04	-0.17
	C-D	-3.16	0.29	0.13	0.06	1.83	0.11	.81	<.001	-280.67	-0.04
	C-A	-5.10	0.63	0.56	0.09	1.07	0.21	.72	<.001	-98.03	-0.07
	D-H	-3.48	0.33	1.93	0.08	0.32	0.11	.82	<.001	-284.00	-0.03
	D-A	-4.20	0.56	1.60	0.22	0.74	0.22	.75	<.001	-104.46	-0.06
	H-A	-4.91	0.86	0.63	0.22	1.60	0.23	.56	<.001	-73.43	-0.09
Total	C-H	-1.49	0.36	0.88	0.06	0.02	0.14	.72	<.001	-258.22	-0.07
	C-D	-1.80	0.21	0.54	0.04	1.01	0.08	.87	<.001	-372.39	-0.02
	C-A	-2.44	0.46	0.75	0.06	0.51	0.15	.83	<.001	-132.01	-0.04
	D-H	-1.60	0.32	1.51	0.08	0.68	0.10	.78	<.001	-296.72	-0.03
	D-A	-0.97	0.66	1.44	0.26	0.52	0.26	.60	<.001	-85.60	-0.08
	H-A	-2.45	0.82	0.98	0.21	1.18	0.22	.54	<.001	-78.42	-0.09

Notes: Equation form is  $\ln(Y) = \ln(c) + a \cdot \ln(X_1) + b \cdot \ln(X_2)$ , where Y is dry mass (g) of shrub component; a, b and  $\ln(c)$  are equation parameters with their respective standard error SE[a, b,  $\ln(c)$ ];  $X_1$  and  $X_2$  are equation variables with crown area (C), basal diameter (D), height (H), or age (A).  $R^2$  (adj): is the adjusted coefficient of determination; p-value is the significance of regression; AIC is the Akaike information criterion, and RE is the relative error.

#### 5 | CONCLUSIONS

We demonstrated that empirically based biomass partitioning and allometric relations provide a useful tool to illustrate the adaptation strategies of a dominant shrub species that occupies a wide range of habitats in Alxa Steppe Desert. The proportion of root increased with age, so as to absorb more water to maintain growth and reproduction in desertified habitat. Root to shoot biomass ratios varied with environmental constraints and individual size, which contributed to the distribution of S. passerina over a wide range of site-specific conditions. Allometry appears to be a useful tool to provide precise descriptions of the biomass allocation pattern. According to the scaling exponents of aboveground biomass components relative to roots, we found that the growth rate of root is faster than aboveground biomass components in desertified habitat. This result also meets the optimal partitioning theory, and confirms the complementarity of the allometric theory and optimal partitioning theory in explaining biomass allocation of S. passerina. Our results suggest that crown area and basal diameter were the best two input variables for biomass estimation, which contributes to accurately predict biomass and carbon storage of S. passerina shrub in Alxa Steppe Desert.

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#### **CONFLICT OF INTEREST**

The authors declare that they have no conflict of interest.

#### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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