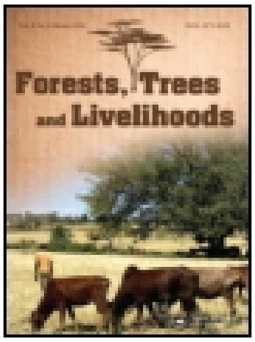

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Preliminary estimate of carbon sequestration potential of *Faidherbia albida* (Delile) A.Chev in an agroforestry parkland in the Central Rift Valley of Ethiopia

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ABSTRACT

Agroforestry parklands are a common land-use in Ethiopia and many parts of the tropics. These systems play an important role in climate change mitigation and adaptation, through carbon (C) sequestration. However, C sequestration in both tree biomass and soil has not been extensively studied for parklands of the Central Rift Valley (CRV), Ethiopia. Therefore, here we sampled a small number of *F. albida* trees and soil from the Adulala watershed, CRV, to provide a preliminary estimate of the C sequestration potential of these systems. Mean above-ground total dry biomass of trees was estimated at 844 kg tree^{-1}. Tree density was 5.80 ha^{-1}, which corresponded to 2.45 t C ha^{-1} in above-ground biomass and 0.76 t C ha^{-1} below-ground; and 118 t C ha^{-1} in soil (0–80 cm depth) under trees, compared to 84 t C ha^{-1} in the soil of crop-only areas. We speculate that if tree density was increased to 100 trees ha^{-1}, the rate of soil C sequestration could be estimated as 0.48 t C ha^{-1} year^{-1} for 42 years. *Faidherbia albida* tree density is sparse in the study area, but could be increased by encouraging farmers to protect planted seedlings or natural regeneration.

KEYWORDS
Biomass allocation; carbon; natural regeneration; pruning; sequestration; soil; tree

1. Introduction

Forests around the world play an important role in storing significant amounts of carbon (C) in their biomass and soil, which helps mitigate climate change (Canadell and Raupach 2008). However, about 119–151 thousand square km of forest are lost to deforestation every year (Bennett 2017). Agroforestry parklands, systems that combine naturally regenerated and scattered trees along with crops (Bayala et al. 2014) provide an opportunity to sequester C both above- and below-ground (Kandji et al. 2006; Jose 2009). Some agroforestry systems including parklands enhance the adaptive capacity of agricultural systems through their ability to improve soil water storage, rainfall use efficiency of associated crops, nutrient cycling, and microclimate for understorey crops (Ong and Leakey 1999; Kandji et al. 2006). A recent meta-analysis of soil C sequestration in agroforestry systems reported that the conversion from agriculture to agroforestry significantly increased soil C stocks by 26–40% depending on soil depth (De Stefano and Jacobson 2018)

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The Clean Development Mechanism (CDM) and Reduced Emissions from Deforestation and Forest Degradation (REDD) programs of the Kyoto protocol have endorsed the potential of agroforestry practices as a greenhouse gas (GHG) mitigation strategy (IPCC 2007). Similarly, an Ethiopian government initiative called the Climate Resilient Green Economy (CRGE) program aims to establish 100 *Faidherbia albida* trees per hectare in cereal cropland across the country (Mekonnen et al. 2013).

Faidherbia albida is one of the main tree species in the parkland agroforestry system of the Central Rift Valley (CRV) of Ethiopia (Endale et al. 2017), and therefore could be important for C storage. Previous studies in the West African Sahel (Takimoto et al. 2008) show substantial C sequestration in above-ground (about 54 Mg C ha^{-1}) and below-ground (about 25 Mg C ha^{-1}) biomass. Additionally, *F. albida* can ameliorate adverse microclimatic conditions for understorey crops and increase crop yields (Sida et al. 2018b) and soil fertility and C (Kamara and Haque 1992; Hadgu et al. 2009). However, many knowledge gaps remain about the biomass and C sequestration potential of this system.

The objective of this study was to determine above-ground biomass of *F. albida* trees and estimate the amount of C stored in soil and biomass of the parkland system of the CRV of Ethiopia. The hypotheses tested in the study are (1) parklands in the CRV of Ethiopia store most C in soil and (2) *F. albida* trees are associated with increased soil C compared to crop-only areas.

2. Materials and methods

2.1. *Study site description*

The study site was a parkland at Adulala in the CRV of Ethiopia, located approximately 104 km south-east of the capital city, Addis Ababa. The study area is situated at 8° 29.5′ N latitude, 39° 20.5′ E longitude and has an average elevation of 1,688 m above sea level.

The location has a bimodal rainfall distribution, with mean annual rainfall of 820 mm. Annual mean minimum and maximum temperatures are 13.9°C and 28.5°C. Soil type is classified as a Fluvisol (Goma 2015). Surface soil (0–20 cm) is characterized by a pH of 7.6 with 0.056% total N, 19 ppm Olsen extractable P, and 155 mg g^{-1} available water holding capacity (Goma 2015). Natural vegetation is dominated by tree species such as *Acacia tortilis, A. seyal* and *F. albida* (previously *A. albida*) (Argaw et al. 1999; Endale et al. 2017), and native understorey was replaced many decades ago by crops. Maize, teff, and wheat are the main crops. Livestock are excluded from crops between sowing and harvesting, but at other times are allowed to roam and browse crop residues.

2.2. *Measurements*

2.2.1. *Tree size characteristics*

A total of 18 *F. albida* trees were randomly selected within an area of 79 ha. All trees had been pruned 2–4 years earlier, and canopies had since regrown; it is a common practice in this area to totally prune tree branches (pollarding) at intervals of 3–4 years. Tree diameter at 1.3 m height (DBH) was measured in May 2015 using a diameter measuring tape, then again for six trees in May 2016. Height to crown base and total height (m) were measured by triangulation using a tape measure and calibrated measuring stick. Crown radius was measured using a vertical sighting method in eight positions around each canopy. Mean crown radius (cr) was then calculated as the quadratic mean of these radii:

$$cr = \sqrt{\left(r^2N + r^2NW + \ldots + r^2NE\right)/8}.$$

where cr = average crown radius, r = radius of individual measurements, N = north, NW = north west, NE = north east

Crown projection area (cpa) was calculated as $cpa = \pi * (cr)^2$.

2.2.2. *Tree density*

Tree density was estimated using a satellite image captured during November 2016 (sourced from Google Earth). The selected trees were scattered across several adjacent farms, within a total area of approximately 79 ha, and measured trees were separated by at least 30 m from any other tree (Dilla et al. 2018). All trees within the total area (79 ha), were counted in 285 plots of approximately equal area (2772 m^2) marked on the image. To correct for other tree species (estimated at 25%, from observation of the study area), the total number of trees ha^{-1} counted in each plot was multiplied by 0.75 to estimate *F. albida* population density. Tree cover ha^{-1} was calculated as the average cpa per *F. albida* tree (59 m^2) multiplied by the number of trees ha^{-1}.

2.2.3. *Tree biomass and C*

Three trees that most closely represented the mean attributes of the 18 parkland trees (in terms of stem diameter over bark at breast height of 1.3 m (DBH) and height), were destructively harvested in November 2016. Each tree was separated into three components: trunk, branches, and twigs+leaves (with twigs defined as branches less than 5 cm diameter). Components were weighed fresh using a field measuring balance or hanging scale. Thereafter, subsamples of each above-ground component were taken, including sub-samples of twigs+leaves, two cubed sub-samples from the trunk (20 x 20 × 20 cm^3) and two from branches (20 x 20 × 20 cm^3) of each tree. Subsamples were weighed then oven-dried at 105°C until a constant weight was obtained and the dry mass to fresh mass ratio calculated. This ratio was then multiplied by the total fresh weight of each component to calculate the dry weight. Above-ground biomass was assumed to be 50% C (UNFCCC 2006). Tree C ha^{-1} was estimated as C per tree multiplied by average tree population density. As this is a coarse estimate of tree biomass (i.e. average of three trees biomass to estimate tree C ha^{-1}), the FAO guidelines general equations for drylands (Brown 1997) was used to compare tree aboveground biomass, as below;

$$Total\ above - ground\ biomass\ (kg)\ ''FAO'' = exp[-1.996 + (2.32 * ln(DBH(cm))]$$

Carbon in below-ground biomass was estimated by using the following equation suggested by UNFCCC (2006).

$$Carbon\ in\ Below - ground\ biomass\,(t\ C/ha) = exp(-1.085 + 0.9256 * ln\ (E)) * 0.5$$

where:
E = estimate of above-ground biomass (t/ha);
0.5 = carbon fraction of dry matter.

2.2.4 *Soil C*

Soil samples were taken under six randomly selected trees at different distances from the tree trunk: Zone A (0–2 m), Zone B (2–4 m) and Zone C (4–6 m) and from control plots (crop-only) c. 30 m away from the tree trunk. Samples under trees were taken at two points in each zone at depths of 0–20, 20–40, 40–60 and 60–80 cm using a core sampler.

Two samples for each combination of distance and depth were mixed to make a total of 12 composite soil samples per tree. Similarly, two soil samples were taken from control plots located randomly. Soil bulk density (BD) samples were also taken from each distance and control plots, at each depth, using a sharpened steel cylinder. Soil samples were air dried and analyzed for organic C (Walkley & Black). Bulk density was determined by drying the sample in an oven at 105°C for 24 h. Carbon content was calculated by multiplying C concentrations by bulk density. Weighted soil C concentration under each tree was calculated as:

$$\frac{(Area1 \times \%Ccon.1) \pm (Area2 \times \%Ccon.2) \pm (Area3 \times \%Ccon.3)}{(Area1 \ + Area2 \ + Area3)}$$

here Area 1 = area of zone A, Area 2 = area of zone B, Area 3 = area of zone C and; % Ccon.1 = soil C concentration under zone A, %Ccon.2 = soil C concentration under zone B and %Ccon.3 = soil C concentration under zone C.

Annual C sequestration potential of soils under *F. albida* trees was calculated as

$$= \frac{\% \text{ area covered by trees } (\text{Soil C under trees} - \text{Soil C in the control})}{\text{Age of trees}}$$

The average age of *F. albida* trees in the parkland was assumed to be 42 years (Sida et al. 2018a)

2.3. *Data analysis*

Data were analyzed using the GLM procedure of SAS 9.4 (SAS Institute 2013). Means of soil carbon under trees and at a distance from trees (control plots) were compared using a t-test (with a significance level of $P < 0.05$). Data from samples at each soil depth was analyzed separately.

3. Results

3.1. *Tree size characteristics and population density*

Tree DBH range was 0.42–0.87 m and crown projection area 43–93 m^2 $tree^{-1}$ (Table 1). Tree diameter measurements in consecutive years (2015 and 2016) show that trees grew about 1 cm in DBH per year.

Across all plots, tree density of *F. albida* ranged from 0–35 trees ha^{-1} (Figure 1), with an average of 5.80 trees ha^{-1}. Therefore, approximately 3.4% of the total study area is covered by tree crowns.

Table 1. Characteristics of *F. albida* trees selected for study in the parkland agroforestry system (n = 18), and those selected for harvest (n = 3).

	Trunk DBH (m)	Crown radius (m)	Height to crown base (m)	Trunk height (m)	Total height(m)	Crown projection area (m^2)
All trees						
Min	0.42	3.70	2.00	4.71	8.40	43.00
Max	0.87	5.45	4.00	7.61	10.21	93.27
Mean	0.61	4.31	3.08	5.87	8.95	59.05
SE(±)	0.03	0.12	0.12	0.19	0.14	3.34
Harvested trees						
Min	0.50	3.70	2.50	5.25	8.50	43.01
Max	0.55	4.24	3.50	6.40	9.60	56.48
Mean	0.53	3.91	2.9	5.72	8.95	48.28
SE(±)	0.01	0.17	0.21	0.35	0.33	4.15

Figure 1. Frequency distribution of *Faidherbia albida* tree density for 285 plots in the parkland of Adulala watershed.

3.2. *Tree biomass and C*

Mean above-ground biomass was 844 kg tree^{-1}; branches contributing 47.9% and trunk 31.5% (Table 2). Above-ground biomass of these trees was about 1359.8 kg tree^{-1}, based on the generic FAO allometric equation estimation. Results of the current study show that trees stored about 2 t C ha^{-1} in their above-ground biomass (mean biomass was 4.9 t ha^{-1}), with the current tree population density of 5.8 trees per hectare. On that basis, above-ground C of *F. albida* trees could be estimated to increase to 42 t C ha^{-1} if tree population density was increased hypothetically to 100 trees ha^{-1}. Mean root

Table 2. Mean above-ground biomass of tree components (n = 3 trees). DM = dry matter.

	Trunk	Branches	Twigs	Leaves	Total	Total (FAO)
Mean biomass (kg DM tree^{-1})	265.6	404.1	123.6	50.2	843.5	1359.8
SE (±)	34.5	45.9	20.7	5.8	-	-

biomass was estimated to be about 1.5 t ha^{-1}, indicating that trees can store about 0.76 t C ha^{-1} in their below-ground (root) biomass with the current tree population density.

3.3. *Soil organic C*

Soil organic C stocks under trees were estimated to range from 28 to 32 t C ha^{-1} per 20 cm depth, and total per profile (0–80 cm depths) averaged 118 t C ha^{-1} (Table 3). Soil organic C stock was significantly greater (P < 0.001) under trees than in the crop-only area (control plots) for all soil depths; with C sequestration potential of approximately 0.03 t C ha^{-1} y^{-1} estimated based on our data.

Soil organic C is estimated to contribute about 98% of the total C (above-ground biomass + soil organic C) stock. This is based on above-ground biomass of 2 t C ha^{-1} and soil of 118 t C ha^{-1}, with the current tree density of 5.80 trees ha^{-1}.

4. Discussion

The current study has estimated that *F. albida* trees in the study area stored about 2 t C ha^{-1} in above-ground biomass, but several studies report that *F. albida* parkland systems can store significantly more C in their above-ground biomass. For example, Beedy et al. (2016) evaluated *F. albida* trees in parkland agroforestry systems of Malawi and reported an average above-ground biomass C of 3 t C ha^{-1}. Takimoto et al. (2008) showed that *F. albida* in parklands in Mali stored about 54 t C ha^{-1} in above-ground biomass. These differences between estimates could partly be attributed to a wide difference in tree stocking; for example, tree stocking in Mali parkland was 21 trees ha^{-1}, whereas at Adulala in the current study it was only 5.8 trees ha^{-1}. While the magnitude of the difference in tree stocking between our study and that in Mali is approx. fourfold, the difference in above-ground C is approx. 10-fold. The lower above-ground carbon storage in the current study area could also be attributed to the pruning practice, i.e. tree branches are pruned (pollarding) at intervals of 3–4 years to increase light availability for understory crops (Dilla et al. 2018). Therefore, continued pruning and removal of

Table 3. Average (weighted for tree zone area) of soil organic C concentrations (OC), bulk density (BD) and C stock under *F. albida* trees compared to away from trees (control plots) at four soil depths (n = 6).

Depth (cm)		Under trees[a] OC (%)	Under trees[a] BD (g cm^{-3})	Under trees[a] C stock (t C ha^{-1})	Control OC (%)	Control BD (g cm^{-3})	Control C stock (t C ha^{-1})
0–20	Mean	1.42	1.12	31.80	1.07	1.15	24.52
	SD	0.09	0.02	1.54	0.11	0.01	2.40
20–40	Mean	1.26	1.12	28.31	0.86	1.15	19.82
	SD	0.10	0.02	1.77	0.10	0.01	2.28
40–60	Mean	1.11	1.37	30.64	0.79	1.34	21.24
	SD	0.15	0.06	3.48	0.10	0.01	2.61
60–80	Mean	1.00	1.38	27.75	0.70	1.34	18.73
	SD	0.18	0.04	4.12	0.11	0.01	3.09
	Total			118.49	–	–	84.32
	SD			5.88	–		1.32

[a]Weighted average of the three zones.

C stored in leaves and branches would reduce C sequestration, and less foliage would also slow tree growth rate. In turn, there would also be less tree litter and less C transferred to the soil C pool (Oelbermann et al. 2004). Moreover, tree age (and therefore size), and sampling methods (only average diameter trees versus sampling across the diameter range) may account for some of these differences. For these reasons, our study is likely to have underestimated the total biomass of trees per hectare compared to other studies (Takimoto et al. 2008; Beedy et al. 2016). Our results need to be interpreted with this consideration in mind. An alternative biomass C estimation method could have relied on general allometric equations that group data for a number of species. However, such methods do not take into account differences between species, which would have resulted in some errors.

The current study estimates that *F. albida* roots in the parkland constitute about 30% of the total biomass, and therefore they could play a significant role in increasing the C pool. Other studies also reported the significant contribution of roots to total biomass. For example, a study in poplar plantations in China, reported that biomass allocated to roots is greater than the biomass allocated to branch and leaf; they ranked biomass production by tree components as stem > root≥ branch> leaf (Fang et al. 2007). The C stored in roots can also represent a significant long-term C sink in agroforestry systems (Oelbermann et al. 2004). However, studies on the potential of roots to sequester C in agroforestry systems are scarce as quantification of belowground biomass is difficult. Thus, future research should include a focus on quantification of below-ground biomass (root biomass) and their potential to sequester carbon.

Faidherbia albida canopies can have positive effects on crop yields and microclimate conditions (Dilla et al. 2018; Sida et al. 2018b). However, the current study indicates that tree crowns cover only 3.4% of the total study area. Increasing tree stocking (as recommended by Ethiopian policy) to 100 trees ha^{-1} would increase cpa to 59% based on our study, if trees were the same age and size. While this highlights obvious benefits for C sequestration, implementation of the policy may be limited by competition for land between crops, trees, and livestock. Further, impacts of high tree stocking on crop production need further investigation in Ethiopian agroforestry systems. Farmer-managed natural regeneration, the practice of farmers protecting naturally regenerating *F. albida* sprouts (Garrity et al. 2010), could be a viable strategy to enhance tree population density in the CRV of Ethiopia.

Faidherbia albida parkland systems are protected in Ethiopia for their benefits to crop yields and soil fertility (Garrity et al. 2010), and the parklands tend to be not usually subjected to major short-term changes in configuration and management (Takimoto et al. 2008). Therefore, C stored in these systems can be considered reasonably stable over time (Takimoto et al. 2008; Beedy et al. 2016). A study in the parklands of the CRV of Ethiopia show that only 48% of the *F. albida* tree population is younger than 42 years (the average age), and suggested little recruitment of the trees within the past 2–3 decades (Sida et al. 2018a). The current study indicates that mean DBH growth of the existing trees is about 1 cm per year. However, the height (where DBH is measured) was not marked at the first measurement to ensure the tape was in exactly the same position the following year; this can led to an error in the estimation of tree growth, as a small difference in height can result in different diameter readings not related to growth.

Soil C content, in the current study, was significantly greater under trees compared to control plots away from trees, which demonstrates the potential of trees to increase soil C stocks. The positive effects of parkland agroforestry systems on soil fertility including soil organic C are documented (Rhoades 1995; Rao et al. 1997). For example, a study by Demessie et al. (2016), in the Gambo district of Southern Ethiopia, suggests that soil C stocks are higher (67 t C ha^{-1}) in the parkland agroforestry system than in adjacent farmland (56 t C ha^{-1}). Carbon sequestration potential of a system refers to long-term storage of CO_2 by the system, which can mitigate global warming and avoid the harmful effects of climate change (Roshetko et al. 2002; Palm et al. 2004). Carbon sequestration potential of agroforestry systems relies on organic C entering soil from turn-over of crop residues, tree litter and fine roots (Oelbermann et al. 2005). Those inputs can help to stabilize soil organic matter and improving soil C stocks (Lal 2004; Oelbermann et al. 2005). A study in *F. albida* woodland of Zimbabwe indicated that organic inputs from litterfall under *F. albida* trees (mean DBH = 0.73 m) was 1.5 t ha^{-1} y^{-1} (Dunham 1991). Other authors have argued that improved soil fertility including soil organic matter under trees is due to the lateral redistribution of nutrients, by domestic and wild animals or due to existing soil fertility conditions that favored natural establishment of tree seedlings (Geiger et al. 1994; Sileshi 2016).

The current study showed that soil C dominated the total C stock (above-ground biomass + soil C), contributing about 98% of the total. Comparably, soil C in a miombo woodland of Mozambique contributed 70% of total C (Ryan and Williams 2011), while Walker and Desanker (2004) reported 60% soil C in the total C stock for a Malawian miombo. A study in the agroforestry systems of the West African Sahel reported that the percentage of soil C (0–100 cm) in the total C was 38% in *F. albida* parkland, 55% in *V. paradoxa* parkland, 84% with live fencing (*Acacia nilotica, Acacia senegal, Bauhinia rufescens, Lawsonia inermis, and Ziziphus mauritiana*), and 94% in a fodder bank (*Gliricidia sepium, Pterocarpus lucens*, and *P. erinaceus)* (Takimoto et al. 2008). Several agricultural systems also can be employed to increase soil C sequestration. For example, minimum tillage can increase soil C by 0.57 t C ha^{-1} y^{-1} and increase soil aggregation and physically C protection (West and Post 2002).

Carbon sequestration rate is calculated as the difference in C content in the system before and after a land use change per unit time (Mg C ha^{-1} y^{-1}) (Roshetko et al. 2002; Palm et al. 2004). The current study estimated that the soil under *F. albida* trees in the agroforestry system can sequester on average 0.03 t C ha^{-1} y^{-1}, assuming the average age of *F. albida* trees in the parkland to be 42 years (Sida et al. 2018a), that the net increase in soil C under trees had accumulated since tree establishment, and that there was linear C sequestration over time. However, this latter assumption can lead to an error in the estimation of carbon stocks over time, as accumulation of carbon is not linear with time (tree age) because of climatic and management variations. Future research could include assessment of tree growth ring data to provide better estimation of annual tree growth and age of trees. This would provide a better insight into the development of carbon stocks over time.

Increasing the current tree density from 5.80 tree ha^{-1} to 100 trees ha^{-1} could potentially sequester 0.48 t C ha^{-1} y^{-1}; which is a low rate relative to the soil C sequestration by other agroforestry systems. A summary of soil C sequestration rates in some major agroforestry systems around the world indicated that the C sequestration potential of agroforestry systems was anywhere between 1.25 and 123 t C ha^{-1} (Nair et al. 2009). The wide difference in the C sequestration rates in agroforestry systems depends on a number of site-specific biological, climatic, soil, and management factors including tree population density (Nair et al. 2009). Carbon storage of *F. albida* parklands can be increased by enhancing trees population density by encouraging farmers to protect planted seedlings or natural regeneration. The current study suggested that further biomass sampling for C sequestration research conducted in the parkland should include higher numbers of replicates (trees) and cover the full range of DBH classes.

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