# Postprint: Biomass Prediction Models for Two Dominant Desert Shrubs on the Northern Slope of the Kunlun Mountains

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## Abstract

Constructing mathematical models is one of the important methods for estimating shrub biomass. This study takes two common desert shrubs, Reaumuria soongarica and Sympegma regelii, in the piedmont desert belt on the northern slope of the middle Kunlun Mountains as research objects. Using the whole-plant harvesting method to collect samples, functional models were established with plant height (H), crown area (S), and plant volume (V) as independent variables, and above-ground biomass (W1), below-ground biomass (W2), and whole-plant biomass (W3) as dependent variables. The coefficient of determination (R2), standard error of estimate (SEE), and significance level of regression test (P-value) were selected as evaluation indices. With P<0.001 as the prerequisite, models with the largest possible R2 and smallest possible SEE were selected as the optimal predictive models for biomass of Reaumuria soongarica and Sympegma regelii. The results showed that the optimal biomass predictive models for both Reaumuria soongarica and Sympegma regelii were quadratic function models, except that the optimal whole-plant model for Sympegma regelii was a linear function model. Plant volume (V) showed the highest correlation with biomass for Reaumuria soongarica, with R2 values of the optimal biomass predictive models ranging from 0.820 to 0.920. Crown area (S) showed the highest correlation with biomass for Sympegma regelii, with R2 values of the optimal biomass predictive models ranging from 0.935 to 0.973. The optimal biomass predictive models for both Reaumuria soongarica and Sympegma regelii passed the significance test (P<0.001), with fitting rates between 84.1% and 95.6%, and can be used for biomass estimation. This study provides a scientific basis for predicting carbon storage and evaluating carbon sequestration potential in desert ecosystems.

# Full Text

# Biomass Prediction Models for Two Dominant Desert Shrubs on the Northern Slopes of the Kunlun Mountains

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## Abstract

Mathematical modeling is an important method for estimating shrub biomass. This study examined two common desert shrubs, *Reaumuria soongarica* and *Sympegma regelii*, in the piedmont desert belt of the northern slopes of the central Kunlun Mountains. Using whole-plant harvesting, we established functional models with plant height (H), canopy area (S), and plant volume (V) as independent variables, and above-ground biomass ($W_1$), below-ground biomass ($W_2$), and whole-plant biomass ($W_3$) as dependent variables. Model selection criteria included the coefficient of determination ($R^2$), estimated standard error (SEE), and regression significance level ($P < 0.001$), with preference given to models showing the largest $R^2$ and smallest SEE.

The results indicated that quadratic function models were optimal for biomass prediction in both species, except for the whole-plant model of *S. regelii*, which followed a linear function. For *R. soongarica*, plant volume (V) showed the strongest correlation with biomass, with optimal model $R^2$ values ranging from 0.820 to 0.920. For *S. regelii*, canopy area (S) demonstrated the highest correlation, with optimal model $R^2$ values ranging from 0.935 to 0.973. All optimal biomass models for both species passed significance tests ($P < 0.001$), achieving fit rates between 84.1% and 95.6%, confirming their reliability for biomass estimation. This study provides a scientific basis for predicting carbon storage and evaluating carbon sequestration potential in desert ecosystems.

**Keywords:** desert shrub; biomass; prediction model; Kunlun Mountains

## Introduction

Biomass in terrestrial ecosystems represents not only a fundamental quantitative characteristic but also a comprehensive indicator of interspecies interactions and species-environment adaptations, playing a crucial role in ecosystem carbon cycling. Shrubs constitute the second-largest vegetation type after grasslands, covering nearly half the area of forests. While shrubs account for only a small proportion of total biomass in forest ecosystems, they dominate in ecologically fragile regions such as deserts, plateaus, dry-hot valleys, barren hills, and rocky desertification areas. Desert shrubs, with their well-developed root systems and strong stress resistance, play vital roles in the protection, restoration, and reconstruction of fragile desert ecosystems and represent important components of vegetation carbon pools.

Current research on terrestrial ecosystem biomass primarily focuses on forest and grassland vegetation, with relatively few studies addressing typical desert shrub biomass. Accurate shrub biomass estimation provides effective pathways for shrub resource conservation and utilization while supplying essential baseline data for calculating terrestrial ecosystem carbon storage. Existing methods for shrub biomass measurement include direct harvesting and indirect estimation. Direct harvesting is time-consuming and labor-intensive, and the removal of vegetation causes severe damage to already fragile desert ecosystems that recover slowly. Therefore, direct harvesting is unsuitable for large-scale application in sparsely vegetated desert areas. Indirect estimation methods construct models using easily measurable shrub parameters to accurately predict biomass, effectively reducing vegetation damage while enabling rapid estimation.

Establishing shrub biomass models requires selecting appropriate easily measurable parameters based on plant morphology, then screening various models using multiple evaluation criteria to obtain optimal prediction models. Common easily measurable factors include single variables such as plant height (H), canopy diameter (C), basal diameter (D), and branch number (N), as well as composite variables derived from single variables, such as $D^2H$ (combining basal diameter and height), $S^2H$, $H^2S$, canopy area (S), and canopy volume (V). Commonly used model forms include power functions, linear functions, and quadratic functions.

Due to the diverse and complex growth environments, the optimal variables and model forms for biomass estimation vary among regions and species, with no unified standard determining which prediction model performs best. Recent studies on desert shrub biomass prediction models have increased, but most focus on above-ground biomass, with limited research on below-ground and whole-plant biomass models. Furthermore, few studies comprehensively evaluate model accuracy. *Reaumuria soongarica* and *Sympegma regelii* are widely distributed dominant species in the piedmont desert belt of the northern slopes of the central Kunlun Mountains. While biomass prediction models for *R. soongarica* have been reported for the southeastern Tengger Desert, Urat Desert, and western Ordos Desert, research on biomass prediction for this species in the Kunlun Mountains piedmont desert belt remains lacking, and studies on *S. regelii* biomass models are scarce.

This study focuses on *R. soongarica* and *S. regelii* as dominant species in the northern slopes of the central Kunlun Mountains. Using plant height (H), canopy area (S), and plant volume (V) as easily measurable factors, we constructed above-ground, below-ground, and whole-plant biomass prediction models. Through comprehensive evaluation and selection of optimal models, we aimed to enable biomass estimation from easily measured plant parameters, providing a scientific basis for studying carbon storage and evaluating carbon sequestration potential in desert ecosystems.

## 1. Materials and Methods

### 1.1 Study Area

The study area is located on the southern edge of the Taklamakan Desert, in the piedmont belt of the northern slopes of the central Kunlun Mountains, at an elevation of 2100–2400 m (36°23 46 -36°27 57 N, 80°42 59 -80°43 25 E). The region has a mean annual temperature of 4.7°C, with extreme maximum and minimum temperatures of 30.4–34.0°C and -25°C, respectively, and annual precipitation of 127.5–201.2 mm. The piedmont belt belongs to the low mountain zone (2200-3000 m) of the southern Tarim geomorphic unit, characterized by gentle slopes and extensive Kunlun loess deposits. Soil types are primarily gravel desert soil and brown desert soil.

### 1.2 Sample Collection

From July to August 2022, we selected 60 *R. soongarica* individuals (45 for model development and 15 for validation) and 60 *S. regelii* individuals (45 for model development and 15 for validation). Sample selection followed a stratified approach covering large, medium, and small canopy sizes. Selected individuals were tagged, and plant height (H), canopy long axis, and canopy short axis were measured in the field. After measurement, whole plants were excavated using the complete excavation method. To ensure accurate below-ground biomass estimation, excavation depth and horizontal extent covered the full root distribution range. All underground roots were extracted, soil was removed, and plant parts were bagged for laboratory processing. In the lab, above-ground and below-ground components were separated using pruning shears, oven-dried at 80°C to constant weight, and weighed to determine dry mass.

### 1.3 Biomass Model Construction

Canopy area ($S = \pi \times$ long axis $\times$ short axis / 4) and plant volume ($V = S \times H$) were calculated. Using plant height (H), canopy area (S), and plant volume (V) as independent variables, we established models for above-ground biomass

($W_1$), below-ground biomass ($W_2$), and whole-plant biomass ($W_3$) as dependent variables.

Sample parameters are shown in . Standard deviations were relatively large because samples were stratified across size classes. Five model forms were selected for fitting analysis:

- Linear: W = a + bX
- Logarithmic: W = a + b · ln(X)
- Power: W = a · X
- Exponential: W = a · e^(bX)
- Quadratic: $W = a + bX + cX^2$

where W represents biomass, a, b, and c are constants, and X represents independent variables (H, S, V).

Model evaluation criteria included coefficient of determination ($R^2$), estimated standard error (SEE), and regression significance level ($P < 0.001$). Models with the largest $R^2$ and smallest SEE were selected as optimal.

### 1.4 Data Analysis

Data statistics and model analyses were performed in Excel, with figures created in Origin. Model accuracy was verified by comparing measured biomass values from validation samples with model predictions through regression analysis.

## 2. Results

### 2.1 Above-Ground Biomass Models

All six above-ground biomass models for *R. soongarica* showed significant correlations ($P < 0.001$), with plant volume (V) demonstrating the strongest correlation and smallest SEE, making it the optimal predictor. For *S. regelii*, above-ground biomass correlated well with all measured factors, with regressions reaching extreme significance ($P < 0.001$). Both canopy area (S) and volume (V) produced $R^2 > 0.95$, indicating good predictive performance. Based on comprehensive evaluation of fit and precision, the model using canopy area (S) was selected as optimal for *S. regelii* above-ground biomass.

### 2.2 Below-Ground Biomass Models

Regression analyses showed all models passed significance tests ($P < 0.001$). Plant height (H) showed poor correlation with *R. soongarica* below-ground biomass, while volume (V) showed the best correlation, making it the optimal predictor. For *S. regelii*, below-ground biomass correlated best with canopy area (S), with the quadratic function using S as the optimal model. Overall, below-ground biomass models for *S. regelii* performed better than above-ground models, all passing $P < 0.001$ significance tests.

### 2.3 Whole-Plant Biomass Models

All six whole-plant biomass models for *R. soongarica* reached extreme significance ($P < 0.001$). Compared to volume (V), plant height (H) and canopy area (S) showed poorer correlation with whole-plant biomass. Therefore, the model using volume (V) was selected as optimal. For *S. regelii*, whole-plant biomass models using canopy area (S) and plant volume (V) both passed $P < 0.001$ significance tests with $R^2 > 0.95$, indicating strong correlations. Based on comprehensive evaluation, the linear model using canopy area (S) was selected as optimal for *S. regelii* whole-plant biomass.

Across all models for both species, those using plant height (H) showed poorer fit compared to those using canopy area (S) or volume (V), indicating that height alone poorly reflects biomass characteristics.

### 2.4 Model Validation

Using validation samples not included in model development, predicted biomass values from optimal models were compared with measured values through regression analysis. Fit rates ranged from 84.1% to 93.5% for *R. soongarica* and 86.8% to 95.6% for *S. regelii* [Figure 1: see original paper], confirming high model accuracy suitable for biomass estimation.

### 2.5 Above-Ground vs Below-Ground Biomass Relationship

Strong correlations existed between above-ground and below-ground biomass for both species [Figure 2: see original paper], enabling below-ground biomass estimation from above-ground measurements. Under the same growing conditions, *R. soongarica* showed a mean root-shoot ratio of 0.59, while *S. regelii* showed 1.17, indicating that *R. soongarica* allocates more biomass above ground to maximize resource utilization, whereas *S. regelii* allocates more below ground.

## 3. Discussion

### 3.1 Independent Variable Selection

Mathematical modeling for vegetation biomass prediction is a common approach that reduces vegetation damage while improving fieldwork efficiency through easily measurable parameters. Model error primarily stems from factor selection and model form. Some studies incorporate additional composite variables like DH, $D^2H$, and $DH^2$ (where D is basal diameter). $D^2H$, representing plant cross-sectional and vertical area, serves as a robust variable across environments. However, in desert regions, shrubs often become sand-buried, forming nebkhas that prevent accurate basal diameter measurement. Multi-stemmed shrubs require individual basal diameter measurements, increasing error and reducing model practicality.

Our results show that models using single variable plant height (H) had lower fit than those using composite variables canopy area (S) and volume (V). Different factors reflect distinct biological meanings: height and basal diameter indicate vertical or horizontal growth, while biomass accumulation integrates multiple changes, making composite variables better indicators of individual biomass characteristics. Previous research confirms that composite variables correlate more strongly with biomass than single variables. Therefore, selecting appropriate composite variables from multidimensional perspectives can improve model fit.

### 3.2 Model Form

High-precision model selection is critical for biomass prediction. Power functions (allometric models) are widely used for shrub biomass and perform well in many studies. However, morphological differences among shrubs cause varying prediction effectiveness. Some researchers suggest quadratic or higher-order polynomial models may yield better results, with increasing complexity potentially improving $R^2$. Studies show quadratic models dominate for understory shrubs in warm temperate forest ecosystems and are ideal for some desert shrubs, achieving high $R^2$ values.

Our results indicate that quadratic models were optimal for all biomass components except whole-plant biomass in *S. regelii*, which followed a linear model. This aligns with previous *R. soongarica* studies but suggests that power functions are not universally optimal. Model form should be selected based on shrub environment and morphology, using different independent variables to establish and screen various functional models.

### 3.3 Root-Shoot Ratio

Biomass allocation patterns in desert shrubs are important indicators for studying ecosystem structure, function, and material/energy flow. The root-shoot ratio, reflecting the relationship between above-ground and below-ground biomass, holds significant meaning for ecosystem function evaluation. Biomass allocation is directly influenced by species characteristics, individual development, and environmental conditions. Plants adjust allocation patterns to respond to environmental conditions, maintaining optimal growth modes and improving survival under stress—an outcome of long-term adaptation.

Our study found significant differences in root-shoot ratios between co-occurring *R. soongarica* (0.59) and *S. regelii* (1.17), reflecting distinct biological characteristics. This demonstrates that species-level allocation patterns cannot be simply extrapolated to community levels. The mean root-shoot ratio of *R. soongarica* in our study (0.59) differs from values reported in western Ordos and Tengger Desert regions (~1.0), likely due to environmental differences affecting allocation strategies. Research shows severe drought stress increases *R. soongarica* root length, surface area, specific root length, and diameter. Beyond drought, interactive effects of water, $CO_2$ concentration, and nitrogen also influence growth, causing root-shoot ratio variations across environments.

## 4. Conclusion

This study developed and validated biomass prediction models for dominant species *R. soongarica* and *S. regelii* in the piedmont belt of the northern slopes of the central Kunlun Mountains. Results show extremely significant correlations between biomass and independent variables ($P < 0.001$), with high model fit and precision. Quadratic functions were the primary optimal model form. All optimal models demonstrated reliability for biomass estimation and can be applied to carbon storage and cycling studies in desert shrub ecosystems.

As *R. soongarica* and *S. regelii* growth varies spatially due to multiple factors, model application outside the study area requires verification and calibration.

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[Figure 1: see original paper]
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