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

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\textbf{ABSTRACT}

\textit{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 an expense of other plant uses for its short-term financial returns. We, therefore, developed allometric equations for estimating aboveground biomass and carbon (C) removal of \textit{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 (\textit{d\textsubscript{10}}), diameter at breast height (\textit{d}), dominate height (\textit{doh}) and mean height (\textit{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\textsuperscript{-1}. The power equation, \textit{AGB} = \textit{b1} × \textit{d\textsubscript{10}}\textsuperscript{c1} × \textit{doh}\textsuperscript{c2}, was the best (highest ranked using goodness-of-fit statistics), explaining 96\% of the variation in aboveground biomass (\textit{p < 0.01}). Models comparisons showed that our best ranked equation (\textit{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 \textit{khat} plant biomass in the study region.

1. Introduction

\textit{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). \textit{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, \textit{khat} plant grows in the range of 1500–2500 m.a.s.l (Lemessa, 2001).

\textit{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 \textit{khat} is also used as a traditional medicine for treating stomach ache. \textit{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 \textit{khat} monocropping in eastern part of Ethiopia (CSA, 20012; Woldu et al., 2015). In few places, \textit{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 \textit{khat} farming and its perennial nature, information is lacking on carbon sequestration capacity of the plant in the study region. Moreover, the \textit{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 \textit{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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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 biomass 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° 18'
recorded. Within each plot all was divided into 10 equal grid points visually. Then, the sample point across the selected farms. To select the sample plot location, the farm A total of 10 sample plots size 20 m and above 25 years-old. Thirdly, those study area. The exotic tree species include Cupressus lusitanica, Carissa spinarum, Phytolacca dodecandra, Acacia species, Cordia africana L., Opuntia ficus-indica, Ficus sycomorus L., Dodonaea angustifolia L. f., African penciledar, Carissa spinarum L., Erica arborea L. and Euphorbia abyssinica. Various exotic plants have also adopted themselves to the local climate in the study area. The exotic tree species include Capruesa lusitanica Mill, Schinus molle Lam. and Eucalyptus species (Znabu, 2014).

The major vegetation in the study sites include Olea europaea L., Phytolacca dodecandra, Accacia species, Cordia africana Lam., Opuntia ficus-indica, Ficus sycomorus L., Dodonaea angustifolia L. f., African penciledar, Carissa spinarum L., Erica arborea L. and Euphorbia abyssinica. Various exotic plants have also adopted themselves to the local climate in the study area. The exotic tree species include Capruesa 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 (d10), diameter at breast height (d) (measure 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 d10 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).

\[ d_e = \sqrt{\sum_{i=1}^{n} d_i^2} \]  
where \( d_e \) is diameter equivalent (d or d10), cm; \( d_i \) is diameter of \( i^{th} \) stem at d or d10, 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 d10 for the sampled plants 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, 10twig 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.
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,
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 (R²), mean absolute bias (MAB), standard error of estimate (SEE), average bias (B), prediction error (MPE) were determined from a leave one out cross validation (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 times until every observation has been left out and predicted. The n errors are used to calculated, RMSE and MPE as below Eq. (2) and (3).

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}, \quad \text{RMSE(%) = } \frac{RMSE}{\bar{Y}} \times 100 \tag{Eq 2}
\]

\[
MPE = \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)}{n}, \quad \text{MPE(%) = } \frac{MPE\times 100}{\bar{Y}} \tag{Eq 3}
\]

where: Yᵢ is the observations of the response variables, \(\hat{Y}_i\) is the predicted value of the Yᵢ, and \(\bar{Y}\) is the average of the Yi.

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

\[
D = 1 - \frac{\sum_{i=1}^{n} (\hat{Y}_i - \bar{Y})^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \tag{Eq 4}
\]

\[
Bias = \frac{\sum_{i=1}^{n} (\hat{Y}_i)}{n} \tag{Eq 5}
\]

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.

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):

\[
Br(\%) = \frac{DW}{FW} \times 100 \tag{Eq 8}
\]

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).

\[
B(kg) = F \times Br \tag{Eq 9}
\]

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

\[
DB = (B \times \text{stand density}) \times 1/1000 \tag{Eq 10}
\]

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 |
|-------|----------|--------------|-----------------------------|
|       |          | b₁, b₂, b₃   | R², SE, Bias, MAB, PRESS, D, Rank |
| M6    | AGBₜ = b₁ × d_{d/2}² × doh⁻³ | 0.4796*** | 1.5818*** | 0.1089 | 0.96 | 2.677 | 0.024 | 1.927 | 2.63 | 0.99 | 1 |
| M2    | AGBₜ = b₂ × d_{d/2}² | 0.4693*** | 1.6629*** | 0.96 | 2.719 | 0.039 | 1.743 | 2.91 | 0.97 | 2 |
| M4    | AGBₜ = b₃ × d_{d/2}² × h⁻³ | 0.4684** | 1.6861*** | -0.038 | 0.96 | 2.725 | 0.039 | 1.955 | 2.96 | 0.99 | 3 |
| M5    | AGBₜ = b₁ × d_{d/2}² × doh⁻³ | 1.1028** | 1.1437*** | 0.4268 | 0.88 | 4.652 | 0.045 | 3.419 | 3.87 | 0.98 | 4 |
| M1    | AGBₜ = b₁ × d_{d/2}² | 1.2399** | 1.4126*** | 0.0340 | 0.87 | 4.916 | -0.001 | 3.423 | 4.72 | 0.98 | 5 |
| M3    | AGBₜ = b₂ × d_{d/2}² | 1.1588** | 1.4154*** | 0.0340 | 0.87 | 4.914 | 0.004 | 3.439 | 7.12 | 0.95 | 6 |

AGBₜ, 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); b₁, b₂ and b₃ are parameters **p < 0.001; ***p < 0.01; *p < 0.05. |
BC_{removed} = DB × C

\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 mean 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 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.

Figure 4. The amount of leaf biomass carbon removed \((\text{Mg ha}^{-1})\) 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 \(b_3\) did not significantly improve the biomass measurements.

In overall, the power equations that combined basal diameter (\(d_{10}\)) 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% (Koonga 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 remained 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 (Gessese, 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 accrated 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 biomass 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 grown 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 will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional Information

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References

Andualem, M., 2002. The prevalence and socio-demographic characteristics of Khat chewing in Jimma town, South Western Ethiopia. Ethiop. J. Heal. Scien. 12 (2), 69–80.
Berhe, L., Arnoldson, G., 2008. Tree taper models for Cypresuss lusitanica plantations in Ethiopia. South 70, 193–203.
Berhe, L., Assefa, G., Teklay, T., 2013. Models for estimation of carbon sequestered by Cypresuss lusitanica plantation stands at Wondo Genet, Ethiopia, southern forests. South. Folklore 75, 113–122.
Bongard, S., Abis, M., Khalil, N., Habori, M., 2011. Khat use and trait anger: effects on affect regulation during an acute stressful challenge. Research report University of Minnesota. Eur. Addiction Res. 17 (6), 285–291.
Brown, S., 1997. Estimating Biomass and Biomass Change of Tropical Forests. Forestry Paper No. 134. Food and Agriculture Organization of the United Nations, Rome.
Central Statistics Authority, 2009. Report on Area and Production of Crops (Private Peasant Holdings, Meher Season). Agricultural Sample Survey Vol. 1. Statistical Bulletin 448, Addis Ababa, Ethiopia.
Chave, J., et al., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145 (1), 78–99.
Chave, J., et al., 2014. Improved allometric Models to estimate the aboveground biomass of tropical trees. Global Change Biol. 20, 3177–3190.
Dube, D.K., Hiranmai, Y.R., Dube, S.K., 2014. Why a shift from coffee to chat? A study of the Kersaworeda in Jimma zone of South Western Ethiopia. Res. Humanit. Soc. Sci. 68, 143–150.
Ehoy, J., Lokombe, J.P., Posette, Q., Sonwa, D., Picard, N., 2011. Allometric equation for predicting aboveground biomass of three tree species. J. Trop. For. Sci. 23, 125–132.
Ezekiel, G., 2005. Leaf of Allah: khat and agricultural transformation in Harerge, Ethiopia. Afr. Stud. Rev. 48, 161–162.
Gesess, D., 2013. Is Khat a Social Ill? Ethical Argument about a Stimulant Among the Learned Ethiopians, As Working Paper. African Study Center, Leiden, The Netherlands.
Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentinii, R., Bernoux, M., Saint-André, L., 2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fenn. 45 (3B), 477–556.
Huffnegel, H.P., 1961. Agriculture in Ethiopia. Rome: Food and Agriculture Organization (FAO). 2 Report to the Secretary of Agriculture USDA Office of Tribal Relations and Forest Service Policy and Procedures Review Indian Sacred Sites, p. 20.
Kallin, R.M., Das, A.K., Nath, A.J., 2015. Allometric equations for estimating above- and belowground biomass in Tea (Camellia sinensis (L.) O. Kunte) agroforestry system of Barka Valley, Assam, northeast India. Biomass Bioenergy 83, 42–49.
Kanoga, M.L., Bayliss-Smith, T.P., 2012. Simulation of carbon pool changes in woodlots in eastern Zambia using the CO2FIX model. Agrofor. Syst. 86 (2), 213–223.
Kennedy, J.G., Teague, J., Rokaw, W., Conney, E.A., 1983. Medical evaluation of the use of khat in north Yemen. Soc. Sci. Med. 17 (12), 783–793.
Kozak, A., Kozak, R., 2003. Does cross validation provide additional information in the evaluation of regression models? Can. J. For. Res. 33, 976–987.
Lemessa, D., 2001. Khat (Catha edulis): botany, distribution, cultivation, usage and economics in Ethiopia (agriculturist). UN-Emergencies Unit for Ethiopia Addis Ababa.
Meles, K., Nigusie, G., Belay, T., Manjur, K., 2009. Seed system impact on farmers’ income and crop biodiversity in the drylands of southern tigray. DCQ Policy Brief 2.
Murphy, H.F., 1999. Report on the Fertility Status of Some of the Soils of Ethiopia, College of Agriculture 2000, Experiment Station Bulletin Alemany, Ethiopia, p. 1, 1959.
Negash, M., Starr, M., Kanninen, M., 2013a. Allometric equations for biomass estimation of Enset (Ensete ventricosum) grown in indigenous agroforestry systems in the Rift Valley escarpment of southern-eastern Ethiopia. Agrofor. Syst. 87, 571–581.
Negash, M., Starr, M., Kanninen, M., Berhe, L., 2013b. Allometric equations for estimating aboveground biomass of Coffea arabica L. grown in the Rift Valley escarpment of Ethiopia. Agrofor. Syst. 87, 953–966.
Raman, R., 1983. Catha Edulis Forsk. Geographical Dispersal, Botanical, Ecological and Agronomical Aspects with Special Reference to Yemen Arab Republic. PhD Thesis. U. Gottingen, Germany, 1983.
Raya Valley Agricultural Development Project (RVADP), 1998. Feasibility study report. Volume II, Water Resources. Annexes:Hydrology and Hydrogeology. Mekelle, Ethiopia.
Ribeiro, E.C., Soares, C.P.B., Fehrmann, L., Jacovine, L.A.G., von Gadow, K., 2015. Aboveground and belowground biomass and carbon estimates for clonal eucalyptus trees in southeast Brazil. Rev. Arvore 39, 353–363.
Seguru, M., Kanninen, M., Soares, D., 2006. Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together. Agrofor. Syst. 68, 143–150.
Snowdon, P., Raison, J., Keith, H., Ritson, P., Grierson, P., Burrows, W., Eamus, D., 2002. Predicting aboveground and belowground biomass of shade trees and coffee bushes grown together. Agrofor. Syst. 571–581.
Van Oijen, M., Schapendonk, A., Hoglind, M., 2010. On the relative magnitudes of photosynthesis, respiration, growth and carbon storage in vegetation. Ann. Bot. 105 (5), 793–797, 2010.
Wabel, N.T., 2011. Psychopharmacological aspects of Catha edulis (khat) and consequences of long term use. A review. J. Affect. Disord. 1, 187.
Woldu, Z., Belew, D., Bentil, T., 2015. The coffee-khat interface in eastern Ethiopia: a controversial land use and livelihood change scenario. J. Agric. Sci. Technol. 5, 149–169.
Zabu, G., 2014. The Effectiveness and Challenges of Soil and Water Conservation Practices in Raya Azebo Woreda of Tigray, Ethiopia. M.S.C Thesis. Addis Ababa University.