Biomass and Carbon Sequestration Potential of Oxytenanthera abyssinica in the Homestead Agroforestry System of Tigray, Ethiopia

Girmay Darcha[1*] Emiru Birhane[2]
1.Mekelle Agricultural Research Center, Mekelle, Ethiopia
2.Department of Land Resource Management and Environmental Protection, Mekelle University, Ethiopia
*Corresponding Author; girmaydarcha@yahoo.com

Abstract
Oxytenanthera abyssinica forms an important constituent in the homestead agroforestry system of Tselemti district of Northern Ethiopia. Biomass and carbon sequestration potential of *O. abyssinica* in the land managed by farmers was studied from November to January 2013/14 in Serako kebele. Samples of six culms per age classes in three replications, 18 culms in total were harvested for biomass analysis. Allometric equations were then developed relating to leaf, branch and culm biomass with breast height diameter (DBH) and Age as independent variables. To evaluate the effect of Age and DBH on total biomass of *O. abyssinica*, 9 different treatments with three replications were used. In total, 27 culms were randomly selected for biomass and carbon stock determination based on the developed allometric equation. Samples were then collected from three levels of age, i.e. less than one year, one to three years and greater than three years at three DBH levels of 2.55 – 3.18 cm, 3.19 – 3.82 cm and 3.83 – 4.46 cm. Carbon fraction of *O. abyssinica* was determined using destructive ashing method by taking sample specimens both from the above ground and below ground biomass. Carbon stock was significantly higher in one to three and greater than three years than less than one year culm age ($P<0.001$). Older culms were capable to sequester more carbon than younger culms with 3.8, 3.9 and 3.5 kg culm^{-1} for the three age classes respectively. *O. abyssinica* has a significant effect on climate change mitigation through carbon sequestration.
Keywords: allometric equation, carbon sequestration, *Oxytenanthera abyssinica*

1. Introduction

Climate change is among the most challenging environmental, economic and social issue worldwide (Chavan & Rasal 2010; Jordan et al. 2009). Global warming, which has been associated with an unprecedented increase in atmospheric green house gas concentrations, is expected to lead to negative impacts on valuable ecosystems (IPCC 1992). One of the most prominent anthropogenic induced green house gases is carbon dioxide (CO_2), contributing to more than 51% of the global warming (Bishaw et al. 2013). Terrestrial ecosystems play an important role in regulating the abundance of atmospheric CO_2 and other green house gases (Pan et al. 2011). There are great opportunities in forestry sector for mitigating further increases in the atmospheric C pool (Albrecht & Kandji 2003; Negash 2013).

Bamboo has a great potential for climate change mitigation and adaptation (Lobovikov et al. 2009; Yiping et al. 2010; Nath & Das 2011, 2012 and Wang, et al. 2011). But, deforestation and forest degradation has led to reduction in bamboo cover especially in the more accessible natural forest areas of the country (Kassahun 2000). The inclusion of fast – growing perennial species like bamboo in farming systems can encourage farmers to avoid deforestation from nearby natural forests and the associated GHG emissions (Nath & Das 2011).

As more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering it in plant tissue above and below ground (Lobovikov et al. 2009; Yiping et al. 2010) resulting in growth of different parts (Chavan & Rasal 2010). To begin carbon trading, land holders need precise and accurate estimates of the carbon sequestered by the trees in their fields (Chave et al. 2014). Accurate estimates of carbon stocks depend to a greater degree on the availability and adequacy of the allometric equations that are used to estimate tree biomass (Litton et al. 2008; Chaturvedi et al. 2012 and Makungwa et al. 2013).

Generalized allometry exists for tropical trees (Brown 1997; Chave et al. 2005), but, there was a scarce of allometric model specific to *O. abyssinica* biomass determination. This is because variability between biomass estimates can be over or under estimate when using allometric models developed elsewhere (Brown et al. 2012). This may be due to the distinction of the climatic zone, species difference and the independent variables used for the regression model have a big influence (Brown et al. 2012; Chave et al. 2005; Chaturvedi et al. 2012). As a solution, different authors, such as (Chave et al. 2004; Litton et al. 2008 and Makungwa et al. 2013), recommended to give preference to allometric models developed on local or regional compilations. Finally we decided to develop own allometric equation specific to *O. abyssinica* biomass and carbon stock estimation.

2. Materials and methods

2.1 Study site description

The study area, *Serako*, is located within $13^{0}05'$N latitude and $38^{0}08'$ E longitude. Site was selected purposively based on the availability of domesticated *O. abyssinica* in their homesteads (Fig. 1).

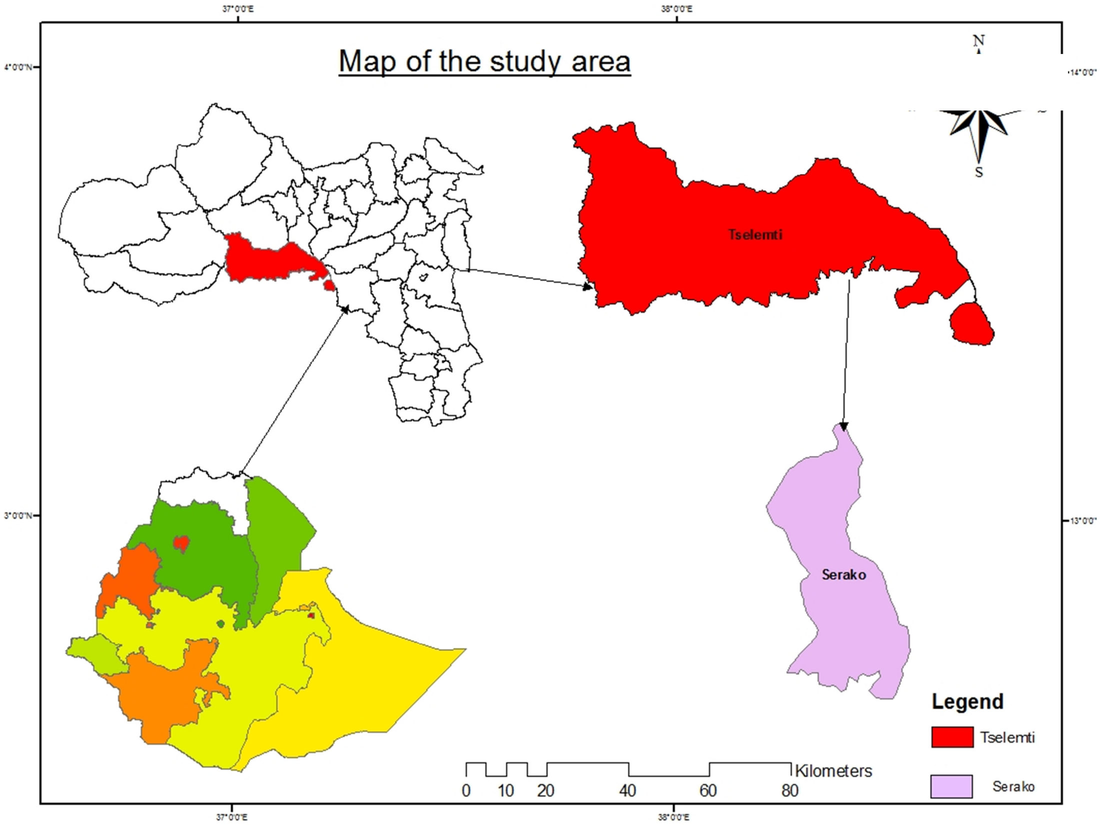


Fig. 3 Geographical location of Tselemti

The agro-climatic condition of the area is hot to dry semiarid lowland plains dictated by a very hot temperature. The maximum temperature ranges from 35.6°C in May to 36.4°C in April, while the minimum temperature is ranging from 15.7°C in December to 21.8°C in May (TNMA 2014) (Fig. 2). The dry season occur between November to March whereas, the rainy season occurs between June to September, which follows a unimodal rainfall pattern (Fig. 2).

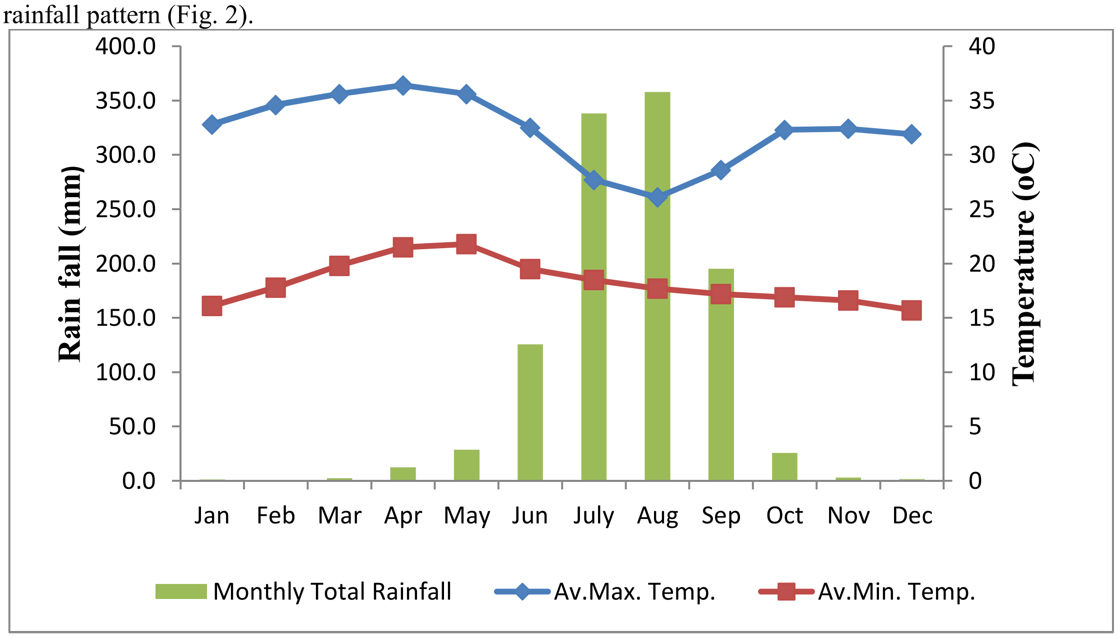


Fig. 4 Six year rainfall and temperature of the study area (Source: TNMA, 2014)

The most dominant soil types of the study area are Cambisols, Nitosols and Vertisols, (TARI 2002). The dominant Combretum-Terminalia vegetation species are *Cordia africana*, *Croton macrostachys, Acacia senegal, Boswellia papyrifera, Anogeisus leiocarpus, Tamarinudus indica, Euphorbia tirucalli, Faidherbia albida and Erythrina abyssica* as farm woodlots, scattered on farm, road sides, farm boundaries (WARD 2014). *O. abyssinica* is dominantly occurring in the homesteads as agroforestry species (Fig.3).

Fig. 5 O. abyssinica planted as Homestead Agroforestry system in Tselemti

Agriculture is the main livelihood of the community in the study area. It is known for its mixed farming system, where the rural people depend on crop and livestock production and in addition with agroforestry practices for their living.

2.2 Methodology used

2.2.1 *Allometric model development for O. abyssinica*

Total culm biomass was considered as the sum of the above ground biomass and belowground biomass (Chavan & Rasal 2012).

Culm selection procedure

Age and DBH were considered as bamboo grass selection criteria (table 1). According to Kassahun et al. (2004), DBH of all bamboo culms in the clump were measured at 1.3 m height grouped in to three age-classes as (<1 year), (1 to 3) year and (>3 year). The age of the culms were identified in the field based on the indicators used by (Wimbush 1945 and Banik 1993) cited in Kassahun et al. (2004) and with the help of the household head.

Table 1 Major indicators used for differentiation of bamboo culms in to respective age classes.

	Culm age classes		
	< 1 year old	**1 - 3 years old**	**>3 years old**
Culm	dark-green color	faded green or pale green culm	dry appearance
Cum texture	smooth culm	slightly rough	rough surface
Culm sheath	fully or partly covered by fresh looking sheath	sheath if present on the lowest node	with no sheath at all
Development of moss or lichen	Free from infestation by moss or lichen	little moss may be found at the nodes	prevalent on the nodes and internodes

Source: Kassahun et al. (2004)

Above Ground Biomass

For regression model development, one clump per village (three villages) as replication were randomly selected and then according to Zemek et al. (2009) and Dietz et al. (2011) two representative culms per sample felled from each age group. Samples of 6 culms per age classes were harvested for the species. Thus a total of 18 (eighteen) culms were harvested for the present study. In the farmer managed *O. abyssinica* DBH class from 2.55 – 4.46cm of eighteen culms were incorporated. These DBH values were small when compared to reports of (kasahun 2004). After cutting the culms at the base, total height was determined with a measuring tape and diameter by using diameter measure tape. Subsequently aboveground components were separated into culm, sheath, leaves, and twigs (Fig. 4).


When dig out sample culms


When separated in to its parts


Root part


Twig parts


Leaf parts


Culm parts

Fig. 6 Above-ground and below-ground biomass determination

The total fresh weight (FW) of the different components was determined on site with sensitive balance. To determine total dry weight of each component (DW), sub-samples of 500g each was taken to Tigray agricultural research institute Mekelle soil research and laboratory and oven dried at 65 ◦C until constant weight was maintained for each component Eq. [1]. The following equation was used to convert subsample (subs.) dry biomass to total dry weight (Zemek 2009):

$$Total\ component\ DW\ (kg) = total\ FW * \frac{sub\ sample\ DW}{subsample\ FW} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . [1]$$

Blow Ground Biomass

The below ground biomass of each culm was estimated from the AGB by multiplying it with a factor of 0.27 (root/shoot ratio) Eq. [2] as described by Moges (2010).

$$BGB\ per\ culm = 0.27 * AGB\ culm^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . [2]$$

2.2.2 *Assessing carbon sequestration potential of O. abyssinica*

To evaluate the effect of Age and DBH on total biomass of *O. abyssinica*, 9 different treatments were used. The experimental design was RCBD in 3x3 factorial arrangements (three levels of age and three levels of DBH); with three replication (table 2). The treatments were assigned by stratified random sampling to each experimental unit within each block.

Table 2 Treatment combinations of Age and DBH levels used in the experiment

S.No	Age class (years)	DBH class (cm)	combination	Treatment description
1	A_1	D_1	(A_1, D_1)	A_1 = less than one year, D_1 = 2.55 – 3.18 in cm
2	A_2	D_1	(A_2, D_1)	A_2 = one to three year, D_1 = 2.55 – 3.18 in cm
3	A_3	D_1	(A_3, D_1)	A_3 = Greater than three, D_1 = 2.55 – 3.18 in cm
4	A_1	D_2	(A_1, D_2)	A_1 = less than one year, D_2 = 3.19 – 3.82 in cm
5	A_2	D_2	(A_2, D_2)	A_2 = one to three year, D_2 = 3.19 – 3.82 in cm
6	A_3	D_2	(A_3, D_2)	A_3 = Greater than three, D_2 = 3.19 – 3.82 in cm
7	A_1	D_3	(A_1, D3)	A_1 = less than one year, D_3 = 3.83 – 4.46 in cm
8	A_2	D_3	(A_2, D_3)	A_2 = one to three year, D_3 = 3.83 – 4.46 in cm
9	A_3	D_3	(A_3, D_3)	A_3 = Greater than three, D_3 = 3.83 – 4.46 in cm

Total culm biomass was considered as the sum of the above ground biomass (AGB) and belowground biomass (BGB). A total of 27 culms, 9 culms from one clump as an experimental unit with three replications (villages) were used for the study. Hence, the ages of all the twenty-seven culms were classified in to three age classes (kasahun, 2004) using the culm selection (Table 2). The above ground biomass of the twenty-seven culms was estimated using the allometric equation developed specific to *O. abyssinica* Eq. [10].

The below ground root biomass of each culm was estimated from the AGB by multiplying it with a factor of 0.27 (root/shoot ratio) as described by Moges (2010) in Eq. [2].

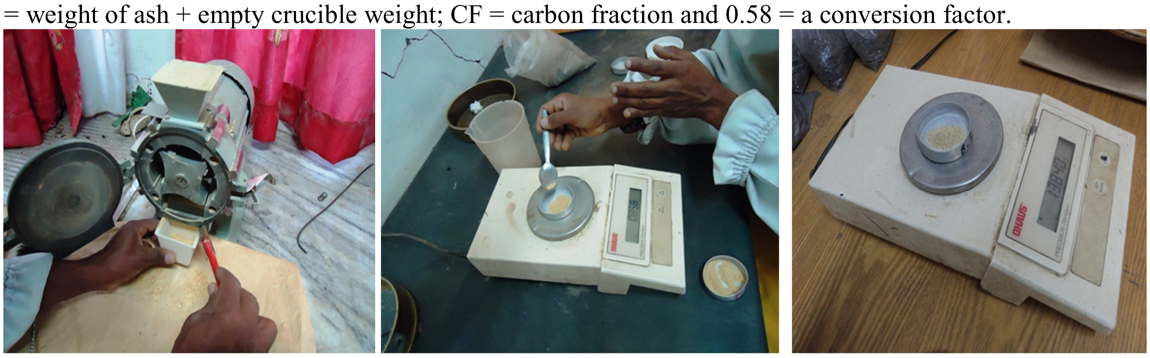
2.2.3 Determination of carbon fraction in *O. abyssinica*

Three culms with different age classes were randomly selected from the total of twenty-seven culms. They were felled using chainsaw. Then, sub-samples were taken from the roots, stems, twigs and leaf. Then after, the specimens were oven dried at 65°C and weighed repeatedly until a constant weight was obtained. Further, specimens of each culm sample were then ground (milled) using a grinding machine and a 0.5gm sieved sample was weighed for ashing (Fig. 5). Ashing was done after burning the sample in a muffle furnace at 550°C for 8 hours until a white ash was obtained (Allen et al., 1986; Ullah *et al*., 2008 and Nath and Das 2012). Finally, the ash content and carbon fraction were calculated using Eq.s [3 and 4] respectively.

$$Ash\ (\%) = \frac{W3 - W1}{W2 - W1} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [Eq.3]$$

$$CF\ (\%) = (100 - \%\ ash) * 0.58 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [Eq.4]$$

Where; W_1 = weight of crucibles; W_2 = weight of oven dried tree samples + empty crucible weight; W_3 = weight of ash + empty crucible weight; CF = carbon fraction and 0.58 = a conversion factor.



Grinding the sample specimens measuring a 0.5 gm sample specimen weighing the ash

Fig.7 Carbon fractionation

2.2.4 **Estimation of carbon stock in *O. abyssinica***

The carbon stock of both the above ground and below ground root biomass was estimated by multiplying total biomass by the carbon fraction as described by IPCC (2003) and Nath and Das (2012) given in Eq. [5 and 6].

$$CAGB = AGB * CF \ldots\ldots\ldots\ldots\ldots\ldots [Eq.5]$$

$$CBGB = BGB * CF \ldots\ldots\ldots\ldots\ldots\ldots [Eq.6]$$

Where, C_{AGB}= the carbon stock in the above ground biomass; C_{BGB}=carbon stock in the below ground root biomass and CF = carbon fraction as described in Eq. [4].

The total carbon stock of the culm is the sum of both the above ground and below ground carbon as described by IPCC (2003) indicated in Eq. [7].

$$TCSc = BTotal * CF \ldots\ldots\ldots\ldots\ldots\ldots [Eq.7]$$

Where, TCS_C = total carbon stock of the culm; B_{Total} = total biomass; CF = carbon fraction

The total carbon stock of *O. abyssinica* per hectare was then the product of the number of culms times the biomass of each culm as described zemek (2009) in Eq. [8]. To relate the individual culm biomass to clumping *O. abyssinica* plants, 8000 total culm of *O. abyssinica* per hectare was adopted from study of (kasahun 2004 and LUSO-Consult 1997). A stand population structure of almost 4:3:1 was simulated for less than one, one to three and greater than three years respectively (own survey, 2014) with 1000 culm annual increment per hectare of *O. abyssinica* (LUSO-Consult, 1997). The higher stand population in the current year may be due to farmers use the older once for different purposes by selective cutting in the homestead agroforestry system.

Total biomass of a whole bamboo plant was then the product of the number of culms times the biomass of a culm as derived from the allometric model developed in this study.

$$Total\ Biomass\ (Kgha^{-1}) = Biomass\ of\ a\ culm\ (Kg) * Total\ culm\ per\ hectar \ldots\ldots [Eq.8]$$

Then, the $CO2^{-e}$ of *O. abyssinica* per hectare was calculated by multiplying the total carbon stock per hectare by a factor of 3.67 Eq. [9] (IPCC, 2003).

$$CO2^{-e} = TCS * 3.67 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [Eq.9]$$

2.2.5 Statistical analysis

A two way analysis of variance (ANOVA) was used with LSD (Least square means difference Duncan test) to compare the mean biomass and carbon stocks at different age and DBH levels with a fixed effect model at (P<0.05). Gen Stat version 14.1 was used for data analysis.

3. Result and discussion

3.1 O. abyssinica Allometry

Scatter plots of woody biomass against DBH showed approximate linear relationship (Fig. 6).

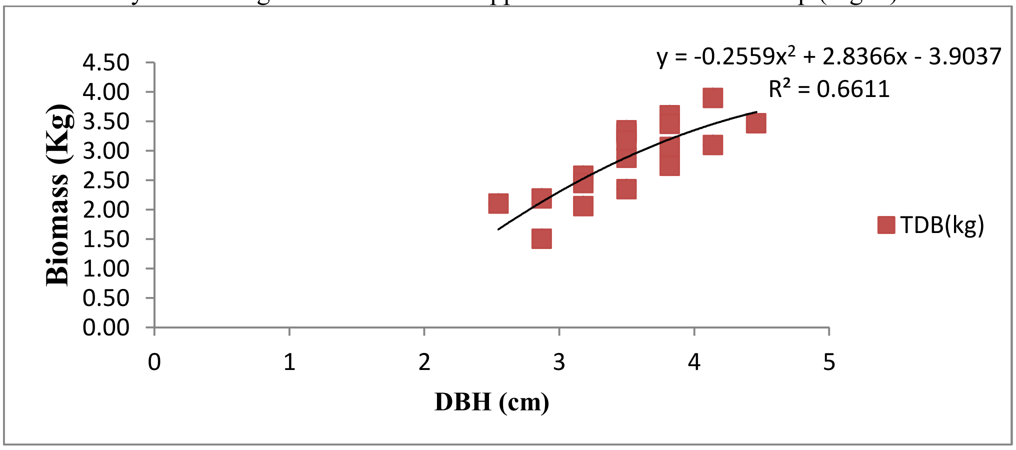


Fig. 8 Allometric model for O. abyssinica biomass against DBH

Allometric model were developed for *O. abyssinica* for different dbh and age groups of culms and best fitted to polynomial function of the study area.

$$Y = -0.2559X^2 + 2.8366X - 3.9037 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [Eq. 3.10]$$

$R^2 = 0.6611$

Where, y = above ground biomass (kg), x = diameter at breast height (2.55-4.66cm range), 0.2559, 2.8366 and 3.9037 are constants.

3.2 Biomass and Carbon Sequestration of O. abyssinica

The biomass of *O. abyssinica* at different age classes was significantly different (Table 3, $P < 0.05$). Culms with an age class of <1 years had an average above ground biomass (AGB) of 2.77 kg $culm^{-1}$ and those 1 to 3 and > 3 three years old had an average AGB of 3.09 kg $culm^{-1}$. Similarly, an increase in the below ground biomass (BGB) of *O. abyssinica* was observed in older culms of 1 to 3yrs with a value of 0.83 kg $culm^{-1}$ comparing to younger ones (<1 yrs), which was 0.75 kg $culm^{-1}$ ($P = 0.03$). This clearly indicates that older aged culms produce higher biomass as compared to younger ones. Similar to age effect, the analysis of variance revealed that DBH showed significant difference on above ground biomass (AGB), belowground biomass (BGB) and total biomass of *O. abyssinica* (Table 3, $P<0.001$). This could also clearly indicate that greater DBH culms produce higher biomass than smaller ones. The interaction effect between age and DBH of *O. abyssinica* also had significance difference on above ground biomass (AGB), belowground biomass (BGB) and total biomass at ($P < 0.001$).

Table 3 Age, DBH and interaction effect on culm biomass

Age class (years)	AGB (kg $culm^{-1}$)	BGB (kg $culm^{-1}$)	Total Biomass (kg $culm^{-1}$)
<1	2.77^a	0.7485^a	3.521^a
1- 3	3.09^b	0.8331^b	3.919^b
>3	3.00^b	0.8109^b	3.814^b
DBH class (cm)			
2.55 - 3.18	2.301^a	0.6213^a	2.922^a
3.19 - 3.82	2.993^b	0.8082^b	3.802^b
3.83 - 4.46	3.567^c	0.963^c	4.53^c
Age (yrs) * DBH class (cm)			
(<1, 2.55-3.18)	1.977^a	0.5337^a	2.51^a
(1-3, 2.55-3.18)	2.397^b	0.6471^b	3.044^b
(>3, 2.55-3.18)	2.53^b	0.6831^b	3.213^b
(<1, 3.19-3.82)	2.89^c	0.7803^c	3.67^c
(1-3, 3.19-3.82)	3.2^d	0.864^d	4.064^d
(>3, 3.19-3.82)	2.89^c	0.7803^c	3.67^c
(<1, 3.83-4.46)	3.45^e	0.9315^e	4.381^e
(1-3, 3.83-4.46)	3.66^e	0.9882^e	4.648^e
(>3, 3.83-4.46)	3.59^e	0.9693^e	4.559^e

Values designated by the same letter were not significantly different, at ($P<0.05$).

3.3 *Carbon stock of O. abyssinica*

The results showed that aboveground biomass carbon stock; belowground root carbon stock and total biomass carbon stock were varied significantly between age, DBH and their interaction (P< 0.001). Age classes of 1 to 3 and greater than three years had the capacity to sequester more carbon in 1.92kg culm^{-1} than the younger ones (Table 4). Older stands could be able to capture more carbon than the younger ones and this could be due to variation in biomass weight.

In addition, higher C was stored in the AGB than in BGB. The higher carbon stock in the AGB was due to the higher above ground biomass production (Table 4).

Table 4 Age, DBH and interaction effect on culm carbon stock

Age class (years)	**C_{AGB} (kg culm^{-1})**	**C_{BGB} (kg tree^{-1})**	**TOC (kg tree^{-1})**
<1	1.358^a	0.3668^a	1.725^a
1to3	1.512^b	0.4082^b	1.92^b
>3	1.472^b	0.3973^b	1.869^b
DBH class (cm)			
2.55 - 3.18	1.13^a	0.30^a	1.43^a
3.19 - 3.82	1.47^b	0.40^b	1.86^b
3.83 - 4.46	1.75^b	0.47^b	2.22^b
Age (yrs) * DBH class (cm)			
(<1, 2.55-3.18)	0.969^a	0.2615^a	1.23^a
(1-3, 2.55-3.18)	1.174^b	0.3171^b	1.491^b
(>3, 2.55-3.18)	1.24^b	0.3347^b	1.574^b
(<1, 3.19-3.82)	1.416^c	0.3823^c	1.798^c
(1-3, 3.19-3.82)	1.568^d	0.4234^d	1.991^d
(>3, 3.19-3.82)	1.416^c	0.3823^c	1.798^c
(<1, 3.83-4.46)	1.691^e	0.4564^e	2.147^e
(1-3, 3.83-4.46)	1.793^e	0.4842^e	2.278^e
(>3, 3.83-4.46)	1.759^e	0.475^e	2.234^e

C_{AGB}= total carbon in the above ground biomass, C_{BGB} = total carbon in the below ground biomass, TOC= total carbon stock of *O. abyssinica* on individual culm. Average values designated by the same letter are not significantly different, at (P<0.05).

The total carbon stock in the aboveground biomass was 11.47 tone ha^{-1} (Table 5), showing differences among different age classes where younger culms (< 1 yrs) could contribute more carbon than older ones. The higher carbon stock in younger culms might be due to large stand population structure contributed to the difference which is in agreement with the result of Nath and Das (2011). Similarly, the belowground root biomass was able to sequester 3.11tone ha^{-1}. The total carbon stock of *O. abyssinica* was then 14.58 tone ha^{-1} (Table 5). C stock of the present study was higher than that reported from the findings of Nath & Das (2011), reported that rate of above ground carbon stock biomass in the bamboo farming system in India was ranged from 6.51 (2004) to 8.95 (2007) tone ha^{-1}. This variation could be due to species and site difference.

Table 5 Total carbon stock of O. abyssinica

Age class (yrs)	No. culms (ha^{-1})	TC AGB (tone ha^{-1})	TC BGB (tone ha^{-1})	TOC (tone ha^{-1})
< 1	4000	5.43	1.47	6.9
1 - 3	3000	4.54	1.23	5.77
>3	1000	1.5	0.41	1.91
Total C stock (t ha^{-1})		**11.47**	**3.11**	**14.58**

TC_{AGB} = total carbon stock in the above ground biomass, TC_{BGB}= total carbon stock in the below ground biomass, TOC= total carbon stock, t ha^{-1}= tone per hectare

4. Conclusion

In this study, we developed an allometric model for estimating the woody biomass of *O. abyssinica* planted on an agricultural landscape under a smallholder farming systems in Ethiopia. The predictive performance of the model was assessed and provided satisfactory estimates of biomass in the study site. The results of the statistical fits of the model were generally good, enabling one to use the model with confidence for the estimation of woody biomass in *O. abyssinica* stands on homestead agroforestry systems from which they were derived. Although the model provides precise estimates of the woody biomass of *O. abyssinica*, its use is limited to the range of the woody grass sizes that were used in its development and site from where the data was collected. Outside these ranges, the model needs to be tested against the field data to determine its appropriateness.

Above ground, below ground and total carbon stock of culms were significantly higher in the one to three and greater than three years compared to less than one year old age of *O. abyssinica. O. abyssinica* can contribute in clean development mechanism through storing carbon in its biomass both through its above ground and below ground biomass.

References

Allen S, Grimshaw H and Rowland A (1986). Chemical Analysis. In: Moore, P. and Chapman, S., (eds.), Methods in Plant Ecology. America, Blackwell Scientific Publications, 285-344.

Albrecht A and Kandji S.T (2003). Carbon sequestration in tropical agroforestry systems: review. *Agriculture, Ecosystems and Environment,* 99:15–27.

Bishaw B, Neufeldt H, Mowo J, Abdelkadir A, Muriuki J, Dalle G, Assefa T, Guillozet K, Kassa H, Dawson I.K, Luedeling E. & Mbow C (2013). Farmers' strategies for adapting to and mitigating climate variability and change through agroforestry in Ethiopia and Kenya. In: Davis, C.M., Bernart, B. & Dmitriev, A. (Eds.). Forestry Communications Group, Oregon State University, Corvallis, Oregon.

Brown S, Grais A, Ambagis S and Pearson T (2012). Baseline GHG emissions from the agricultural sector and mitigation potential in countries of East and West Africa. CCAFS Working paper no.13. CGIAR research program on climate change, agriculture and food security (CCAFS). Copenhagen, Denmark. Available online at: www. Ccafs.cgiar.org.

Brown S (1997). Estimating biomass and biomass change of tropical forests. Forest Resources Assessment Publication. Forestry Papers 134, FAO, Rome.

Chaturvedi R, Rghubanshi A and Singh J (2012). Biomass Estimation of Dry Tropical Woody Species at Juvenile Stage, *The Scientific World Journal*, 5.

Chavan B and Rasal G (2012). Total Sequestered Carbon Stock of Mangifera indica, *Journal of Environment and Earth Science*, 2(1): 37-49.

Chave J, Andalo C, Brown S, Cairns M, Chambers, J, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure J, Nelson B, Ogawa H, Puig H, Riera, B and Yamakura T (2005). Tree Allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145, 87-99.

Chave J, Mechain M and Burquez A *et al*. (2014). Improved allometric models to estimate the above ground biomass of tropical trees. *Global change biology*, 20: 3177-3190.

Dietz J and Kuyah S (2011). Guidelines for establishing regional allometric equations for biomass estimation through destructive sampling (version one). World Agroforestry center, Nairobi, Kenya.

IPCC (Intergovernmental Panel for Climate Change) (1992). The 1992 IPCC supplement scientific assessment. Working group I. Intergovernmental panel on climate change. Geneva.P.1-22. http://www.ipcc.ch/ipccreports. Accessed on 22 January, 2015.

IPCC (Intergovernmental Panel for Climate Change) (2003). Good Practice Guidance for Land Use. Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories Programme. Kanagawa, Japan.

Kassahun E (2000). The indigenous bamboo forests of Ethiopia: An overview. Ambio, 29(8): 518-521. URL: http:// www.jstor.org/stable/4315085. >: accessed on 5 January 2014.

Kassahun E, Weih M, Ledin S and Christersson L (2004). Biomass and nutrient distribution in a highland bamboo forest in southwest Ethiopia: Implications for management. *Forest Ecol. Manage*., 204: 159-169.

Litton C and Kauffman J (2008). Allometric Models for Predicting Aboveground Biomass in Two Widespread Woody Plants in Hawaii, *BioTropica*, 40(3): 313-320.

Lobovikov M, Lou Y, Schoene D and Widenoja R (2009). The Poor Man's Carbon Sink. Bamboo in Climate Change and Poverty Alleviation, Food and Agricultural Organization, Rome, Italy, 72.

LUSO- Consult (1997). Study on Sustainable Bamboo Management. 2nd Interim Report, Hamburg.

Makungwa D, Chitock A, Skolr l, Phiri Y and Woodhouse H (2013). Allometry for Biomass Estimation in Jatropha Trees Planted as Boundary Hedge in Farmers' Fields. Forests, 4: 218-233.

Moges Y, Eshete Z and Sisay N (2010). Ethiopian Forest Resources: Current Status and Future Management Options in View of Access to Carbon Finances, Ethiopian Climate Research and Networking and the United Nations Development Programme, Addis Ababa.

Nath A and Das A (2011). Carbon storage and sequestration in bamboo-based smallholder homegardens of Barak Valley, Assam. *Current Science*, 100: 229-233.

Nath A and Das A (2012). Carbon pool and sequestration potential of village bamboos in the agroforestry system of northeast India: *Tropical Ecology*, 53(3): 287-293.

Negash M (2013). The indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia: Their biodiversity, carbon stocks and litterfall, University of Helsinki, Finland.

Pan Y, Birdsey R, Fang J, Houghton R, Kauppi P, Kurz W, Phillips O, Shvidenko A, Lewis S, Canadell J, Ciais P, Jackson R, Pacala S, Mcguire A, Piao S, Rautainen A, Sitch S and Hayes D (2011). A large and persistent carbon sink in the world's forests. Science, 333: 988-993.

TARI (Tigray Agricultural Research Institute) (2002). Spatial stratification of agroecologies in Tigray, Mekelle.

Ullah M and Al-Amin M (2008). Organic carbon stock of Albizia procera and Cassia fistula seedlings under climate change scenarios, Chittagong University, Bangladesh.

Wang B, We W, Liu C, You W, Niu X and Man R (2013). Biomass and carbon stock in moso bamboo forests in subtropical China: Characteristics and implications. *Journal of Tropical Forest science*, 25(1): 137-148.

WARD (Woreda of Agriculture and Rural Development) (2014). Annual report of Office of the agricultural and rural development of Tselemti Woreda, Tselemti.

Yiping L, Yanxia L, Buckingham K, Henley G, Guomo Z (2010). Bamboo and Climate Change Mitigation: a comparative analysis of carbon sequestration. International Network for Bamboo and Rattan, 30.

Zemek O (2009). Biomass and Carbon Stocks Inventory of Perennial Vegetation in the Chieng Khoi Watershed, NW Viet Nam. MSc thesis, University of Hohenheim, Viet Nam.