Biomass equations and assessment of carbon stock of *Calligonum polygonoides* L., a shrub of Indian arid zone

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Biomass equations of *Calligonum polygonoides* L. were derived for the arid districts of Rajasthan, India for assessment of carbon stock. Plants varied spatially in growth and biomass (0.03–54.19 kg/plant). Contribution of stems and roots was 45.7% and 48.0% of total biomass respectively. Nonlinear models were found to be the best in predicting biomass of stems, roots, above-ground and total biomass of *C. polygonoides* using collar diameter as the predictor. Carbon concentration was highest in twigs followed by stems, roots and leaves. Carbon density due to this species ranged between 0.37 and 1.84 t/ha. Conclusively, collar diameter alone is sufficient to predict the biomass of different components of this plant. Varying climatic and human-induced stresses were found to affect the biomass and carbon sequestration by this species.

Keywords: Allometric equation, arid region, biomass allocation, carbon stock.

DUE to varying topography, soil conditions and habitats, the Indian arid zone is an area of great ecological significance[1,2]. *Calligonum polygonoides* L., locally known as ‘phog’, is an important species of the Indian desert occupying active dune type of habitat and found favourable for other plants to grow in its association[3]. It is a slow-growing and highly branched shrub, 1–2 m in height under natural conditions with well developed root system as an adaptation[4,5]. The thick branching stem and roots are used as fuelwood because of its high calorific value together with other uses, including extraction of essential oil from flowers and fruits[6,7]. The species also provides green cover to the desert under adverse climatic conditions and helps control desertification either alone or in association with other plants like *Lasiurus sindicus*, *Panicum turgidum*, *Cenchrus ciliaris*, *Aerva pseudotomentosa*, *Dipterygium glaucum*, *Leptadenia pyrotechnica*, etc.[8–11]. Earlier this species existed abundantly in the sandy area near Jodhpur, Rajasthan, but at present difficult to observe this species within 60–70 km range of Jodhpur city. Changing land-use pattern, removal for cultivating agricultural and commercial crops like *Arachis hypogea*, and overexploitation of this species for supplying wood to brick and lime manufacturing industries have resulted in the reduction in its habitat and abundance[12,13]. According to an observation about 300–400 camel carts each containing 1.0–1.2 tonnes dry wood of *C. polygonoides* are transported each day to Bikaner city (pers. obs.). As biomass is 10–15 kg per plant, about 35,000 plants are uprooted per day. This creates ecological imbalance in the region because of enhanced desertification and making the desert ecosystem more fragile[13,14]. Increasing human and livestock populations are causing depletion of vegetation and related carbon stock in this desert ecosystem, where the role of this species is more significant in terms of soil and water conservation and carbon sequestration. Studies indicate that almost two to three times more biomass is available below ground compared to that above ground in this species[9,13].

Industrialization, land clearance and deforestation, forest degradation and burning of fossil fuel have caused an increase in atmospheric carbon dioxide (CO_2) and have disrupted the global carbon cycle[14]. Absorption by plants through photosynthesis and accumulation into biomass are processes of lowering atmospheric CO_2. Despite low levels of carbon sequestration due to recurring droughts and low water availability, arid soils rank fifth with total storage of 110 Pg carbon due to vast areas of arid region[15]. This indicates the potential of carbon sequestration in the region. Promoting natural vegetation, including *C. polygonoides*, on farmlands as a part of carbon farming under reducing emission from deforestation and forest degradation with sustainable management of forests, conservation of forest carbon stocks and enhancement of forest carbon stocks (REDD+) may be an option to conserve such species for enhancing carbon stock and maintaining land productivity in the regions where growing agriculture crops is not economical[16]. The increase in biomass with age contributes to increase in carbon sequestration and subsequent increase in carbon stock[17]. However, estimating biomass and carbon stocks of *C. polygonoides* is crucial and time-consuming because of the widely distributed, multi-tiller and deep-rooted nature of this species[18]. Use of equations in predicting biomass is one option as biomass prediction equations have been developed for more than 300 tree species in temperate and tropical regions of the world[19–24] and India[25–29]. However, most of these equations are limited to tree species, except a few for shrubs[30,31], particularly for arid regions. Further, variations in age, size, environmental heterogeneity, allometry, wood density, and architecture affect biomass and its relationships with growth variables of individual species[32–34]. Thus accurate estimation of shrub biomass at a fine resolution is required by developing equations at the regional level for scientific purposes and obtaining financial rewards for the sequestered carbon through conservation.

Therefore, the objectives of this study were: (i) to derive equations for predicting the above-ground and below-ground biomass of *C. polygonoides*, and (ii) to

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Table 1. Geographical location and rainfall in the area where *Calligonum polygonoides* shrub was harvested

Location	District/ division	N Latitude	E Longitude	Altitude (m)	Rainfall (mm/yr)	Human population density	Sample shrub (no.)
Falodi-I	Jodhpur	27°08′36.6″	72°22′38.9″	219	274.4	161	1
Udat	Jodhpur	27°33′04.2″	72°42′10.6″	252			1
Malamsingh ki sid	Jodhpur	27°24′57.7″	72°32′53.8″	222			1
Shergarh	Jodhpur	26°19′47.2″	72°18′47.3″	228			1
Tanot	Jaisalmer	28°47′09.6″	70°29′99.7″	114	158.4	17	2
Nachna	Jaisalmer	27°29′37.7″	71°44′07.4″	155			1
Dav	Jaisalmer	26°25′08.1″	70°27′42.0″	153			1
DNP	Jaisalmer	26°21′06.1″	70°27′39.4″	145			1
Ghantiyali	Jaisalmer	27°46′19.5″	70°22′53.8″	104			1
Borabas	Barmer	25°55′33.5″	72°05′42.6″	123	243.4	92	4
Sundra	Barmer	25°59′36.5″	70°10′25.5″	75			2
2 KYM	Bikaner I	28°46′43.0″	72°27′41.1″	136	228.7	78	1
7 BLD	Bikaner I	28°34′21.9″	72°41′24.9″	146			1
21 KJD	Bikaner I	28°38′54.6″	72°34′36.7″	127			2
1 RSM	Bikaner I	28°52′39.2″	73°23′46.5″	175			1
5 TM	Bikaner I	29°00′13.0″	73°22′40.8″	180			1
Kotadi	Bikaner I	28°00′01.7″	73°17′02.1″	222			3
2 LKD	Bikaner II	28°36′53.6″	73°53′59.4″	195			1
Beechwal	Bikaner II	28°07′53.4″	73°21′14.5″	217			1
6KDD	Hanumangarh	29°10′00.2″	74°20′15.1″	201	252.5	184	1
5 RJM	Ganganagar	29°04′08.5″	73°38′03.6″	197	201.4	179	1
Total							29

account for carbon at different component levels of this species.

The study was conducted in the Indian desert spreading between 24°37′–31°12′N lat. and 69°30′–75°37′E long. covering 12 arid districts of Rajasthan, where human population density varies from 17 persons/km^2 in Jaisalmer district to 361 persons/km^2 in Jhunjhunu district with an average value of 133 persons/km^2 (Table 1). Diurnal and temporal variations in temperature are high as the maximum temperature rises to about 50°C in the day during summer months and the minimum drops to below 0°C at night during winter. Average annual rainfall ranges between 450 mm in Jhujhunu district and minimum of 160 mm in Jaisalmer district. Wind velocity in the summer months is 20–60 km/h. *C. polygonoides* growing sites are undulating sand dune, either active or semi-stabilized, with loamy sand to sand soil texture (coarse loamy, mixed hyperthermic family of Typic Camborthids according to the US soil taxonomy). Soils are slightly alkaline in reaction and very low in soil organic carbon (0.06%–0.345%), available ammonium (1.15–6.43 mg/kg), (0.09–3.08 mg/kg) nitrogen and phosphorus (5.40–14.24 mg/kg soil)[35].

Sampling plots of 0.1 ha (31.5 m × 31.5 m) were laid out in homogeneous forest areas covering all 12 arid districts of Rajasthan during 2009–2012. *C. polygonoides* shrubs were counted for their population and measured for total height and collar diameter (15 cm above soil surface) or the tiller diameter (5 cm above the soil surface) in case of tillering from ground surface. Total number of tillers was also counted. Individual shrubs of variable growth parameter (height and collar/tiller girth) were selected from different geographical locations spread in seven forest divisions covering six desert districts for destructive sampling (Table 1). Twenty-nine plants of *C. polygonoides* were harvested and excavated. Height, collar diameter and crown diameter of the selected shrubs were measured before felling. The felled shrubs were immediately fragmented into stems, branches and foliage (twig and leaf) to record fresh biomass of each component. The roots of felled shrubs were excavated by mechanical digging up to root diameter of 0.5 cm. Rooting depths and horizontal spreads of the roots were measured. Fresh weight of stems, branches and foliage (leaves and twigs) and root fractions were recorded immediately after harvesting of the shrub. Samples of stem, branch, foliage and root were also collected for dry biomass estimation. Dry weight of each component was taken after oven-drying the sample at 80° ± 2°C for a constant weight and carbon analysis was performed (Elementar CNS Analyzer Model Vario EL Cube, Hanau, Germany).

Dry weight of stems, branches, foliage and roots were calculated based on the weight loss during drying of the samples. Summed-up dry weights of stems, branches and foliage constituted the above-ground biomass. Dry weight of roots was added to the above-ground dry biomass to obtain the shrub total biomass. Due to the multi-stem nature of this shrub, we calculated collar diameter (D) to normal multiple- and single-shrub in a similar metric[36]

$$\text{Collar diameter } (D) = \sqrt{d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2}, \qquad (1)$$

where n is the number of stems at the collar with diameter 2.5 cm or larger, and d is the diameter of individual stems (live or dead) at the collar.

Separate equations were developed based on D, as well as D and height combined using linear and nonlinear models to estimate stem biomass, above-ground biomass, root biomass and total biomass. These were based on a total of eight allometric biomass equations selected from the literature[19–28], depending upon their wide applications (Table 2). Growth and biomass data of 29 harvested shrubs were used to fit the models. Then the model with the lowest residual mean square error (RSME), highest coefficient of determination (R^2) and significant fit ($P < 0.05$) was selected as the best fit model. Error of estimate was calculated for each final model as given in eq. (2) below, and was also used to test the accuracy of the selected models

$$\text{Error of estimate} = \frac{\sum_{i=1}^{n}\left[\frac{\text{Observed} - \text{Predicted}}{\text{Observed}}\right]}{n} \times 100. \quad (2)$$

C. polygonoides population showed a negative logarithmic relationship ($R^2 = 0.179$, $P < 0.05$, $n = 36$) with human density. Height and collar diameters of felled shrubs ranged from 0.35 to 3.15 m and 1.10 to 11.45 cm respectively (Table 3). In general, the shrub biomass increased with increase in collar diameter and ranged from 0.03 to 54.19 kg/plant. Across the harvested plants, dry foliage was 29.4% of the above-ground biomass and 16.8% of the total biomass. Dry weight of stem (>1 cm diameter) was 70.6% of the above-ground biomass and 40.4% of the total biomass. Distribution of total biomass into above-ground biomass and roots biomass was 57.2% and 42.8% respectively. Biomass accumulation in *C. polygonoides* was 16.8% in foliage, 40.5% in stems and 42.8% in roots. The ratio of root to above-ground dry biomass was 0.75. Allocation to stem biomass (stem biomass/total biomass) increased, whereas allocation to foliage and root biomass decreased with increase in total biomass (Figure 1).

Table 2. Equations for the above-ground, below-ground and total biomass tested in the study

Equation	Model no.
$Y = a + b * D^2H$	1
$Y = a + b * (\log D^c)$	2
$\ln Y = a + b * D + c * \ln(D)$	3
$Y = a + b * D + c*(D^d)$	4
$Y = a * D^b$	5
$Y = \exp^{(a+b/D)}$	6
$\ln Y = a * D^2H^b$	7
$Y = a*D**^b * H^c$	8

Y, Biomass (kg); *D*, Collar diameter (cm); *H*, Total height (m); *a–d*, Equation parameters.

Among the eight algebraic equations tested, five equations represented the use of D and three represented the use of both diameter and height in predicting biomass. The equation of type $Y = a * D^b$ was observed to be the best ($P < 0.001$) in predicting stem biomass, above-ground biomass, root biomass and total biomass (Figure 2). These diameter-based nonlinear models were considered as the best models ($P < 0.01$) because of lowest RMSE and SEE, highest R^2 and best-fit plot compared to the other models based on diameter and height combined (Table 4). The values of RMSE and SEE increased, whereas the value of R^2 decreased when height was included in the models to predict the biomass of different components (Supplementary Table 1). The values of RMSE and absolute per cent deviation between observed biomass and predicted biomass were lowest for the derived equations. The predicted stem biomass and above-ground biomass of *C. polygonoides* were higher by only 0.12% and 1.13% respectively; whereas the predicted root biomass and total biomass were lesser by 4.59% and 1.81% respectively, compared to the observed biomass values. The residuals also showed random distribution for the equations in estimating stem, above-ground, root and total biomass, and there were no systematic trends in the errors (Figure 2).

Average concentration of carbon across the plant parts was 46.18%. However, carbon concentrations in leaves, twigs, stems and roots was 42.30%, 49.88%, 47.94% and 47.01% respectively. Carbon density due to *C. polygonoides* ranged between 0.37 t/ha in Jodhpur and 1.84 t/ha in Jaisalmer (Table 5). Jodhpur with relatively high human population and interference had the lowest carbon density, whereas areas in Jaisalmer and Barmer districts

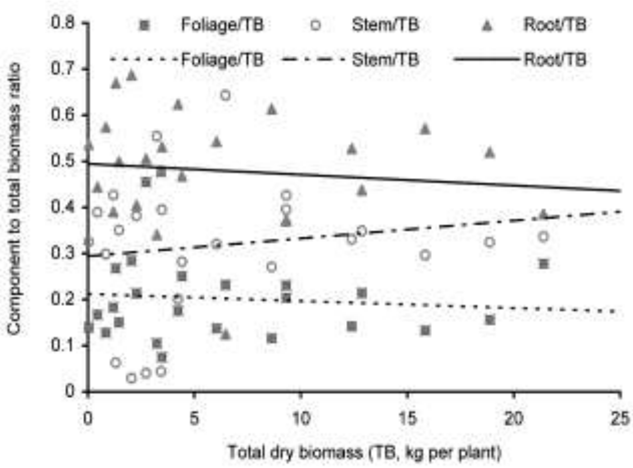

Figure 1. Observed (dotted) and trend line (solid line) indicating biomass allocation in relation to increased total dry biomass of *Calligonum polygonoides* plants.

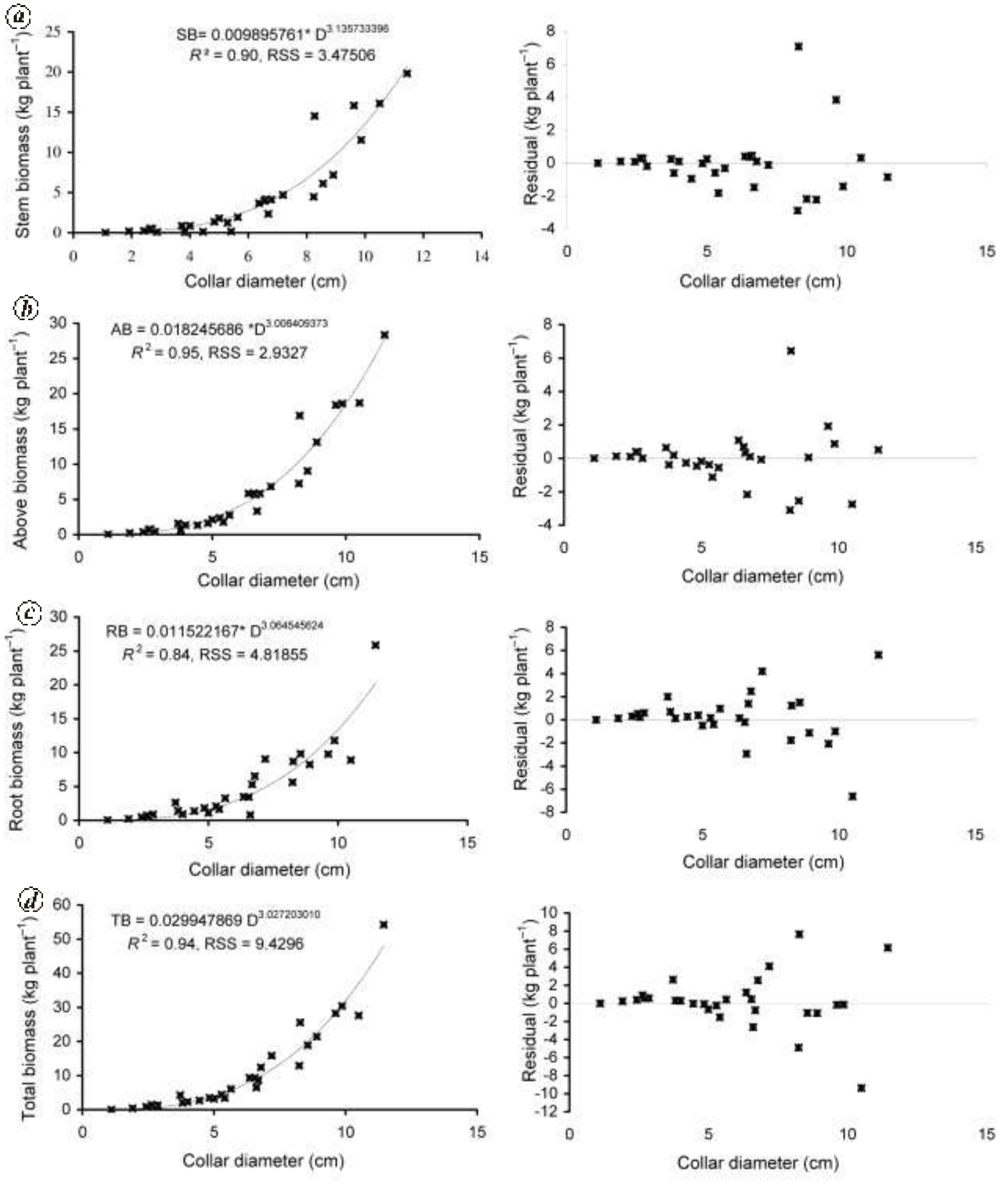

Figure 2. (Left) Observed (×) and predicted (solid line) stem biomass (***a***), above-ground biomass (***b***), root biomass (***c***) and total biomass (***d***). (Right) Corresponding residual plots representing nonlinear model fitted to the scatter plot of data of *C. polygonoides*.

with minimum human interference and remoteness had high carbon density.

Though *C. polygonoides* has adapted to extremely harsh environmental conditions and survived in areas with low soil water and nutrients[13], its growth depends upon availability of soil resources, competitive effect of the associated vegetation and biomass allocation to roots for accessing soil resources[38,39]. The proportional

Table 3. Growth variables and component-wise biomass of harvested *C. polygonoides* shrubs in the study area (arid zone of Rajasthan)

Component	Minimum	Maximum	Mean	Standard deviation
Height (m)	0.35	3.15	1.76	0.81
Collar diameter (cm)	1.10	11.45	5.91	2.75
Crown diameter (m)	0.46	4.05	2.16	1.10
Root girth (cm)	3.45	39.00	19.41	9.62
Root length (cm)	80.0	1360.0	399.7	355.7
Number of roots	1	12	3.64	3.30
Stem biomass (kg)	0.01	19.83	4.43	5.63
Foliage biomass (kg)	0.00	8.50	1.84	2.08
Above-ground biomass (kg)	0.02	28.33	6.27	7.35
Below-ground biomass (kg)	0.02	25.86	4.70	5.43
Total biomass (kg)	0.03	54.19	10.97	12.51

Table 4. Parameter estimates and statistical variables of best-fit nonlinear model for estimating biomass of *C. polygonoides* shrub (in the study area)

Component	Model no.	Parameters	Estimate	R^2	RMSE	SEE	*P*-value
Stem biomass	5	*a*	0.009895761	0.90	3.47506	–0.0452	<0.001
		b	3.135733396				
Above-ground biomass	5	a	0.018245686	0.95	2.93272	–0.0039	<0.001
		b	3.006409373				
Below-ground biomass	5	*a*	0.011522167	0.84	4.81855	0.1584	<0.001
		b	3.064545624				
Total biomass	5	*a*	0.029947869	0.94	9.42964	0.0638	<0.001
		b	3.027203010				

RMSE, Residual mean square error; R^2, Coefficient of determination; SEE, Standard error of estimate, P, Probability of significance.

distribution of biomass among various components changed with size, stature and availability of soil resources. As both stems and roots are woody and are used as fuelwood, the increased biomass in stems and roots in larger individuals of the species makes it economically more important. Total biomass continued to increase with increase in collar diameter. About 16.8% biomass was allocated to foliage, where contribution of thick twigs was maximum. *C. polygonoides* invested almost equal biomass in both above- and below-ground parts. Biomass allocation towards roots than above-ground biomass was due to the well-developed root system for survival and to access scarce soil water and nutrients in this environment[3,9], where above-ground biomass appeared most sensitive to water deficit[40]. However, evidences indicate relatively low soil water use by *C. polygonoides* to produce higher biomass compared to *Acacia tortilis* and *Prosopis juliflora*[9].

Smaller values of RMSE and SEE and higher value of R^2 for the diameter-based equations for all components compared to the equations involving both diameter and height, indicate the accuracy of the equations. Further, diameter-based model estimated 1.85% less total biomass as compared the observed value indicating the accuracy of the model. While using the common regression equation for shrubs to estimate the biomass of *C. polygonoides*[37], the estimated total biomass was 36.27% lower than the observed value. This highlights the importance of developing models for individual species on a regional basis to predict the biomass more accurately. Increase in the values of RMSE and SEE and decrease in R^2 value when height was included in the models, suggest better applicability of the diameter-based models[41]. Weak relationship between height and collar diameter is because of the bushy nature of the species, while variability in height under sand trapping might be the reason of decreasing accuracy of height–diameter-based model compared to diameter-based model of *C. polygonoides*. Despite higher values of R^2 in estimating biomass of some of the components, eqs (2), (3) and (6) showed more negative values or less values on the lower side of the prediction than the observed values, and hence did not appear better than eq. (5) (Table 2). Further, diameter-based biomass prediction model is usually more convenient, to use and well-suited for foresters, managers and farmers in accurately and precisely calculating biomass and carbon sequestered by promoting and conserving this species either in forestlands, community lands or farmlands.

Carbon sequestration is determined by the growth and consequently accumulated biomass/carbon. Variations in carbon concentration in different components, i.e. twigs > stems > roots > leaves were due to varying climatic and edaphic factors[37], which along with genetic characters influence plant growth, biomass and carbon concentration

Table 5. Biomass and carbon density due to *C. polygonoides* shrub in forests of the studied districts of Rajasthan

District	Biomass (t/ha)			Carbon (t/ha)		
	Above-ground	Roots	Total	Above-ground	Roots	Total
Barmer	1.91	1.38	3.29	0.89	0.65	1.54
Bikaner	0.52	0.36	0.88	0.24	0.17	0.41
Jaisalmer	2.28	1.65	3.93	1.06	0.78	1.84
Jodhpur	0.45	0.33	0.78	0.21	0.16	0.37
Sri Ganganagar	1.75	1.21	2.96	0.82	0.57	1.39
Average	1.38 ± 0.84	0.99 ± 0.61	2.37 ± 1.45	0.65	0.46	1.11

in different parts of plants[42,43]. The results are similar to a study on *Larix olgensis*[44], which showed varying carbon concentration in different parts of the plant at different ages with mean carbon concentration of 48.15%. Wide spatial variation in carbon density due to *C. polygonoides* was due to variations in growth and population of this species in different districts as affected by climatic and anthropogenic interferences like removal of vegetation and cultivation of commercial crops like groundnut and castor[12]. This is also indicated by highest density in Jaisalmer followed by Barmer, where human population and such interferences are negligible or less because of remoteness of the area, whereas lowest carbon density in Jodhpur is related to high population and corresponding interferences[11].

Conclusively, *C. polygonoides* varied widely in growth, population and biomass (0.03–54.19 kg/plant). Contribution of stem biomass was 45.7% and that of root biomass was 48.0% of the total biomass. Nonlinear models using collar diameter as the predictors were found to be the best in predicting biomass of *C. polygonoides* and accounting for carbon. Carbon concentration varied in the order: twigs > stems > roots > leaves. Carbon density showed significant spatial variations, indicating its dependency on varying climatic and human-induced stresses affecting biomass and carbon sequestration. This emphasizes conservation of the species to reduce land degradation in the study region.

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Seed desiccation responses in *Saraca asoca* (Roxb.) W.J.de Wilde

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***Saraca asoca* is one among the 36 endangered medicinal plants of South India. As seeds are the main propagule with short viability, the present study has been carried out to assess the level of dehydration tolerance as a prerequisite to maintain extended viability. The viability and vigour of the seeds declined when their moisture content was reduced by different methods of desiccation. The critical moisture content (CMC) of the seeds was found to be 45–46%. Irrespective of the method of drying, dehydration of seeds resulted in the loss of viability, confirming their recalcitrant nature. Desiccation responses were investigated by exposing the seeds to five different conditions: (a) 30° ± 2°C, (b) silica gel, (c) 40° ± 2°C, (d) 20° ± 2°C and (e) 0° ± 2°C. The duration for reaching the critical moisture level was the longest in seeds kept in an air-conditioned room (20° ± 2°C) and minimum for those kept in a freezer (0° ± 2°C). The lowest critical moisture level (36.3%) was observed in silica gel and highest (49.2%) under freezer condition. Both the attainment and level of CMC showed marked variation under different desiccation treatments, which indicates the influence of storage temperature on CMC of *S. asoca* seeds.**

Keywords: Critical moisture content, desiccation, germination, *Saraca asoca*.

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