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Research article

Allometric equations for estimating aboveground biomass of *khat* (*Catha edulis*)-stimulate grown in agroforestry of Raya Valley, Northern Ethiopia

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ABSTRACT

Khat plant (*Catha edulis* Forsk) is an evergreen perennial cash crop cultivated in east Africa, southwest Arabia, and Madagascar. The plant is known for its production of stimulant fresh leaves, and expanding as expense of other land uses for its short-term financial returns. We, therefore, developed allometric equations for estimating aboveground biomass and carbon (C) removal of *khat* grown in farmlands of Raya Valley, Northern Ethiopia. A total of 31 plant individuals were harvested destructively on the basis of their diameters and age ranges. The equations were parametrized using biometric variables such as basal diameter (d_{10}), diameter at breast height (d), dominate height (doh) and mean height (h). Results of the analysis showed that, stem accounted for 58%, branch 32% and foliage 10% of the aboveground biomass (AGB). Commercial foliage biomass C removal ranged from 2.3 to 2.7 Mg ha^{-1}. The power equation, AGB $= b_1 \times d_{10}^{b2} \times doh^{b3}$, was the best (highest ranked using goodness-of-fit statistics), explaining 96% of the variation in aboveground biomass ($p < 0.01$). Models comparisons showed that our best ranked equation (M6) improved the aboveground biomass estimate by 44% and 48 % that of generic and other species-site specific equations developed in the tropics, respectively. Thus, our best species-site specific equation developed in this study can accurately estimate aboveground of *khat* plant biomass in the study region.

1. Introduction

Khat plant (*Catha edulis Forsk*) is an evergreen tree or shrub of Celastraceae family cultivated for its stimulant leaves primarily in East Africa, southwest Arabia, and Madagascar (Kennedy et al., 1983; Lemessa, 2001). *Khat* originated from eastern Ethiopia with a gradual expansion to other parts of the country, Yemen and some parts of the tropics (Huffnagel, 1961). The plant usually grows up to 7 m in height but also as high as 15–25 m in the wild (Raman, 1983). It requires well drained, dark red-brown, sandy loam soil with a low percentage of clay and pH of 6.0–8.3 (Murphy, 1999). In East Africa, *khat* plant grows in the range of 1500–2500 m.a.s.l (Lemessa, 2001).

Khat is economically important and potentially lucrative cash crop in Ethiopia. The plant has rapidly expanded, and covered 63,000 ha owned by 2.2 million farmers in the country. It becomes the most exported item next to coffee and oil seeds, and generates 10% of Ethiopia's export income (Andualem, 2002; Bongard et al., 2011; Ezekiel. 2005; Wabel, 2011). Besides financial benefits, the plant also serves for fuelwood, construction and farming tools (Gesess, 2013). Leaf and root extracts of *khat* is also used as a traditional medicine for treating stomach ache. *Khat* farming is replacing forest, and coffee farms in some parts of Ethiopia (Lemessa, 2001; Dube et al., 2014; Woldu et al., 2015). For instance, there was a huge shift in land use cover where 63% of the total coffee lands being uprooted and converted into *khat* monocropping in eastern part of Ethiopia (CSA, 20012; Woldu et al., 2015). In few places, *khat* is also planted with annual food crops and perennial crops in home garden agroforestry (Lemessa, 2001). The plant can tolerate drought, low impact on intercropped, stabilize soil and water conservation structures (Woldu et al., 2015).

In spite of a wider coverage of *khat* farming and its perennial nature, information is lacking on carbon sequestration capacity of the plant in the study region. Moreover, the *khat* leaf biomass is commercially harvested 2–3 times per year, however, its impact on carbon stock removal is not well known. These are partly attributed to absence of means to estimate the biomass. Despite the fact that equations to estimate aboveground biomass are largely available for most tropical tree/shrub species in forest ecosystems (Brown, 1997; Henry et al., 2011; Chave et al., 2014) equation is lacking to estimate biomass of *khat* plants grown in farm lands. Using generic or mixed species equations developed for other species would under or overestimate the biomass owing to the

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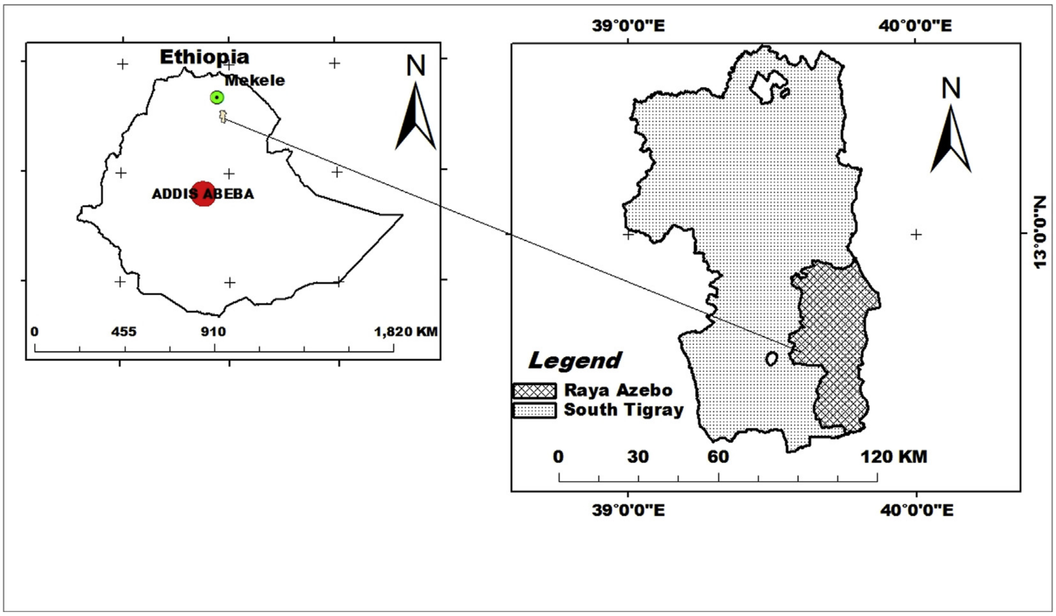

Figure 1. Map showing the location of the study area (main map shows the study country and the inset map of study area).

Table 1. Location and characteristics of the ten farms used for harvesting sampled *khat* plants to allometric equations for estimate aboveground biomass in Raya Valley of Northern Ethiopia.

Site type	Farm no.	Location			Aspect	No. of plants Harvested	Age class, years
		Latitude(N)	Longitude(E)	Elevation (m)			
Site 1	Farm#1	12˙ 36′ 15``	39˙ 34′ 20″	1932	North	5	C1
	Farm#2	12˙ 36′ 22``	39˙ 34′ 22``	1844	North	3	C2
	Farm#3	12˙ 36′ 13``	39˙ 34′ 16``	1985	South	2	C3
	Farm#4	12˙ 36′ 54``	39˙ 34′ 23``	1804	East	3	C3
	Farm#5	12˙ 35′ 57``	39˙ 34′ 21``	1810	East	3	C2
Site 2	Farm#1	12˙ 39′ 28``	39˙ 35′ 37``	1742	East	4	C1
	Farm#2	12˙ 40′ 00``	39˙ 37′ 26``	1712	South	2	C2
	Farm#3	12˙ 40′ 1``	39˙ 37′ 22``	1674	East	4	C2
	Farm#4	12˙ 39′ 27``	39˙ 38′ 20``	1546	East	3	C3
	Farm#5	12˙ 39′ 37``	38˙ 35′ 47``	1735	South	2	C3

C1 (class 1)> 25 years, C2 (class 2)16–25 years, C3 (class 3) 5–15 years.

Table 2. Summary statistics of biometric parameters of the harvested *khat* plants (n = 31).

Parameter	Mean	SD	Minimum	Maximum
d	6.37	3.05	2.50	13.00
d_{10}	8.29	3.70	3.50	16.43
h	3.53	1.39	1.50	6.40
doh	4.10	1.46	2.00	7.60

d refers to diameter at breast height(1.30 m), cm, d_{10} diameter at 10 height, cm, h mean height, m, *doh,* dominant height for multistems, m, *SD* standard deviation.

differences in plant architecture, growth habit, stand structure, management practices and site conditions. The overall objective of this study was, therefore, to develop allometric equations for estimating standing biomass and foliage biomass removal of the *khat* plant grown in monoculture in Raya valley of Northern Ethiopia. More specifically objectives were to: (i) determine the dry biomass of aboveground and components biomasses of the *khat* plant, (ii) identify the best predictor variable explaining aboveground and components' biomasses, (iii) develop allometric equations best estimate the aboveground biomass, and (iv) compare equations derived in this study with previously developed generic and other species-site specific equations. We hypothesis that the best biomass's predictor variable for *khat* plants could vary among biomass components and age groups, and using the equation developed for other woody species would over or underestimate the biomass.

2. Material and methods

2.1. Description of the study site

The present study was conducted in Raya Azebo district, which is found in one of the Ethiopian Great Rift Valley systems called Raya Valley in the Northern Ethiopia. Geographically, it is located between 12^0 18′

Table 3. Biomass models used to predict aboveground and components' biomasses of *khat* plants.

Model	Equation	Model	Equation
M1	$Y = b_1 \times d^{b2}$	M4	$Y = b_1 \times d_{10}^{b2} \times h^{b3}$
M2	$Y = b_1 \times d_{10}^{b2}$	M5	$Y = b_1 \times d^{b2} \times doh^{b3}$
M3	$Y = b_1 \times d^{b2} \times h^{b3}$	M6	$Y = b_1 \times d_{10}^{b2} \times doh^{b3}$

Y refers to biomass, kg dry matter/plant, *d* diameter breast height, cm, d_{10} stump height at 10 cm, cm, *h* mean height of stems, m, *doh* dominant height, m, *b1, b2, b3* parameters of the models.

Table 4. Mean (±SD) of dry biomass mass (kg/plant) and C contents of harvested *khat* plants (n = 31).

Biomass components	Dry matter, kg	% C
Foliage (twigs + leaves)	2.05 ± 1.41	46 ± 1.14
Branch	5.72 ± 3.55	48 ± 0.77
Stem	10.23 ± 8.24	49 ± 0.65
Aboveground biomass	17.94 ± 12.75	48 ± 0.36

43'' - 12^0 53′ 24″ N latitude and 39^0 33′ 3″- 40^0 2′ 27″ E longitude (Figure 1). The area cover 60 % of the Raya Valley. The elevation ranges from 1500 - 1985 m.a.s.l (TARI, 2009). The mean minimum and maximum monthly temperature 16 °C and 30 °C, respectively, and total annual rainfall ranges from 426 mm to 826 mm (Meles et al., 2009). Vertisols is the dominant soil type, covering over 70 % of study area (RVADP, 1998; Znabu, 2014).

The major vegetation in the study sites include *Olea europaea* L.*, Phytolacca dodecandra, Acacia species, Cordia africana* Lam.*, Opuntiaficus-indica, Ficus sycomorus* L.*, Dodonaea angustifolia* L. f.*, African pencilcedar, Carissa spinarum* L.*, Erica arborea* L. and *Euphorbia abyssinia*. Various exotic plants have also adopted themselves to the local climate in the study area. The exotic tree species include *Cupressus lusitanica* Mill, *Schinus molle* Lam. and *Eucalyptus species* (Znabu, 2014).

Khat farming is planted mainly mono-crop with hedge plantation of different shrubs including *Euphorbia tirucalli* L., *Arundo donax* L. and *Maerua aethiopica*. *Khat* is the commonest perennial cash crops dominating the farming system in the study area, and occupied in average 0.47 ha per farming household.

The practice of *khat* leaf biomass harvesting passes to consumers is through various steps. Firstly, farmers harvested foliage biomass from standing *khat* plant, referred as total leaf biomass (TLB). Secondly, portion of the harvested TLB would be available to market for *khat* consumer as a stimulant, hereafter, named as commercial leaf biomass (CLB). While the remaining portion of TLB would be discarded, and is considered as wasted leaf biomass (WLB). WLB serves for a feed for animals, particularly sheep and goats, and fuelwood particularly for preparation of local alcoholic drink or damped on farms as a source of organic matter.

2.2. Farm selection and inventory

First, two adjacent sites dominantly growing *khat* as cash crop were purposively selected in Raya Azebo district. Secondly, the major age categories of *khat* farming were identified using key informants. Accordingly, three age categories were identified, namely, 5–15, 16–25 and above 25 years-old. Thirdly, those *khat* farms were listed, followed by random selection of 10 farms in the two sites (5 each). The number of farms in each age category was determined proportionally (Table 1). A total of 10 sample plots size 20 m × 20 m were randomly laid down across the selected farms. To select the sample plot location, the farm was divided into 10 equal grid points visually. Then, the sample point was selected using a lottery system by assigning a random number to each grid point. The GPS location of the selected sample plot was also recorded. Within each plot all *khat* plants having breast height diameter ≥2.50 cm and height ≥1.50 m were measured and recorded. The following biometric parameters of each sampled *khat* plant were measured before felling them: basal diameter at 10 cm height (d_{10}), diameter at breast height (*d*) (mean of measurements taken in two perpendicular directions at 1.30 m), mean height (*h*) and dominant height (*doh*). Mean height refers to the distance from the ground to the petiole of the last leaf to emerge. Dominant height refers the height of the tallest plant in the case of multi-stemmed plants. For multi-stemmed *khat* plants (in our case 2–10 stems per plant), *d* and d_{10} of each stem was measured, and the equivalent diameter of the plant calculated as the square root of the sum of diameters of all stems per plant (Snowdon et al., 2002).

$$de = \sqrt{\sum_{i=1}^{n} di^2} \quad \text{Eq.1}$$

where *de* is diameter equivalent (*d* or d_{10}), cm; d_i is diameter of i^{th} stem at *d* or d_{10}, cm.

2.3. Harvesting sample plants

After measuring the biometric parameters for all the standing *khat* plants in a plot, a total of 31 khat plants, constituting 11 young (aged <15 years-old), 11 mature (16-25 years-old) and 9 old individuals (>25 years-old), were randomly selected. The number of individual *khat* plants was determined on the basis of their relative proportion in each age category. The harvested plants were in good condition, this means foliage (leaf plus twig) fully flourished. We also considered farmers' willingness to harvest their *khat* plants.The values of *d* and d_{10} for the sampled pants ranged from 2.50 cm to 13.00 cm, and 3.50 cm–16.43 cm, respectively. The mean height was within the range of 1.50 m–6.40 m. Detailed biometric characteristics of sampled *khat* plants are shown in Table 2.

The approach for biomass harvest followed Negash et al. (2013b). The sampled *khat* plants were harvested closest to the ground and partitioned into three biomass components: foliage (twig plus leaves), branch and stem. In this study, stem referred to main shoot from the ground to the top of apical meristems. Samples of 5cm discs were taken at 1m interval from each stem of harvested plant. We arranged all the branches horizontally on the floor, and 5cm long samples disks were taken from each. For the foliage component, 10 twigs and leaves each were taken from a stem branches. The fresh weight of sub-sample for each biomass component should be measured accurately in field too, with an error allowance of ±1g. Sub-samples were taken to laboratory for determination of dry to fresh weight ratios. The stem and branch samples first sun-dried a week and twigs plus leaves for 3 days. The subsamples of stem and branches were oven-dried at 105 °C whereas at 70 °C for foliage for 24 h. The fresh to oven-dry mass ratios were determined and used to convert the fresh weights of each biomass component into oven-dry weights.

The C content (%) of *the khat* biomass samples were determined from organic matter contents through loss-on-ignition (LOI at 550 °C for 2 h), assumed 50 % of the organic matter lost through burning is C content (Berhe et al., 2013). The *khat* biomass on average organic matter contents in stem, branch and foliage biomasses were 98, 96 and 92 %, respectively. Multiplying these values by 50 % to get C content.

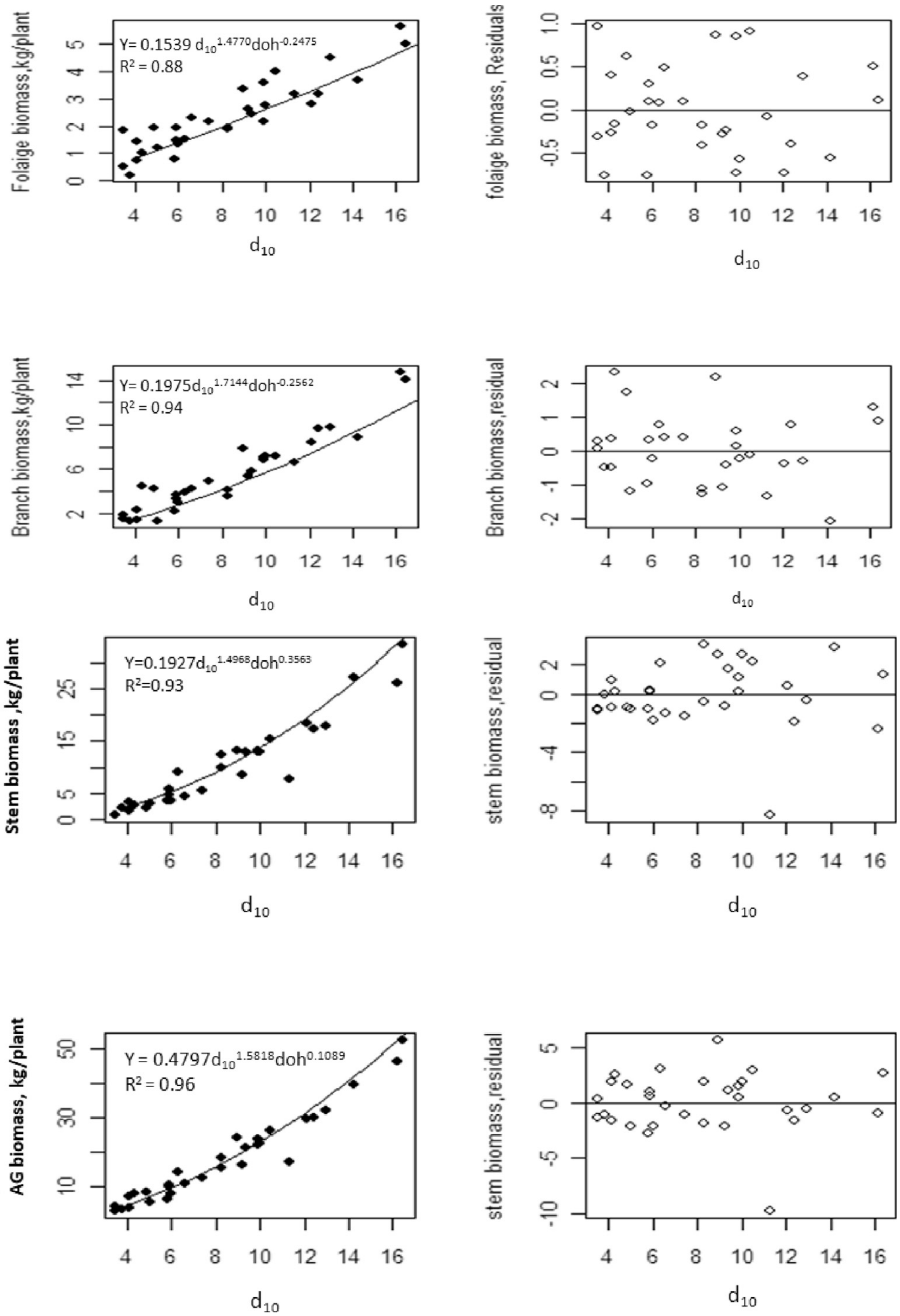

Figure 2. Relationship between biomass components of *khat (Catha edulis)* and stump diameter (DSH) at 10cm height (left) and corresponding residual plots (right).

2.4. *Sampling commercial khat foliage biomasses*

A survey was conducted on randomly selected 30 farms to determine the foliage biomass turnover rate per harvesting season. In each farm 3 individuals of *khat* plant were randomly selected, making a total of 90 plants. Foliage biomasses samples were collected across three harvesting periods including December–January, June–July and September–October. These periods were selected because of the peak foliage biomass harvest to *khat* plant in the study area. Besides, *khat* growers were interviewed using checklists to validate the measured values. The major discussion points in household interviews included *khat* foliage biomass production per harvesting period (local unit '*zurba*' was used, i.e. one '*zurba*' = 1.3 kg), production season, management practices, farm size, and yield of single plant. History recorded in selected farms included slope, aspect, stand age, and elevation gradients. Moreover, thirty samples of '*zurba*' were randomly selected in the local market and fresh foliage biomass weighed (in kg). Oven dry to fresh weight ratio of foliage biomass was determined.

2.5. *Khat biomass determinations*

The biomass equations were separately determined for each biomass component (foliage, branch, stem and total aboveground biomass) using non-linear regression and power function ($y = ax^b$). Power equations,

Table 5. Spearman correlations between biomass components (kg dry matter) and biometric parameters of harvested *khat* plant (n = 31).

Biomass component	*d* (cm)	d_{10} (cm)	*h* (m)	*doh* (m)
Foliage	0.865**	0.910**	0.609*	0.617**
Branch	0.889**	0.946**	0.647**	0.670**
Stem	0.925**	0.949**	0.621**	0.661**
Aboveground biomass	0.933**	0.968**	0.608**	0.743**

d refers diameter at breast height; d_{10} basal diameter at 10 cm height, *h* mean height, *doh* dominant height, $^{**}p < 0.01$, $^{*}p < 0.05$.

square power and fractional powers were fitted to determine the relationship between aboveground biomass (kg dry matter/plant) and either stem diameter alone (*d* or d_{10}) or both stem diameters (*d* and d_{10}) and *h* or *doh* (Table 3).

We parameterized 6 equations for each biomass component and total aboveground biomass using R statistical software version 3.11 (Team RC, 2015). The performances of the equations were evaluated using various goodness-of-fit statistics including coefficient of determination (R^2), mean absolute bias (MAB), standard error of estimate (SEE), average bias (B), prediction residuals sum of squares (PRESS) and index of agreement (D) (Kozak and Kozak, 2003; Berhe and Arnoldsson).

For cross validation of the equations, of the 31 harvested individuals, both root mean square error (RMSE) and mean prediction error (MPE) were determined from a leave one out cross variation (LOOCV) procedure. This procedure leaves one observation for validation, and the remaining n-1 observations for model train. The excluded observation is predicted and the error is computed. The procedure is repeated n time until every observation has been left out and predicted. The n errors are used to calculated, RMSE and MPE as below Eqs. (2) and (3).

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(Y_i - \hat{Y}_i)^2}{n}},\ \mathrm{RMSE}(\%) = \frac{\mathrm{RMSE}}{\overline{Y}} * 100 \quad \text{Eq 2}$$

$$\mathrm{MPE} = \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)}{n},\ \mathrm{MPE}(\%)\ \frac{\mathrm{MPE}*100}{\overline{Y}} \quad \text{Eq 3}$$

where: Y_i is the observations of the response variables, $\hat{Y}_i$ is the predicted value of the Y_i, $\overline{Y}$ is the average of the Yi.

The performance of each equation was evaluated using the following goodness of fit statistics criteria:

$$D = 1 - \frac{\sum_{i=1}^{N} (e_i)^2)}{\sum_{i=1}^{N} (|\hat{Y}_i - \overline{Y}| + |Y_i - \overline{Y}|)^2} \quad \text{Eq 4}$$

$$Bais = \frac{\sum_{i=1}^{n} (e_i)}{n} \quad \text{Eq 5}$$

$$MAB = \frac{\sum_{i=1}^{n} |e_i|}{n} \quad \text{Eq 6}$$

$$PRESS = \sum_{n=1}^{n} \delta_i^2 \quad \text{Eq 7}$$

where: $e_i = \hat{Y}_i - Y_i$; $\delta_i = Y_i - \hat{Y}_{i,-i}$; i = 1, 2,...., n; n is the number of observations, Y_i is the observations of the response variables, $\hat{Y}_i$ is the predicted value of the Y_i, is the average of the Yi, δ_i is i^{th} prediction error, $\hat{Y}_{i,-I}$ is the prediction of the i^{th} data point by a model that did not make use of the i^{th} point in the estimation of the parameters.

The best preforming equation should have the highest R^2 and D, and the lowest Bias, SEE, MAB and PRESS values. All the equations were ranked according to each goodness of-fit statistic and the ranks summed to give an overall model performance rank.

2.6. Estimation of annual carbon removal via foliage biomass

The ratio of dry to fresh foliage biomass (*Br*) was calculated as follow (Ribeiro et al., 2015):

$$\mathrm{Br}(\%) = \frac{\mathrm{DW}}{\mathrm{FW}} \times 100 \quad \text{Eq 8}$$

where: *Dw* and *Fw* refer to dry and fresh weights (kg) of the sub-sampled foliage biomass of *khat* plant, respectively. The Br in this study was estimated to 38 %. Then, the ratio was multiplied with the total fresh foliage biomass weighed per plant on the farm (kg) (*F*), to obtain the total dry foliage biomass removed of the single *khat* plant (*B*).

$$\mathrm{B\ (kg)} = \mathrm{F\ x\ Br} \quad \text{Eq 9}$$

The amount of foliage biomass removed across the three seasons (Mg ha^{-1}) was computed as follow:

$$\mathrm{DB} = ((\mathrm{B} \times \text{stand density})\ \mathrm{x}\ 1/1000) \quad \text{Eq 10}$$

where DB refers dry leaf biomass harvested, Mg ha^{-1}; B dry weight of foliage biomass harvested from single *khat* tree in the three surveyed seasons, kg; stand density, stems ha^{-1}.

Table 6. Allometric equations and goodness of fit performance statistics for estimating aboveground biomass (kg dry matter/plant) of khat (*Catha edulis*) grown in monoculture khat farming.

Model	Equation	Coefficients			Model performance statistics						
		b_1	b_2	b_3	R^2	SE	Bias	MAB	PRESS	D	Rank
M6	$AGB_t = b_1 \times d_{10}^{b2} \times doh^{b3}$	0.4796***	1.5818***	0.1089	0.96	2.677	0.024	1.927	2.63	0.99	1
M 2	$AGB_t = b_1 \times d_{10}^{b2}$	0.4693***	1.6629***		0.96	2.719	0.039	1.743	2.91	0.97	2
M4	$AGB_t = b_1 \times d_{10}^{b2} \times h^{b3}$	0.4684**	1.6861***	-0.038	0.96	2.725	0.039	1.955	2.96	0.99	3
M5	$AGB_t = b_1 \times d^{b2} \times doh^{b3}$	1.1028**	1.1437***	0.4268	0.88	4.652	0.045	3.419	3.87	0.98	4
M1	$AGB_t = b_1 \times d^{b2}$	1.2399**	1.4126***		0.87	4.916	-0.001	3.423	4.72	0.98	5
M3	$AGB_t = b_1 \times d^{b2} \times d^{b3}$	1.1558**	1.4154**	0.0340	0.87	4.914	-0.004	3.439	7.12	0.95	6

AGB_t aboveground biomass, *SEE, Bias, MAB* are in kg per plant, n: 31; d: diameter at breast height (1.30 m); $d_{10:}$ stump diameter at 10 cm height; *doh*: domain height (m); h: mean height (m); b_1, b_2 and b_3 are parameters $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

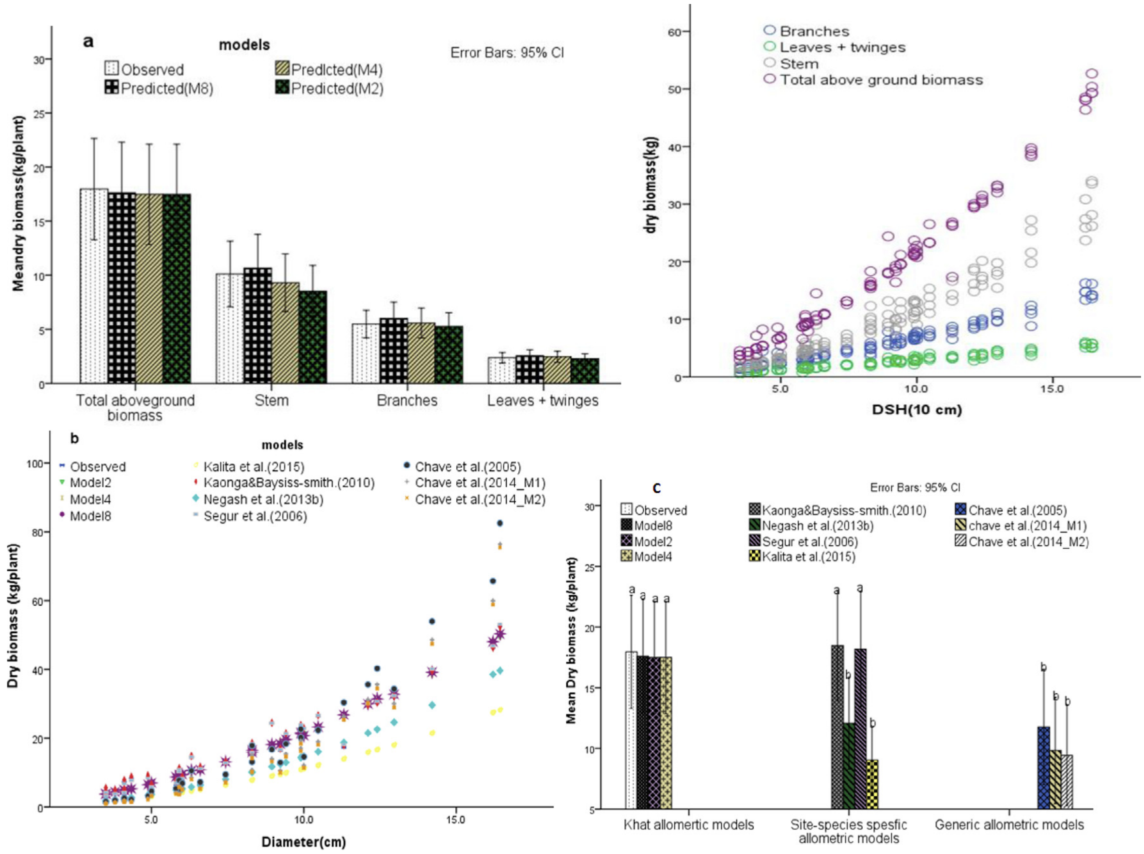

Figure 3. The relationship of stump diameter (d_{10}) versus observed and predicted aboveground and components dry weight using equations developed in this study; relationship between stump diameter (DSH) at 10cm height and dry biomass of components for study site level (a); Model comparisons for dry aboveground biomass versus DBH (b) and species-site and mixed species specific equations (c), similar letters shows no significant differences and different letter refer significant differences at 5% level of significance.

$$BC_{removed} = DB \times C \quad \text{Eq 11}$$

where: $BC_{removed}$ refers to biomass carbon stocks removed via total foliage biomass harvest, Mg ha^{-1}; C is carbon contents of the harvested foliage biomass, i.e. 46%as determined through LOI.

3. Results

3.1. Aboveground biomass and carbon (C) content

The aboveground biomass and carbon (C) content of *khat* were estimated to 18 kg dry matter/plant and 48%, respectively (Table 4). The C content was relatively highest for stem, followed by branch and foliage (twig plus foliage). The stem, branch and foliage contributed 58 %, 32 % and 10% of the aboveground biomass.

3.2. Biomass predictor variables

Both diameters and heights measured for *khat* plant significantly and positively correlated to aboveground and components' biomasses ($p < 0.01$) (Table 5). Stem, branch and foliage biomasses more strongly correlated with diameters than heights measurements. Pearson correlation was the highest between aboveground biomass and diameter at basal height (d_{10}) ($r = 0.968, p < 0.01, n = 31$) and the least with mean height (*h*) ($r = 0.608, p < 0.01, n = 31$). The dominate height (*doh*) strongly and positive related ($r = 0.617$-$0.674, p < 0.01$) with all of the studied biomass components than men height (*h*) ($r = 0.608$-$0.647, p < 0.05$). While dominant height showed strongest correlation with above ground biomass, followed by branch, stems and foliage biomass.

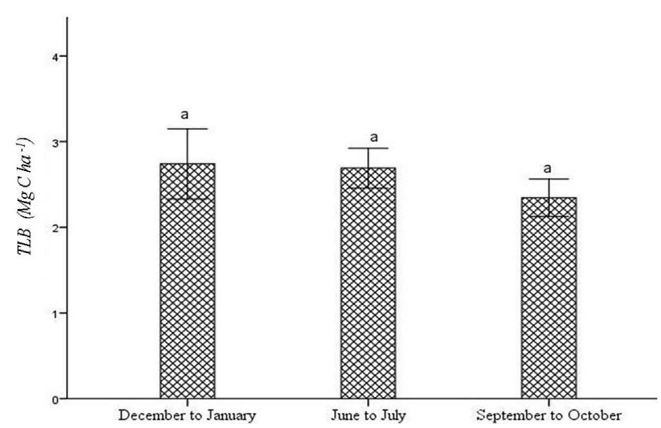

Figure 4. The amount of leaf biomass carbon removed (Mg ha^{-1}) across three harvesting periods from sampled *khat* plants (n = 30).

3.3. Biomass equations for khat

The parameterized power equations for predicting aboveground and biomass components of *khat* plant are presented in Table 6 and Appendix 1. Allometric equation (M6) that combined d_{10} and *doh* ranked first for estimating aboveground and stem biomasses (Table 6), and explained 96 % and 93 % of the biomass variations (Appendix 1), respectively. And also, the model overestimated the aboveground biomass by 2.4 % whereas it underestimated the stem biomass by 6 %. M2 that used d_{10} only had also explained 96% of the variance in aboveground biomass. Both *h* and *doh* did not much improve the performance of the equations for estimating aboveground biomass. For instance, combing dominate height to d_{10} at equation M6 improved the performance of aboveground and stem biomasses' estimation by only 7.6 % and 5.8 % in reference to the second best equation M2 and M4, respectively. The highest under estimation for aboveground biomass recorded to M3 (5.2%) and the least was M6 (2.4%) from observed biomass. The coefficients b_1 and b_2 significantly influenced aboveground and components' biomasses whereas coefficient b3 did not significantly improve the biomass measurements.

In overall, the power equations that combined basal dimeter (d_{10}) with mean height (h) or dominant height (M6) were the best predictors to estimate foliage and branches, and stem and aboveground biomasses (Figure 2).

3.4. Performances of allometric equations in this study over published generic and species-specific equations

Comparisons of the performances of best allometric equations in this study of *khat* plant over published generic and species-specific equations are shown Figure 3. The best ranked equations (M6, M4, M2) estimated aboveground and components' biomasses of *khat* plants were within the range of observed values (Figure 3a). The mixed species generic equations (Chave et al., 2005) and species-site specific equations (Negash et al., 2013a, b; Kalita et al., 2015) underestimated aboveground biomass of *khat* for those breast height diameters > 5cm and overestimated for >15cm (Figure 3b). Other species-site specific equations were (Henry et al., 2011; Negash et al., 2013a) comparable to our equations in estimating aboveground biomass estimation of the *khat* plant.

Mixed species generic equations (Chave et al., 2005; Chave et al., 2014) and species-specific equations (Negash et al., 2013b; Kalita et al., 2015) underestimated aboveground biomass of *khat* plant by 35–44 % and 22–49 %, respectively. While overestimation of aboveground was observed species-species equation by 5.4% Kaonga and Bayliss-Smith, 2012).

3.5. Effects of khat twig plus leaf biomass harvest on carbon stocks

Three commercial *khat's* foliage biomass harvesting seasons were identified (Figure 4). The carbon removal through total leaf biomass harvest (commercial plus wastage) slightly varied among harvesting seasons ($p < 0.05$) (Figure 4). Seasonal harvests of June to July, December to January, September to October contributed 42 %, 31 % and 27 % of total leaf biomass carbon removal, respectively. Commercial leaf biomass accounted for 52% of the total biomass carbon removal and remainder one wastage biomass.

4. Discussion

Stem and branches altogether accounted for 90% of aboveground biomass of the *khat* plant in the study area. This result was comparable with the findings of Segura et al. (2006) for coffee plant in agroforestry system in Costa Rica and within the range of what was reported by van Oijen et al. (2010). But, it was slightly lower than that of coffee grown in agroforestry in southern Ethiopia (Negash et al., 2013b), and for tree species elsewhere in the tropics (Henry et al., 2011; Ebuy et al., 2011). The difference may be attributed to variation in growth characteristics (e.g. multistems, leaf biomass production), age and managements practice (e.g. spacing, pollarding). For instance, leaf biomass of *khat* plant is harvested 2–3 times per year, which is not the case in coffee plant. The harvesting practices obviously affect the foliage biomass as a case observed between pruned and unpruned stand of coffee plant (Segura et al., 2006). The *khat* leaf biomass production also depend on stand age, harvesting frequency and season, and application of compost.

Seasonal removal of carbon stocks through commercial leaf biomass harvest of the *khat* plant may hamper the carbon sequestration capacity of the plant. Moreover, given the lucrative nature of *khat* farming to generate income in short span, it may expand alarmingly into forest ecosystem and replace perennial cash crop such as coffee (Gesess, 2013). In effect, large amount of biomass carbon stocks could be lost due to deforestation and forest degradation in *khat* replacing land use. The impact in turns may lead to termination of litter inputs and reduce the soil organic carbon stock.

Commercial leaf biomass production of the *khat* plant in our study was slightly lower than those reported nationally in Ethiopia (CSA, 2009), however, it was higher than what was reported in eastern Ethiopia (mean 0.7–1 Mg ha^{-1}) (Woldu et al., *2015)*. The variations may be accreted to differences in sites, management practices and method of data collection. For example, our study estimated foliage biomass of *khat* plant based on empirical data from the field measurement whereas Woldu et al. (2015) reported based on literature review and oral interviews.

Basal diameter (d_{10}) was found to be the best predictor for estimating total aboveground and components biomasses of *khat* plant. The better performance of basal and stump diameters for estimating aboveground biomass were also reported in elsewhere in the tropics (Segura et al., 2006; Negash et al., 2013b). For instances, stump diameter best performed in estimating aboveground biomass for coffee plant gown in agroforestry in Ethiopia (Segura et al., 2006; Negash et al., 2013b), coppicing and non-coppicing woody plants in eastern Zambia (Kaonga and Bayliss-Smith 2012), and tea plant in India(Kalita et al. (2015)].

When d_{10} combined with *doh* yielded the best equations for estimating aboveground and components biomasses of the *khat* plant (Table 6, Appendix 1). We can also use M2, which only uses d_{10} alone that explains 96% of variance to estimate aboveground biomass estimate. Model 8 showed the best performance regardless of the age of the *khat* plant. The coefficient of determination values in our study are higher than those reported coffee (Negash et al., 2013b) and tea cash crops (Kaonga and Bayliss-Smith, 2012), which have similar growth habits and management practices that of *khat*.

As hypothesized, using mixed species generic equations (Chave et al., 2005, 2014) and equations developed for other species (Negash et al., 2031b; Kalita et al., 2015) underestimated aboveground biomass of *khat* plant. This confirms the need to develop species specific equations for accurate and reliable measurement of biomass.

5. Conclusions

The *khat* biomass harvest and its associated carbon removal vary across seasons and harvesting frequency in the study region. The commercial foliage biomass carbon removal accounted for 52 % of total biomass carbon stocks harvested per year. Stump diameter (d_{10}) was found to be the best predictor parameter of aboveground biomass. The power equation using d_{10} with *doh* could explain 96 % of the variation in aboveground biomass, but using d_{10} alone can also estimate 96 % of the variation. Thus, allometric equation developed in this study accurately estimate aboveground biomass, and can be used in similar climatic zones of the tropics.

Declarations

Author contribution statement

Desalegn Getnet: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mesele Negash: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional Information

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