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Rooting pattern and equations for estimating biomasses of *Hardwickia binata* and *Colophospermum mopane* trees in agroforestry system in Indian desert

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ABSTRACT

In addition to conserving soil and water, improving land-use efficiency and increasing economic returns, agroforestry practice is also one of the better options of sequestering atmospheric CO_2 and contributing to mitigate climate change effects with the secondary benefits of food security. We studied root growth pattern and biomass allocation in roots, stem, branches and foliage (twig+leaves) of 18-year old *Colophospermum mopane* J. Kirk ex Benth. and *Hardwickia binata* Roxb and developed equations for precise carbon accounting, environmental health monitoring and sustainable management of agroforestry systems in dry areas. Roots of both these species mined the area >1.5 times the canopy area. Roots of *C. mopane* were more confined to top 80 cm soil layer and almost parallel to soil surface and appeared to be more competitive as compared to that in *H. binata*, where roots were relatively deep penetrating. Biomass allocation to roots and foliage decreased with increase in tree total biomass. Such decrease was at the cost of increased branch biomass in *H. binata* and both branch and stem biomass in *C. mopane*. Among the linear and nonlinear equations developed for estimating above ground biomass, root biomass and total biomass using diameter at breast height (DBH) and height as the predictors, DBH alone was sufficient to predict these biomasses. Inclusion of height in the models did not improve the results. Average total dry biomass ranged between 4.49 to 135.85 kg per tree for *H. binata* and 5.91 to 130.41 kg per tree for *C. mopane* trees. Biomass accumulation in stem was higher (45.7%) in *H. binata* than in *C. mopane* (28.6%) trees. A reverse trend was observed in case of foliage, the contribution of which to the total biomass was 40.2% in *C. mopane* and 23.5% in *H. binata* trees. Findings on rooting pattern cautioned in selecting agroforestry tree species, whereas predicting standing biomass more accurately for carbon accounting may be beneficial in promoting tree cover and help mitigate climate change effects.

INTRODUCTION

Land use and land use changes are approaches that became popular in the context of the Kyoto protocol and current face of climate change. Sequestering carbon in tree biomass by way of integrating trees into landscapes as agroforestry, forestry and plantations is a cost-effective climate change mitigation strategy [1-3]. Suitably selected trees in an agroforestry system enhance the system productivity and act as sink for atmospheric carbon. The system as a whole contributes to mitigate climate change with secondary benefits of food security, increased farm income, restored biodiversity, maintained watershed hydrology and improved soil health and people livelihood [4-6]. The estimates of carbon stored in agroforestry systems range from 0.29 to 15.21 Mg ha^{-1} yr^{-1} aboveground and 30 to 300 Mg ha^{-1} up to 1-m depth in the soil [7]. While total loss of carbon due to desertification is about 18-28 Pg (peta gram, 10^{15} gram), the potential of total carbon sequestration in vegetation and soils by way of combating desertification appears to 12-18 Pg [8]. Thus, agroforestry systems shows multifunctional role by promoting biomass production and help relieve pressure on timber extraction from natural forests and contribute to forest conservation with additional benefits of climate change adaptation and mitigation [9]. Hence, accurate estimation of biomass and related carbon stock in these tree based agroforestry systems are very much relevant for scientific purposes and obtaining financial rewards for sequestered carbon.

Studying biomass partitioning into different component of a tree and root structure will be useful in selecting most suitable woody perennials for an agroforestry system. Reducing Emissions from Deforestation and Forest Degradation (REDD+) and commitment to Kyoto protocol focus more attention on methods for precise assessment of biomass and carbon stocks [10]. Thus estimating aboveground biomass with sufficient accuracy is increasingly important for its applications in carbon accounting in different land uses [11]. Several biomass-prediction equations have been developed for more than 300 tree species, but most of them are from tree species of tropical forest stands [12-20]. Tree biomasses are also estimated by common allometric equations which are generally applied over a large area or ecological range [21,22]. However, a number of factors like stand age, species type, topography, environmental heterogeneity and human interferences affect tree biomass. Indirect methods are also attempted in estimating tree biomass [23,24] by using easily accessible forest inventories (wood volume and specific gravity) and applying correction factors too. Therefore, considerable amounts of uncertainty exist in estimating spatial distribution of biomass [25].

Because tree species differ in allometry, wood density and architecture, which affect the relationship between the measurements taken during forest inventories and the biomass of the individual trees there is need to develop species-specific allometric equations at regional level. Wherever species-specific information like size classes and total height is available and equations developed to estimate biomass of a particular species, it provides more accurate estimates of biomass [26-31]. However, we did not find robust method to estimate biomass of standing *Hardwickia binata* Roxb. and *Colophospermum mopane* J. Kirk ex Benth. trees, which are potential agroforestry species of Indian drylands [32,33].

The objectives of the present study were to: (i) monitor biomass partitioning in different tree components such as root, stem up to 5 cm diameter, branch up to 2 cm diameter and foliage (twig and leaf), (ii) monitor structure and distribution of roots in soils, and (iii) develop equations for predicting the above ground biomass, root biomass and total biomass of *H. binata* and *C. mopane* planted in a dry land agroforestry system.

MATERIALS AND METHODS

Study area

The study was conducted in the experimental field of Arid Forest Research Institute, Jodhpur, situated at 26°45' N latitude and 72° 03'E longitude in Rajasthan province in northwestern India. *H. binata* and *C. mopane* trees were block planted separately (in randomized block design) in July 1994 at 5 m × 5 m spacing and intercropped with different agricultural crops, i.e. *Vigna radiata* as fixed crop in all years as one treatment and trees with rotation crop (*V. radiata* rotated by non-legume crops like *Pennisetum glaucum*/*Sesamum indicum* in alternate years as the second treatment. Thus there were two-subplots for each tree species and the experiment was in three replications. The maximum temperature rises to as high as 48°C in the summer and the minimum drops to 0°C in the winter. Annual rainfall of Jodhpur is 350 mm, in which maximum rainfall occurs during monsoon months i.e., July to September. Wind velocity in the summer months is 20–30 km h^{-1}. The experimental farm is flat land with loamy sand soil (coarse loamy, mixed hyperthermic family of typic camborthids according to US soil taxonomy) with a thick concretion of calcium carbonate at a depth of 75 cm. The soil in the study area had low organic carbon (0.27%), available P (10.2 mg kg^{-1} soil), NO_3-N (4.01 mg kg^{-1} soil) and NH_4-N (5.92 mg kg^{-1} soil), and was slightly alkaline in reaction (pH 7.8) [34]. Soil moisture storage in the upper 75 cm layer varied from 120 mm at -0.01 MPa to 35 mm at -1.5 MPa [5].

Tree selection and harvesting

A total of 62 trees (thirty one trees of each species) of *H. binata* and *C. mopane* were harvested in June 2012 and measured for height and diameter at breast height (DBH). The above-ground parts of the felled trees were separated into stem, branches (up to 2.0 cm diameter) and foliage (twig of <2.0 cm diameter and leaves). Roots of the felled trees were excavated by mechanical digging up to 0.5 cm diameter to measure root penetration in soil profile as well as their horizontal spread [35]. Visual appearance and shape of the root structures in soil profile was also monitored. Fresh mass of stem, branches, foliage and roots was recorded immediately after harvesting of the tree and separating it into different components. Sample discs from stem, branch and root were collected from the base and the top of each 1.5 m section and fresh weight of these samples were taken immediately in the field. Samples collected from stem, branches, foliage and root were oven dried at 80 °C and dry biomass recorded until constant weight [24]. Dry mass of the samples were used to calculate stems, branches, foliage and roots biomasses of both *H. binata* and *C. mopane* trees. The dry biomass of stems, branches and foliage were summed as above ground biomass, whereas root dry biomass was added to the above dry biomass to obtain the whole tree biomass.

Biomass equations

Diameter at breast height (DBH)-based and DBH together with height-based linear and nonlinear models were used to develop the relationships between these growth variables and above-ground, roots biomass and total biomass of trees for both three species. We selected 8 types of models from the existing literatures based on their wide application. Growth and biomass variables of 31 trees of each species were used to fit the models for both the species separately. The models with the lowest error of estimate, mean square error (MSE) and highest coefficient of determination (R^2) and significant fit plots ($P<0.05$) were selected as the best fit models. The absolute or unsigned deviation, also known as error of estimate, was calculated using SPSS version 8.0 statistical package for each best fit model as given below to test the accuracy of the models. Further, to check and tests to ensure that analysis have proceeded within the bounds of the basic assumptions; we checked the pattern of the residuals by means of residual plots.

$$d = \frac{\sum_{i=1}^{n} |(\text{Observed} - \text{Predicted})/\text{Observed}|}{n} \times 100$$

RESULTS

Tree growth and root development

Height and DBH of the felled trees of *H. binata* ranged from 3.25 m to 9.10 m and 4.45 cm to 17.50 cm, respectively, whereas respective variables for *C. mopane* trees varied from 3.00 m to 6.20 m and 2.90 cm to 17.50 cm (Table 1). Average tree height, crown diameter (spread), numbers of roots in 0-30 cm and <30 cm soil layers and rooting depth were greater for *H. binata* as compared to that of *C. mopane*, whereas DBH and rooting diameter were greater for *C. mopane* than in *H. binata*. Horizontal spread in the roots of both species was greater as compared to the crown spread. As compared to the canopy area, the rooting area was 1.25 times greater for *H. binata* and 1.77 times greater for *C. mopane*. Roots of *H. binata* were in general deep penetrating even the calcium carbonate layer available below 80 cm, and were in bell shape in structure, whereas the roots of *C. mapane* confined to <80 cm top soil layer in most of the trees and observed spreading parallel to the soil surface. In some of the cases, the roots of *C. mopane* observed orienting parallel to the calcium carbonate layer after a futile effort of trying to penetrate the hard layer of calcium carbonate.

Table 1: Shoot and root growth variables of *H. binata* and *C. mopane* trees grown in an agroforestry system in arid region of Rajasthan.

Species	Component	Minimum	Maximum	Mean	±1SD
H. binata	Height (m)	3.25	9.10	5.81	1.25
	DBH (cm)	4.45	17.50	9.50	3.22
	Crown spread (m)	4.22	6.10	4.89	0.72
	Nos.of roots (0-30 cm soil layer)	7	13	11.4	3.05
	Nos.of roots (<30 cm soil layer)	2	3	2.40	0.55
	Root diameter (cm)	473	610	547.2	62.77
	Root depth (cm)	70	175	145	42.87
C. mopane	Height (m)	3.0	6.2	4.47	0.67
	DBH (cm)	2.9	17.5	9.92	3.17
	Crown spread (m)	3.60	5.88	4.74	0.81
	Nos.of roots (0-30 cm soil layer)	7.0	9.0	7.3	1.03
	Nos.of roots (<30 cm soil layer)	1.0	2.0	1.83	0.41
	Root diameter (cm)	460	891	630	149.3
	Root depth (cm)	55	91	73.5	12.8

Biomass allocation in tree components

Biomass of both *H. binata* and *C. mopane* trees generally increased with increase in diameter at breast height (DBH). Total dry biomass ranged from 4.49 to 135.85 kg tree^{-1} for *H. binata* and between 5.91 kg per tree and 41.92 kg per tree for *C. mopan*. Biomass variations in different components were significantly ($P<0.05$) greater in *H. binata* as compared to *C. mopane*. Average biomass of stem, branches and roots were greater ($P<0.05$) in *H. binata* as compared to *C. mopane*, whereas average foliage biomass showed an opposite trend. In *H. binata*, total leaf biomass was 8.63% of the aboveground biomass and 6.88% of the total biomass, whereas twig (<2 cm diameter branches) contributed 20.97% and 16.73% biomass in above ground and total biomass, respectively. Dry mass of branches (>2 cm to <5 cm diameter) was 16.19% of the above-ground biomass (stem+branches+foliage) and 13.12% of the total biomass, whereas the contribution of stem was 57.35% in above-ground and 45.60% in total biomass. In *C. mopane*, total leaf biomass contributed 10.86% in above ground biomass and 8.70% in total biomass, whereas twig biomass contributed 39.65% and 31.74% in respective biomass category. Dry biomass of branches of *C. mopane* was 15.94% of the above and 12.88% of the total biomass, whereas the stem biomass was 35.61% of the above and 28.54% of the total biomass.

Ratio of root dry biomass to above-ground dry biomass was 0.24 in *H. binata* and 0.22 in *C. mopane*. The ratios, foliage biomass: total biomass, stem: total biomass and root biomass: total biomass decreased, whereas branches: total biomass increased with increase in total biomass in *H. binata* (Figure 1). In *C. mopane*, foliage: total biomass and root biomass: total biomass ratios showed declining trend; and foliage: total biomass and stem biomass: total biomass ratios indicated increasing trend. However, the decrease in foliage: total biomass with increase in total biomass was significantly high in *C. mopane* as compared to *H. binata* (Figure 1).

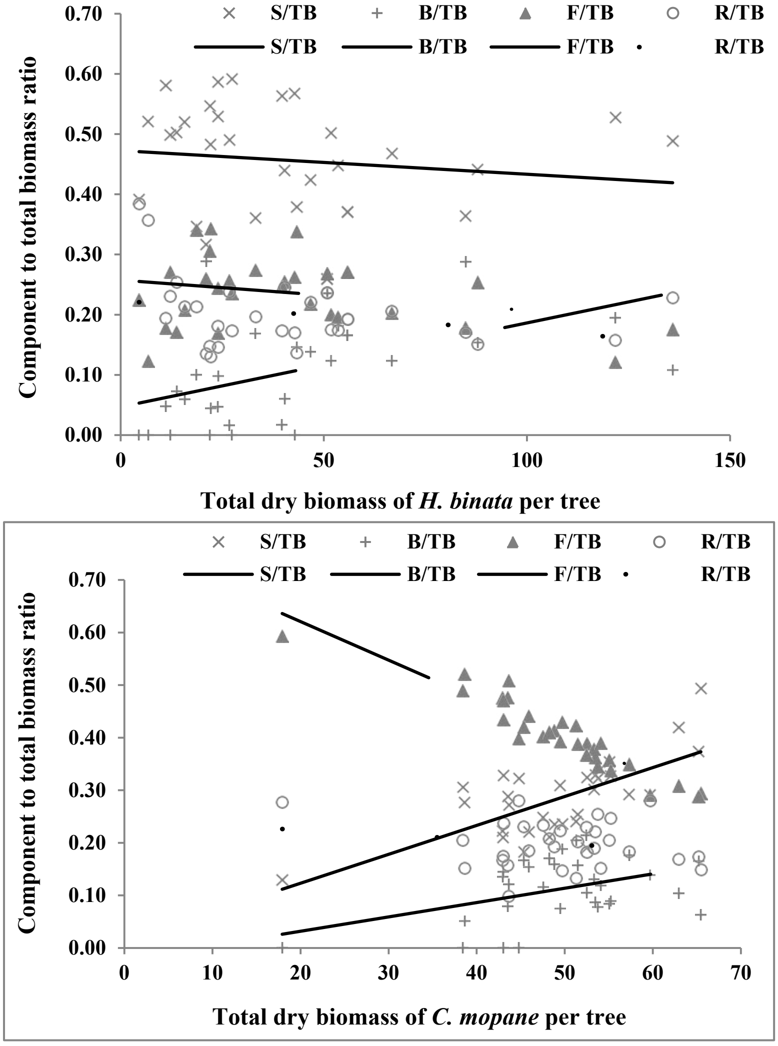

Figure 1: Biomass partitioning in different components of *H. binata* (top) and *C. mopane* (below) trees in an agroforestry system in dry region of Rajasthan, India.

Allometric biomass equation fitting

Total biomass, above ground biomass and root biomass of *H. binata* showed nonlinear relationship with diameter at breast height (DBH) and best fitted with the equation 5 (Table 2 and Figure 2). When both DBH and tree height were considered, the non-linear model following model 8 appeared best in predicting total biomass, above-ground biomass and root biomass of *H. binata* (Figure 3). Both linear and non-linear equations were observed suitable to estimate the biomass of different components of *C. mopane* using DBH only as the variable. The models 6, 5 and 3 showed better fitting to predict total biomass, above-ground biomass and root biomass of *C. mopane*, respectively (Table 3 and Figure 4). While considering both DBH and height, the best fit model was linear following model 1 in estimating total biomass and above-ground biomass of *C. mopane* trees (Figure 5a and 5b), whereas the non linear model 7 found best fitted in predicting root biomass of this species (Table 4 and Figure 5c).

DBH based models of the form models 3, 5 and 6 showed the lowest error of estimate (σ) and MSE, highest R^2 and significantly fitted ($P<0.01$) in predicting biomasses of different components of both these tree species. Involving both DBH and height, the best fitted models took the form of 1, 7 and 8, which showed the lowest σ and MSE, highest R^2 and best fit plot (Table 4). The nonlinear model 5 predicted only 0.96%, 0.72% and 2.31% lesser total biomass, above-ground biomass and root biomasses, respectively than the observed biomass of *H. binata*. As compared to the observed biomasses of *C. mopane*, the models 6, 5 and 3 predicted 0.74% higher total biomass, 1.56% lesser above-ground biomass and 0.016% lesser root biomass, respectively. The nonlinear model 8 underestimated total, above-ground and root biomass by 0.54%, 0.32% and 1.75%, respectively in *H. binata*. The estimated total biomass and above-ground biomass of *C. mopane* using linear model 1 showed insignificant differences (i.e., 0.0004% and 0.00009%, respectively) between observed and the predicted biomass, whereas the predicted root biomass using linear model 7 was greater by 0.15% as compared to the observed biomass. The plots of residuals with respect to the predicted total biomass, above-ground biomass and root biomass estimated through model 1, 3, 5, 6, 7 and 8 showed random distribution (Corresponding left panels of Figures 2-5) and there were no systematic trends in the these residuals error terms. This indicates the accuracy of these equations in predicting the biomass of different components of the two tree species.

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

Model	Equation type	Reference Numbers
1	Y=a + b*D^2H	[12]
2	Log Y=a + b* (log D^{**c})	[55]
3	Ln Y=a + b*D + c*Ln$(D)^{**d}$	[12]
4	Y=a+ b* D+ c*(D^{**d})	[55]
5	Y=a*D^{**b}	[27]
6	Y=a* $\exp^{**\ b*D}$	[54]
7	Y=a *D^2H^{**b}	[27]
8	Y=a*D^{**b}* H^{**c}	[55]

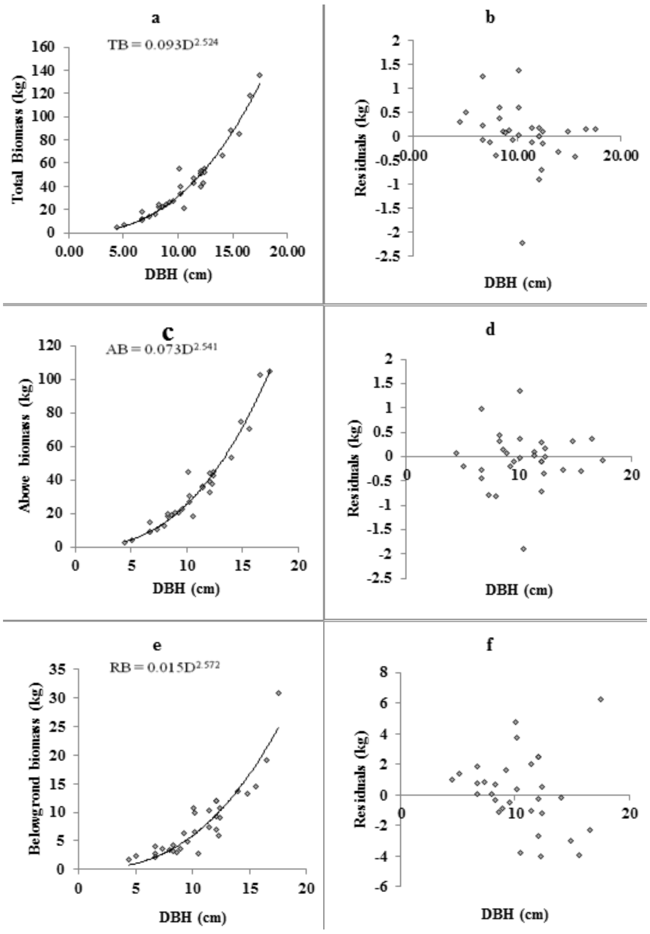

Figure 2: Relationships of DBH with dry biomasses of different components of H. binata trees. Observed and predicted biomasses (left panels) and corresponding residual plot (right panels). The solid line represents the linear/nonlinear model fitted to the scatter plot of data. TB = Total biomass, AB = Above biomass and RB = Root biomass.

DISCUSSIONS

Competition between tree species and understory crops not only exists aboveground for light but also from belowground for soil moisture and nutrients [36]. Below-ground completion generated by roots for soil resources particularly soil water is the primary factor affecting crop yields followed by light, though deficiency of the soil nutrients also has a significant impact on the crop yields of the system [37]. However, variations in the cropping pattern, i.e. fixede crop of *V. radiata* and rotation crop (*V. radiata* rotated by *Pennisetum gluacum/Sesamum indicum*) also influenced growth pattern of these tree species [32-33]. Rooting depth and root spread regulate the intensity of competition and appears major constraint that affects stability and function of the agroforestry systems. To minimize these competitive effects, management like regular pruning, creating root barriers, additional irrigation and fertilization are generally applied so that agricultural production could be enhanced [38]. Increased horizontal spreads in the roots of both species beyond their canopy zone is to access the minimal available resources and is the characteristics of the species of dry areas [39]. However, deep rooting pattern but relatively less spreading roots (hence less soil resource mining area) in *H. binata* as compared to *C. mopane* trees suggests more suitability of *H. binata* in agroforestry system [39]. This is also evidenced by lesser rooting area under *H. binata* as compared to that under *C. mopane*. There were 7–13 primary structural roots that emanated from the root collar and descended obliquely into the soils before becoming horizontal within a short distance of the trunk in *C. mopane*. These roots are concentrated in top 80 cm soil layer that made *C. mopane* more competitive with the associated agriculture crops [40]. This type of rooting in the planted *C. mopane* trees is in contrast to the earlier study, where seed sown 9 months old plants of 18 cm height extended its root to 121 cm that has penetrated the hard layer of calcium carbonate available at 70 cm soil depth [33]. This might be due to opportunistic nature of roots that grow wherever environmental conditions permit, though variations in rooting pattern might also be due to variations in seedling sources, i.e. nursery and direct seeding. For example nursery production also alters root system architecture, regardless of propagation technique [41,42]. However, species also differ in their foraging strategies, either proliferating in nutrient-rich zone, or extending widely to explore the largest soil volume [43-45].

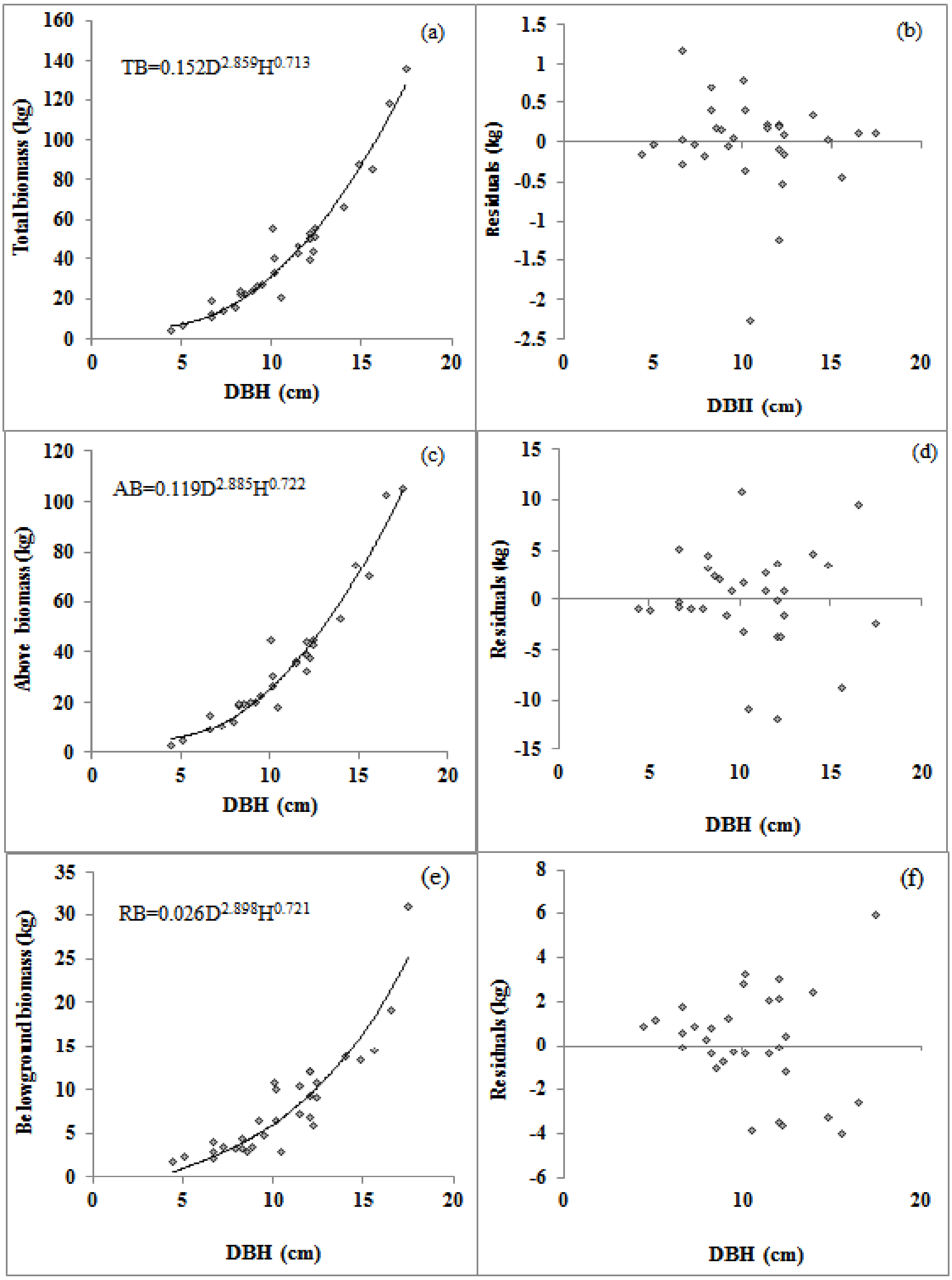

Figure 3: Relationships of DBH and height combination with dry biomasses of different components of *H. binata* trees. Observed and predicted biomasses (left panels) and corresponding residual plot (right panels). The solid line represents the linear/nonlinear model fitted to the scatter plot of data. TB: Total Biomass; AB: Above Biomass; and RB: Root Biomass.

Table 3: Component wise biomasses (kg tree^{-1}/component^{-1}) of *H. binata* and *C. mopane* trees grown in arid zone agroforestry system.

Species	Component	Minimum	Maximum	Mean	±1SD	Skewness	Kurtosis
H. binata	Stem biomass	1.76	66.38	19.27	15.21	1.86	3.92
	Branch biomass	0.43	24.43	7.20	6.75	1.23	1.28
	Foliage biomass	0.83	23.82	9.91	5.78	0.57	0.15
	Above biomass	2.76	104.88	34.23	25.51	1.40	1.95
	Below biomass	1.73	30.98	8.07	6.15	1.91	5.29
	Total biomass	4.49	135.85	42.17	31.01	1.43	2.20
C. mopane	Stem biomass	1.08	35.51	11.99	7.74	1.25	1.79
	Branch biomass	0.98	15.83	6.34	4.48	0.65	-0.76
	Foliage biomass	2.48	66.26	16.87	12.06	2.33	8.46
	Above biomass	4.54	117.61	34.38	22.70	1.63	4.72
	Below biomass	1.36	15.16	7.54	3.55	0.48	-0.56
	Total biomass	5.91	130.41	41.92	25.65	1.35	3.27

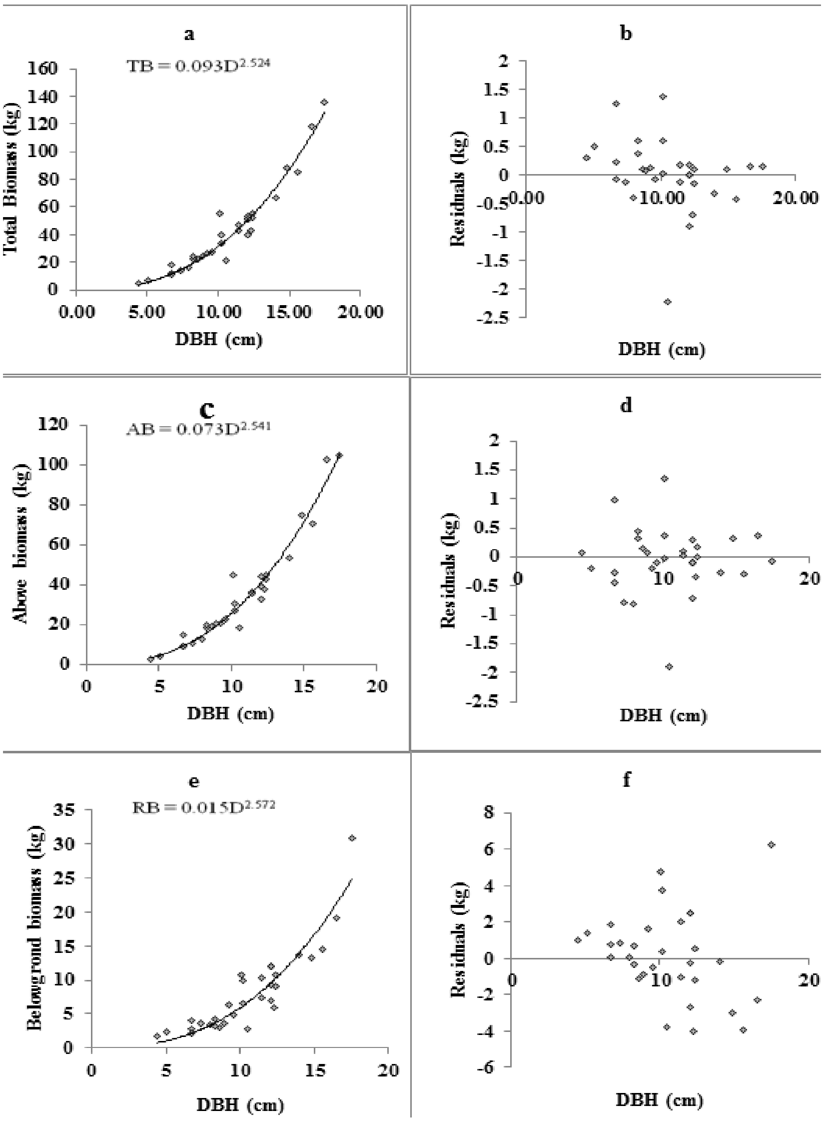

Figure 4: Relationships of DBH with dry biomasses of different components of C. mopane trees. Observed and predicted biomasses (left panels) and corresponding residual plot (right panels). The solid line represents the linear/nonlinear model fitted to the scatter plot of data. TB = Total biomass, AB = Above biomass and RB = Root biomass.

While using both DBH and height either individually or in combination to develop biomass equations to predict the tree biomass of the both the species, we observed a decrease in the values of the MSE and unsigned deviation for all tree components (i.e., above-ground, root and total biomass) for *C. mopane* trees when height was included in the models. This suggests that better biomass predicts can be obtained from DBH and height based models [6,50]. However, DBH based models for all tree components of *H. binata* tree was observed best because of smaller values of the MSE and unsigned deviation. Though DBH alone was found to give best results for estimating biomass of *H. binata* in dry region agroforestry, but height was a secondary variable for the below ground biomass estimation and it brought additional information into the estimates [51,52]. Because of weak relationships between height (m) and dbh (cm) of both the tree species might be responsible in reducing the performance of DBH and height based biomass equations as compared to the DBH alone base equations. Besides, height is less important for crown biomass estimation [51]. Thus DBH based biomass prediction equations are best for these species. Further, DBH observed commonly used variables to predict stem and tree biomass and appears more useful because of commonly measured variable in large scale national forest inventories [53]. Because of convenience in DBH measurement and biomass calculation, these models may be more acceptable among foresters, managers and farmers.

Table 4: Parameter estimates, mean square error (MSE), coefficient of determination (R^2), error of estimate (σ) and P value for *H. binata* and *C. mopane* trees grown in arid zone agroforestry system.

Component	Eq.	Parameter	Estimate	R^2	σ	MSE	P value
			H. binata				
DBH based models							
Total biomass	5	a	0.0938	0.951	0.03089	48.7999	<0.0001
		b	2.5247				
Above-ground biomass	5	a	0.0731	0.952	0.02329	32.5948	<0.0001
		b	2.5419				
Root biomass	5	a	0.0157	0.846	0.07443	6.0252	<0.0001
		b	2.5726				
DBH and height based models							
Total biomass	8	a	0.1523	0.962	0.01732	39.0172	<0.0001
		b	2.8599				
		c	-0.7138				
Above-ground biomass	8	a	0.1192	0.963	0.01028	25.6787	<0.0001
		b	2.8858				
		c	-0.7281				
Root biomass	8	a	0.0265	0.856	0.05637	5.8510	<0.0001
		b	2.8987				
		c	-0.7214				
			C. mopane				
DBH based models							
Total biomass	6	a	7.0170	0.898	0.01853	69.2657	<0.0001
		b	0.1672				
Above-ground biomass	5	a	0.1742	0.889	0.05037	59.2391	<0.0001
		b	2.2407				
Root biomass	3	a	0.9842	0.728	0.00013	0.01589	<0.0001
		b	-0.2537				
		c	0.4057				
		d	2.5887				
DBH and height based models							
Total biomass	1	a	8.2610	0.922	0.00014	52.9510	<0.0001
		b	0.0651				
Above-ground biomass	1	a	4.5718	0.924	0.00001	40.6100	<0.0001
		b	0.0576				
Root biomass	7	a	0.3183	0.701	0.00471	3.8885	<0.0001
		b	0.5170				

CONCLUSION AND RECOMMENDATIONS

Both these species tried to access soil resources by spreading their root even beyond their canopy and appeared to be competitive with the companion crops. However, integration of these species under farmlands is more in favour of *H. binata*. Allocation of biomass to roots and foliage decreased with increase in tree total biomass, but it was at the cost of increased biomass allocation to branch in *H. binata* and in both branch and stem in *C. mopane* favouring development of canopy cover. As biomass allocation among tree parts is particularly dynamic in the early phases of the growth the resource manager probably has the greatest opportunity to influence a plant's future deployment of carbon. Thus evaluation of the performance indicators such as carbon sequestration and nutrient storage require more accuracy and these species-specific DBH based equations in predicting biomass could be more useful in view of Kyoto protocol and REDD+.

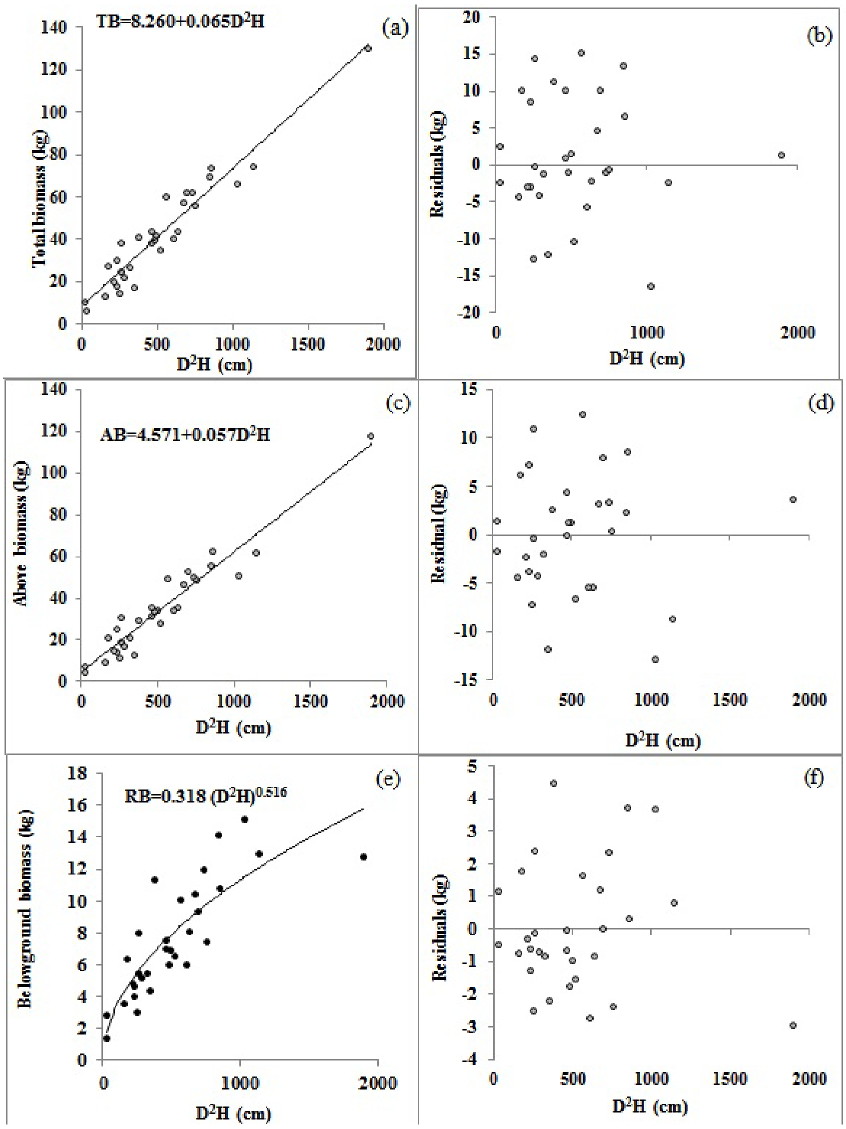

Figure 5: Relationships of DBH and height combinations with dry biomasses of different components of C. mopane trees. Observed and predicted biomasses (left panels) and corresponding residual plot (right panels). The solid line represents the linear/nonlinear model fitted to the scatter plot of data. TB=Total biomass; AB: Above Biomass; and RB: Root Biomass.

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