JARQ 54 (2), 185-191 (2020) https://www.jircas.go.jp

Estimation of the Stem Volume of 30-year-old *Eucalyptus globulus* in the Northern Ethiopian Highlands

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Abstract

The development of forest monitoring methods for the plantation eucalypt forests in Ethiopia is crucial as eucalypts play an important role in the country's wood supply. We assessed the stand structure and estimated the total stem volume of a 30-year-old *Eucalyptus globulus* forest in the highlands (>3000 m altitude) of northern Ethiopia. Census data were collected from 186 trees, of which 28 trees were destructively sampled. The forest stand density was 581 trees ha^{-1}, mean ± SD diameter at breast height was 21.2 ± 6.4 cm, and mean ± SD predicted tree height was 22.0 ± 4.2 m. The estimated stem volume was 269.7 m^3 ha^{-1}. An allometric model to predict tree height was derived using the measured diameter at breast height of the sampled trees. Moreover, an allometric model was developed to estimate stem volume for standing trees in order to describe the relationship between the stem volume and diameter at breast height squared × tree height (incorporated as a compound variable), using data on 38 trees for which height could be measured reliably. The findings suggest that the diameter at breast height alone can be used to estimate stem volume, and thus may be useful for simple forest monitoring in the study region. This study is one of the few to assess the stand structure and stem volume of a high-altitude *Eucalyptus* plantation.

Discipline: Forestry
Additional key words: allometry, Bahr-Zaf, forest monitoring, high altitude

Introduction

The first eucalypt plantation in Ethiopia was reportedly established in 1895 as an initiative of Ethiopian Emperor Menelik II (1844-1913) to alleviate the shortage of fuel wood (Pohjonen & Pukkala 1990, Von Breitenbach 1961). Subsequently, eucalypts have become a highly valued natural resource for Ethiopians (Mesfin & Wubalem 2014). In particular, *Eucalyptus globulus* (Tasmanian blue gum) is well-adapted to the Ethiopian environment and widely planted across the country, not only as a source of fuel but also for construction and carpentry (Mesfin & Wubalem 2014).

Allometric equations describing select relationships between wood volume or biomass and tree size measurements, such as stem diameter and tree height, have been developed for planted *E. globulus* stands in the Ethiopian regions of Oromia, Amhara, and Addis Ababa (Henry et al. 2011, Hailu 2002, Pukkala & Pohjonen 1989, Zewdie et al. 2009). Currently, 30 equations for *E. globulus* describing the tree volume and biomass of various tree parts such as the branch, leaf, stem, and root have been published (Henry et al. 2011). However, there is a lack of sufficient empirical data on tree growth in plantation eucalypt forests in the highlands of the Tigray region, although such data are important for efficient wood processing and forest monitoring in the region. Eucalypt timber is now expected to be utilized for volume-based uses, such as processed lumber, rather than for quantity-based uses, such as construction poles (Mesfin & Wubalem 2014). Bekele (2011) reported that 39,700 ha of eucalypt plantations have been established in the Tigray region. Using tree census data from two 0.16 ha *E. globulus* plots in northern Ethiopia, the current study aimed to 1) develop an allometric equation for non-destructive prediction of tree height (H), 2) develop an allometric equation describing the relationship between V_{stem} and tree diameter at breast height (DBH), and 3)

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Received 1 November 2018; accepted 5 August 2019.

compile forest census data as a case study of a high-altitude eucalypt forest. The present results, although not generally applicable owing to a lack of comparative data, provide valuable information for an assessment of *E. globulus* stands in the southern Tigray region.

Materials and methods

1. Study site

An *E. globulus* stand on the outskirts of the town of Maichew in the southern Tigray region of northern Ethiopia was selected as the study site (Fig. 1). The eucalypt stand (12°51′39.91″N, 39°31′6.50″E) is located in a mountainous region called Debar ridge (Fig. 2). The landscape is characterized by steep slopes, is extensively exploited for cultivation of wheat (*Triticum* spp.) and legume crops, and is also used as grazing land for cattle, goats, and sheep. For this reason, the planting of trees is limited to hilltops or along the sides of rivers (or gullies) in this region. The natural vegetation type in the study area is categorized as dry evergreen Afromontane forest and grassland complex (Friis et al. 2011), characterized by succulents (e.g., euphorbias, aloes), deciduous acacias, and junipers (Demissew & Nordal 2010). Leptosols are the dominant soil type (Jones et al. 2013) at the study site.

The eucalypt stands are managed by a wood-processing factory in the town of Maichew. Approximately 180 ha of tree plantations have been established since 1981 for the commercial production of wood products.

The study site is located on north-facing slopes with an incline of 30°. The altitude is between 3,200 and 3,300 m above sea level, and the site is located about 20 km from Maichew. The climate is classified as a steppe climate (Bsh: Köppen climate classification) with annual mean rainfall of approximately 745 mm (National Meteorology Agency of Ethiopia (NMA) 2013, unpublished data), and mean monthly temperature between 13.2 and 19.7°C (NMA 2013, unpublished data) (Fig. 3). Approximately 60% of annual rainfall occurs during the rainy season from July to October. In spite of the tropical latitude, the climate is temperate and occasionally cool throughout the year owing to the high altitude.

2. Tree census

The study was conducted during November 2013, at the beginning of the dry season. Two study plots (each 0.16 ha; 40 m × 40 m) were established in the same eucalypt stand. The stand age was determined to be 30 years by counting apparent annual rings from disk

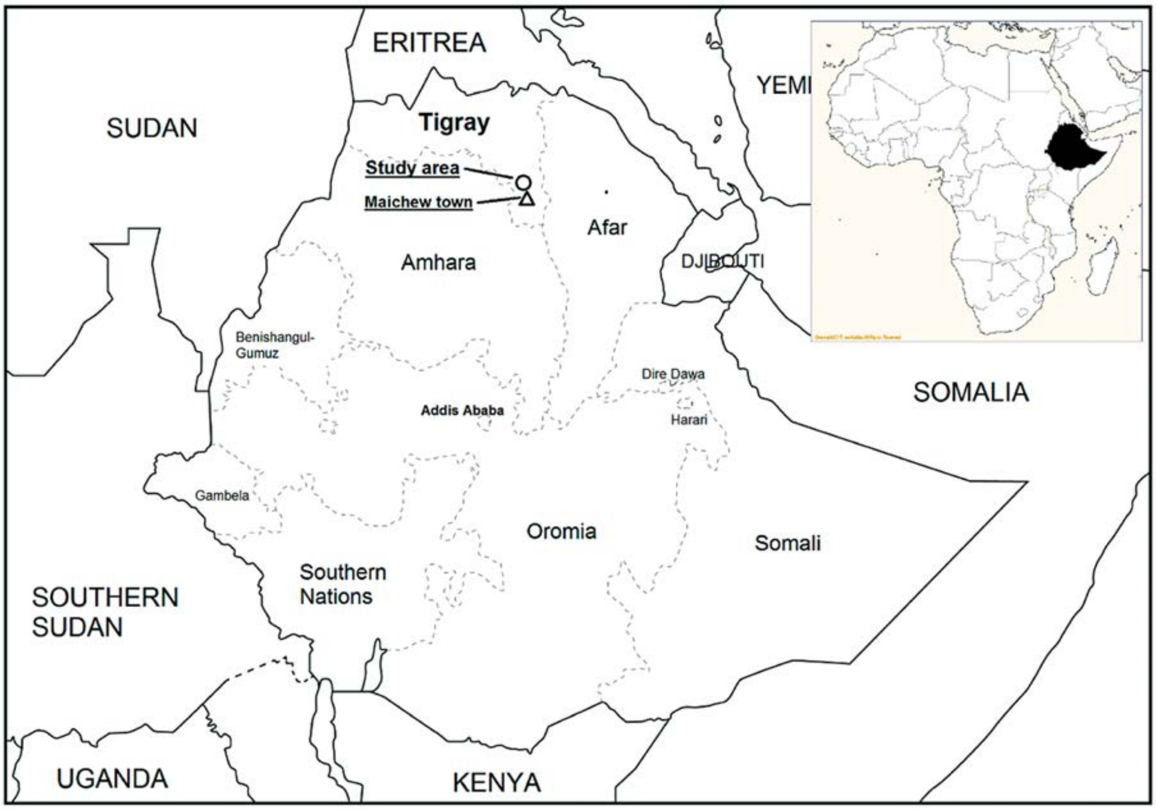

Fig. 1. Regional map of Ethiopia
(http://www.sekaichizu.jp/atlas/africa/index.html: accessed on 13 March 2017)

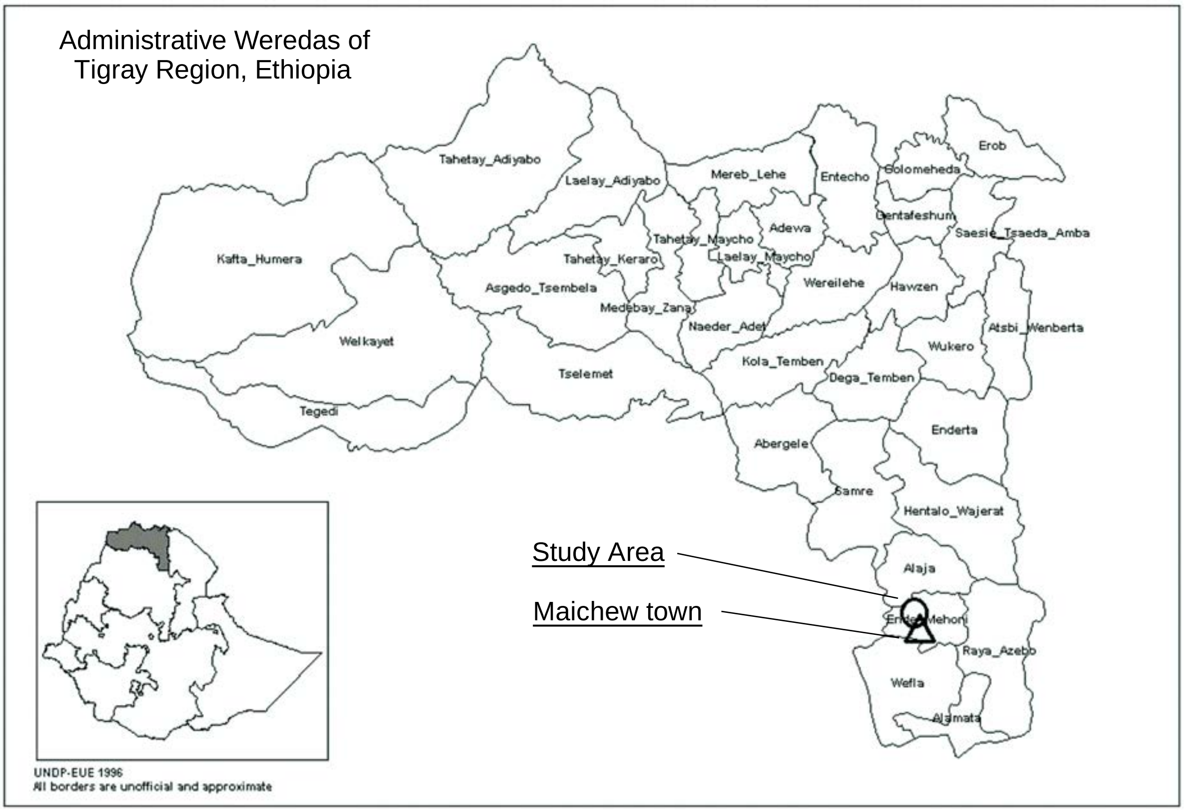

Fig. 2. Location of the study site near Maichew town in southern Tigray, Ethiopia
(http://www.africa.upenn.edu/eue_web/menu4596.htm: accessed on 11 January 2016)

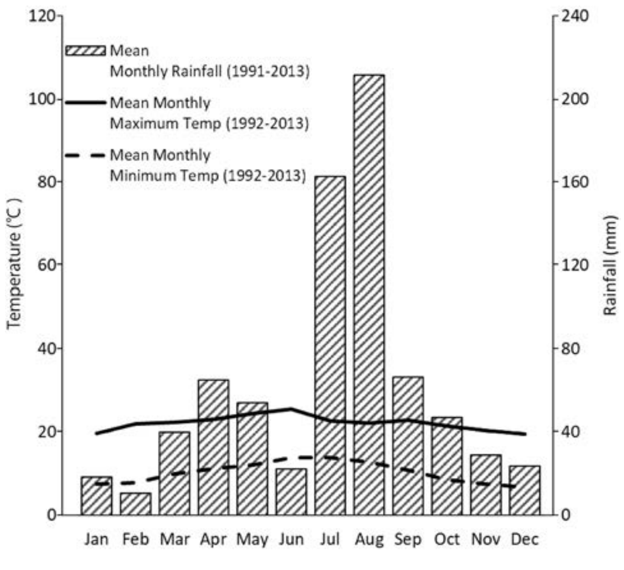

Fig. 3. Mean monthly rainfall and mean monthly-maximum and -minimum temperatures at Maichew, Tigray Region, in 1991-2012
(source: National Meteorology Agency of Ethiopia)

samples, indicating that the trees were planted circa 1984. All 186 trees in the two study plots were marked and measured. The *DBH* of all standing trees was measured using diameter tape. The condition of each tree was assessed to select trees that represented the range in *DBH* distribution for more accurate measurement in a destructive sampling. Each tree was assigned to one of the following categories: 1) non-damaged with a straight stem, 2) non-damaged with a curved or leaning stem, or 3) damaged. To calculate V_{stem}, we selected 30 sample trees that represented the entire range of *DBH* in the stand. Of the 30 trees, 28 were felled by chainsaw and subsequently used for measurements; the remaining two were destroyed upon impact with the ground after felling. Stem diameters were measured using diameter tape at ground level (0 m in height), 0.3 m, 1.3 m, and at 2.0-m intervals from the 1.3-m mark to the stem tip. The total height of the tree (*H*; m) was measured for allometric calculations.

Given the natural and human-caused damage at the tips of 34 small trees ($DBH < 15$ cm) among the 186 trees, we measured the sizes of 10 additional sample trees for use as substitute data. The additional sample trees were of $DBH < 15$ cm and located just outside the study plots, but within the same region. The *DBH* and *H* of the 10 non-destructively sampled trees were measured using diameter tape and a Vertex IV hypsometer (Haglöf, Långsele, Sweden), respectively. The data for the 10 substitute trees were included together with the 28 destructively sampled trees to develop equations expressing the relationship of *DBH*-*H* and V_{stem}-DBH^2H.

3. Allometry to estimate tree height

Although we can directly measure the stem diameter to assess *DBH*, it is difficult to accurately measure tree height in a non-destructive manner. A compound factor ($DBH^2 \cdot H$) is often used in allometric equations for the estimation of biomass or stem volume. Therefore, estimating *H* from *DBH* is vital for the estimation of biomass or stem volume (Yoda 1971). We determined the relationship between *DBH* and *H* (Eq. 1) for the 38 sample trees using the following generalized allometric model (Ogawa & Kira 1977):

$$\frac{1}{H} = \frac{a}{DBH^h} + \frac{1}{H_{max}} \qquad (1)$$

where H_{max} is the predicted maximum height of the forest (m), and *a* and *h* are parameters unique to the tree species and location.

$$a = \frac{\sum H^2 \times \sum \frac{H}{DBH^h} - \sum H \times \sum \frac{H^2}{DBH^h}}{\sum H^2 \times \left(\sum \frac{H}{DBH^h}\right)^2 - \left(\sum \frac{H^2}{DBH^h}\right)^2}$$

$$b = \frac{\sum H \times \sum \left(\frac{H}{DBH^h}\right)^2 - \sum \frac{H}{DBH^h} \times \sum \frac{H^2}{DBH^h}}{\sum H^2 \times \left(\sum \frac{H}{DBH^h}\right)^2 - \left(\sum \frac{H^2}{DBH^h}\right)^2}$$

$$H_{max} = 1/b$$

H_{max} is predicted as the inverse of parameter *b*. Parameters *a* and *b* were derived by applying the abovementioned formulae, which were proposed to calculate the parameters using a weighted least-squares method (Hozumi & Shinozaki 1960). Parameter *h* in the generalized allometric function can be mostly regarded as 'h = 1' for a shade-intolerant tree forest. In the case of a shade-tolerant tree forest, however, *h* can be considerably higher than 1. Hence, the determination of *h* can influence the relationship between *DBH* and *H* in Eq. 1. We applied Eq. 1 using different values of *h* in iterations of 0.1 (i.e., h = 1.0, 1.1, 1.2,…, 1.8). The fitting was evaluated by calculating the coefficient of determination (R^2) and root mean squared error (RMSE) between measured *H* versus predicted *H*. This relationship between *DBH* and *H* for the 38 sample trees was used to predict *H* for the remaining trees in the study plots.

4. Stem volume

To estimate stem volume, we assumed that the shape of a tree stem was that of a series of circular truncated cones and a terminal cone. We calculated the stem volume of each section (V_i) by applying Smalian's formula (Eq. 2), and subsequently summing the volume of individual sections to calculate the total stem volume, V_t (Eq. 3). The apical portion of the tree was considered a cone; its volume (V_c) was calculated using Eq. 4. Thus, the total V_{stem} (Eq. 5) was calculated as the sum of Eq. 3 and Eq. 4. The full thickness of the bark on both sides was included in each measurement of diameter.

$$V_i = \frac{(A_1 + A_2)}{2} l_i \qquad (2)$$

where
V_i: Volume of stem section *i*, with bark (m^3)
A_1: Area at lower end of stem section *i* (m^2)
A_2: Area at upper end of stem section *i* (m^2)
l_i: Length of stem section *i* (m)

$$V_t = \Sigma V_i \qquad (3)$$

where
V_t: Sum of volumes of stem sections (m^3)

$$V_c = \frac{A_b l}{3} \qquad (4)$$

where
V_c: Volume of the cone (m^3)
A_b: Sectional area at bottom of the cone (m^2)
l: Length of the cone (m^3)

$$V_{stem} = V_t + V_c \qquad (5)$$

5. Allometry to estimate V_{stem}

We developed an allometric model that includes two independent variables, *DBH* (cm) and *H* (m), combined as a compound factor ($DBH^2 \cdot H$) through nonlinear regression to the measured data computed using BellCurve for Excel statistical software (version 3.00). The fitting was evaluated by calculating R^2 and RMSE between the stem volume of the 38 sampled trees (calculated by Smalian's formula) and the estimated stem volume of those at the study site. Subsequently, V_{stem} was estimated using the following equation:

$$V_{stem} = a[DBH^2 \cdot H]^b \qquad (6)$$

where *a* and *b* are constants.

Results

1. Stand structure

Table 1 summarizes the structure of the *E. globulus* stand. Stand density was calculated as 581 trees ha^{-1}. The mean ± SD *DBH* was 21.2 ± 6.4 cm (range: 6.6-39.8 cm). The mean ± SD *DBH* of the 28 trees destructively sampled was extremely similar to that of the 186 trees overall in the study plots. The *DBH* range for the 10 additional small-sized trees was 7.0-12.1 cm. The mean ± SD *DBH* was 9.9 ± 1.8 cm. The mean ± SD and range of *H* for the 28 felled sample trees and 10 additional measured trees were 22.3 ± 3.3 m (range: 15.8-29.2 m) and 11.0 ± 1.5 m (range: 8.3-13.2 m), respectively.

Figure 4 shows the quasi-normal frequency distribution pattern of *DBH* from the *E. globulus* stand, although not adhering to normality as assessed by the Shapiro-Wilk test (P = 0.034). Trees of *DBH* between 20 and 25 cm comprised 31% of the total, and 57% of the trees were of *DBH* between 15 and 25 cm.

2. Relationship between *DBH* and *H*

In comparisons of different values for parameter h in Eq. 1 using the measured height and predicted height for the 38 sampled trees, h = 1.5 showed the highest gradient in the linear regression model and the lowest RMSE (RMSE = 2.3435). For all values of h, the coefficient of determination was high ($R^2 > 0.8023$; Table 2). We determined h = 1.5 to be the optimal value for inclusion in Eq. 1. Equation 7 was used to derive the values a = 1.70 and H_{max} = 37.8 m. Figure 5 shows the tree-height curve (derived using Eq. 7) representing the relationship between *DBH* and *H*, which was used for further estimation of *H* for all trees in the study plots. Applying Eq. 7, the mean ± SD *H* of all sample trees was predicted to be 22.0 ± 4.2 m (range: 7.9-30.1 m).

$$\frac{1}{H} = \frac{1.70}{DBH^{1.5}} + \frac{1}{37.8} \quad (R^2 = 0.8382,\ \mathrm{RMSE} = 2.3435) \tag{7}$$

3. Relationship between $DBH^2 \cdot H$ and V_{stem}

Values of V_{stem} for the 28 destructively sampled trees and the 10 substitutional samples were calculated using Eqs. 2, 3, 4, and 5. The mean V_{stem} ± SD was 0.31 ± 0.26 m^3. In comparisons of the V_{stem} of 38 sampled trees versus the estimated V_{stem} of those using Eq. 8, the coefficient of determination was high (R^2 = 0.9657) and RMSE was low (RMSE = 0.0724). In addition, we tested the *DBH* data of the 38 sampled trees for homogeneity of variance using the F-test in comparison with the *DBH* data for the 186 trees in the study plots. Homogeneity of variance between the two groups was not statistically rejected ($F_{(37,185)}$ = 1.588, P = 0.2529). Figure 7 shows the relationship between $DBH^2 \cdot H$ and V_{stem} as expressed by the allometric equation below.

$$V_{stem} = 5.01 \times 10^{-5} (DBH^2 H)^{0.974}$$
$$(R^2 = 0.9897,\ \mathrm{RMSE} = 0.0724) \tag{8}$$

Equation 8 was used to estimate V_{stem} for all trees in the study plots (186 trees in total). The developed equation showed a high coefficient of determination (R^2 = 0.9897). The mean ± SD V_{stem} was 0.46 ± 0.34 m^3 (range: 0.02-1.80 m^3 $stem^{-1}$). The estimated total V_{stem} per hectare, calculated from the total V_{stem} of trees in the total area of the plots (0.32 ha), was 269.7 m^3 ha^{-1}.

Discussion

A small percentage of the trees (18%; 34 trees out of the total 186 trees) were small (DBH < 15 cm) and damaged at the tips of the stem; therefore, we substituted some data with those from similarly small-sized trees

Table 1. Description of *Eucalyptus globulus* forest at study site, Debar ridge, Tigray region (November 2013)

Location	Altitude (m)	Age (yrs)	Area (m^2)	Number of trees*	Tree density (trees/ha)	*DBH* range (cm)	Mean ± SD of *DBH* (cm)	Measured *H* range (m)	Mean ± SD of measured *H* (m)	Remarks
Debar ridge	3,250 - 3,300	30	3,200	186	581	6.6 - 39.8	21.2 ± 6.4	-	-	Censused
				(28)	-	15.8 - 29.2	21.3 ± 5.4	15.8 - 29.2	22.3 ± 3.3	Sacrificed samples
Maichew area	3,000	30	-	[10]	-	7.0 - 12.1	9.9 ± 1.8	8.3 - 13.2	11.0 ± 1.5	Alternative values for trees DBH < 15 cm

*The number of trees in parenthesis is included in the total number of trees (186).
*The number of trees in brackets is additionally measured substitute data on the total number of trees (186).

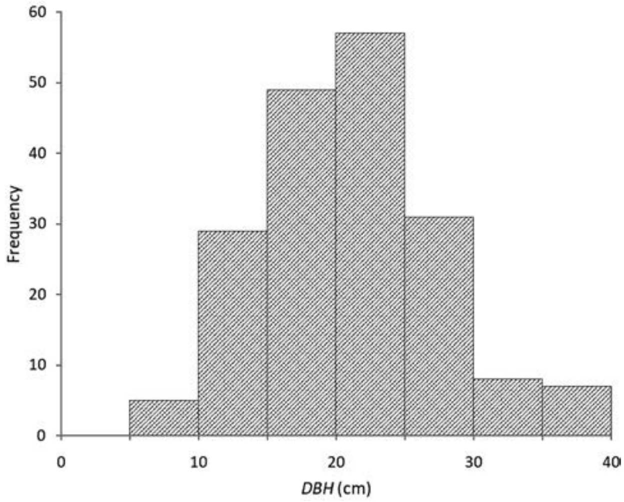

Fig. 4. Frequency distribution of tree diameter at breast height (*DBH*; cm) classes in the study plots

Table 2. Evaluation results for comparison of coefficient *h* in Eq. 1 between measured tree height and predicted height

h	*A*	*B*	R^2	RMSE
1.0	0.4706	0.1260	0.8023	10.6579
1.1	0.5854	0.0174	0.8070	8.5537
1.2	0.6928	0.1027	0.8143	6.3992
1.3	0.7794	0.6261	0.8230	4.3893
1.4	0.8347	1.6332	0.8316	2.8426
1.5	0.8534	3.1217	0.8382	2.3435
1.6	0.8373	5.0022	0.8416	2.9543
1.7	0.7926	7.1376	0.8408	3.8943
1.8	0.7276	9.3765	0.8355	4.7751

h: parameter for Eq. 1
A: gradient
B: intercept of linear regression model ($y = Ax + B$)
R^2: coefficient of determination
RMSE: root mean square error

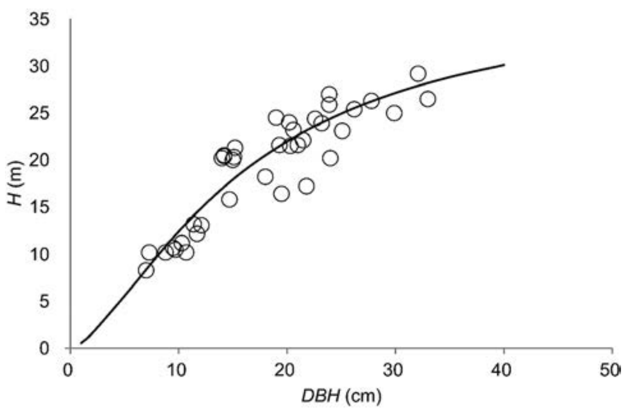

Fig. 5. Relationship between tree diameter at breast height (*DBH*; cm) and height (*H*; m) in the study plots

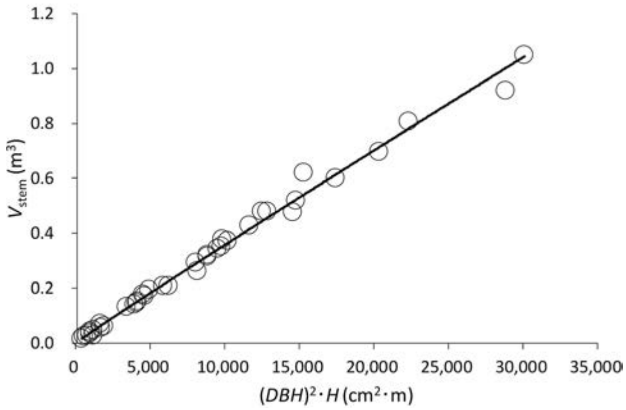

Fig. 6. Relationship between diameter at breast height squared * height ($DBH^2 \cdot H$; $cm^2 \cdot m$) and stem volume (V_{stem} ; m^3)

located close to the sampling site. However, this procedure is not completely reliable, as it is not as accurate as actual measurements made with undamaged trees. The 34 small, damaged trees in the study plots were also estimated for V_{stem} as undamaged trees.

This investigation represents a case study of a eucalypt forest in the highlands of Ethiopia. In the Tigray region, the land available for forestry planting is extremely limited as steep mountainous slopes are occupied by small-scale farms, even at high elevations. We calculated the total V_{stem} per hectare of an approximately 30-year-old eucalypt stand in this environment. The present estimate of stem volume per unit area was approximately 36% that of an estimate by Pukkala & Pohjonen (1990) for the same species in Addis Ababa, Ethiopia. The relatively high elevation of the present study area might have led to the lower estimate of stem volume than has been observed in other areas; therefore, we attempted to develop an additional equation to enable a comparison between the current study area and other *E. globulus* stands. However, this equation necessitated the collection of component data, such as the dry weights of leaves, branches, and roots, which was not undertaken in the present study. Thus, we cannot assess the merits of the allometric equation developed in this study relative to allometric equations already developed in previous studies. We, therefore, stress that our findings are limited in application primarily to areas with specific conditions similar to southern Tigray, but the data are useful as a case study.

Conclusions

Using data collected from a eucalypt plantation in southern Tigray, we developed an allometric equation to estimate *H* from *DBH* (Eq. 7), and an additional equation to describe the relationship between V_{stem} and $DBH^2 \cdot H$ (Eq. 8), with a high coefficient of determination and low RMSE value. With regard to the equation for estimation of the *DBH-H* relationship (Eq. 7), the value of parameter *h* in the generalized allometric model can alter H_{max} in the results for other parameters linked to a variation in *h*. The evaluation of *h* is the most important factor in the development of allometric equations. A linear regression model using $h = 1.5$ to analyze the *DBH-H* relationship showed a high coefficient of determination ($R^2 = 0.8382$) and accuracy was confirmed by the low RMSE (2.3435). However, the mean height of a forest can be influenced by environmental factors, such as climate, soil, and elevation. It is, therefore, uncertain whether Eq. 7 is applicable for all highland eucalypt forests in Ethiopia. We, however, assume that the equation could be assessed for estimation of the *DBH-H* relationship of eucalypt plantations in the highlands of Ethiopia by taking the same approach and accumulating data at other sites. The coefficient of determination and RMSE for Eq. 8 were $R^2 = 0.9657$ and RMSE = 0.0724, respectively, which shows that the equation developed for the estimation of stem volume was highly accurate at the specific site. This finding suggests that *DBH* alone can be used to estimate V_{stem} and thus may be useful for simple monitoring. However, additional information, including measured branch, leaf, stump, and wood densities, would be required to determine the biomass of the entire forest. Further surveys are expected to improve monitoring of forests for commercial uses in the study region.

Acknowledgements

This paper reports the results obtained in the JIRCAS project "Establishment of Sustainable Rural Society with Low GHG Emission in Tigray Region, Ethiopia (F.Y. 2011-2015)" in collaboration with Mekelle University, Ethiopia.

We would like to express our sincere appreciation and gratitude to Maichew Particleboard Manufacturing PLC in southern Tigray and its technical staff who assisted us in the field. Special thanks to the transportation staff members of the company and residents living around the Debar ridge area. We also thank the reviewers for suggestions that greatly improved the manuscript. Finally, we wish to thank Robert McKenzie, PhD, from the Edanz Group (www.edanzediting.com/ac), for editing a draft of this manuscript.

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