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Conversion of degraded agricultural landscapes to a smallholder agroforestry system and carbon sequestration in drylands

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Abstract

Purpose – This paper aims at providing the evidence about how carbon sequestration in terrestrial ecosystems could contribute to the decrease of atmospheric CO_2 rates through the adoption of appropriate cropping systems such as agroforestry.

Design/methodology/approach – Stratified randomly selected plots were used to collect data on tree diameter at breast height (DBH). Composite soil samples were collected from three soil depths for soil carbon analysis. Above ground biomass estimation was made using an allometric equation. The spectral signature of each plot was extracted to study the statistical relationship between carbon stock and selected vegetation indices.

Findings – There was a significant difference in vegetation and soil carbon stocks among the different land use/land cover types ($P < 0.05$). The potential carbon stock was highest in the vegetation found in sparsely cultivated land (13.13 ± 1.84 tons ha^{-1}) and in soil in bushland (19.21 ± 3.79 tons ha^{-1}). Carbon sequestration potential of the study area significantly increased (+127174.5 tons CO_2e) as a result of conversion of intensively cultivated agricultural lands to agroforestry systems. The amount of sequestered carbon was found to be dependent on species diversity, tree density and tree size. The vegetation indices had a better correlation with soil and total carbon.

Originality/value – The paper has addressed an important aspect in curbing greenhouse gases in integrated land systems. The paper brings a new empirical insight of carbon sequestration potentials of agroforestry systems with a focus on drylands.

Keywords Ethiopia, Agricultural lands, Carbon trade, Land use/Land cover change, Vegetation indices, Zongi

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1. Introduction

For decades, there has been evidence of growing accumulation of greenhouse gases (GHGs) in the upper atmosphere, particularly atmospheric carbon dioxide (CO_2) which has led to changes in climate, mainly increases in the average global temperature, drought and flood events (Lal, 2004). The removal and storage of atmospheric carbon (C) in the terrestrial biosphere through existing vegetative trees, natural regeneration of forests, reforestation, afforestation, agroforestry (AF) and other good practices are options which have been proposed to compensate GHG emissions (Albrecht and Kandji, 2003; IPCC, 2007).

Among other factors such as an increase in population growth rate, inappropriate natural resources management, deforestation, unreliable access to food and water and climate change have been reported as the key poverty-environment linkages in Ethiopia (César and Ekbom, 2013). The impacts of climate change on Ethiopia's agriculture include crop failure, decreased productivity, water shortage, soil erosion, reduced income, food insecurity and decreased ability to meet other basic needs (Keller, 2009). Agriculture, however, in turn contributes to climate change. It has been projected that if climate-smart agricultural practices are not integrated in the farming systems of Ethiopia, emissions from agricultural sector would increase from 12 Mt CO_2e to more than 60 Mt CO_2e by 2030 due to the increasing cultivated land (GoE, 2011).

Agricultural lands are believed to be a major potential sink of C, and could absorb large quantities of C if trees are introduced to these systems and judiciously managed together with crops and/or animals (Albrecht and Kandji, 2003). AF systems have been reported to offer important opportunities of creating interaction between both adaptation and mitigation actions with a technical mitigation potential of 1.1-2.2 Pg C in the global terrestrial ecosystems over the next 50 years (IPCC, 2007). The C sequestration potential of AF systems was estimated at 12 and 17 Tg C $year^{-1}$ for 2010 and 2040 in developed countries, and 14 and 28 Tg C $year^{-1}$ for 2010 and 2040 in developing countries, respectively (IPCC, 2000). Moreover, AF systems act as buffers against both biophysical and economic risks (Verchot *et al.*, 2007). They successfully make tradeoffs between sustainable biodiversity conservation, resource utilization and human needs, hence their capability to ensure food security (Pandey, 2002).

AF systems play important roles for the people of Ethiopia and the country's prospects to reduce poverty, enhance welfare and sustain economic growth (César and Ekbom, 2013). Zongi village represents a model AF site in northern Ethiopia (Chiemela *et al.*, 2017; Noulèkoun *et al.*, 2016, 2017). The community through regeneration of under-forest and afforestation broke the jinx of severe land degradation that affected their livelihood. As a result, a substantial amount of land area (51.9 per cent) has been converted from intensively cultivated land use (LU) type to less intensively used LU types such as sparsely cultivated and shrublands (Chiemela *et al.*, 2017). The importance of indigenous AF systems, such as the one of Zongi village, is receiving wider recognition not only in terms of agricultural sustainability, climate change mitigation but also as a means for diversified income source for landowners. Hence, evaluating the environmental value of the transformation of degraded landscapes to AF systems through their potentials to sequester C as part of a global mitigation effort for atmospheric C sequestration is crucial for designing relevant policies aiming at sustainable use of land resource.

The United Nations Framework Convention on Climate Change (UNFCCC) Kyoto approach, as most recently articulated in the 2007 Bali conference, can be summarized into three resolutions:

1. developed countries should adopt national emission reduction targets;
2. developing countries should undertake mitigation actions; and
3. developed countries should provide developing countries with mitigation financing (Howes, 2009).

Payment for environmental services, which is an incentive-based mechanism for sustainable resource conservation and management and for poverty alleviation, has thus been initiated to provide additional source of income to the participating households (Isreal *et al.*, 2014).

To further encourage climate change mitigation efforts by communities, C trade under the Clean Development Mechanism (CDM) has been developed to acknowledge and compensate for the work done by land owners who manage the land in ways that contribute to the long-term security of ecosystem functions, through sustainable forms of land use (Notman *et al.*, 2006). However, some challenges, such as security of land tenure, execution without a proper monitoring or control mechanism and offering of perverse incentives to land users, hamper the successful implementation of CDM (Dougill *et al.*, 2012; Isreal *et al.*, 2014). The standardization of CDM crediting rules (called methodologies) that are used for CDM projects could enhance transparency, predictability, objectivity and reduce transaction costs, but also runs the risk of over-crediting and allowing many projects into the CDM that are simply "free-riders."

East Africa is currently the most favored destination for international C sequestration investors in Africa (Rohit *et al.*, 2008). Some of the beneficiaries in Africa are in countries like Kenya, Uganda, Tanzania, Mozambique and Ethiopia. In Nhambita Community C Project in Mozambique, local households receive a cash payment at a rate of US$4.5 per tCO_2 for C sequestered in their AF systems (Chomba and Minang, 2009). Under the International Small Group Tree Planting Program (TIST) in Tanzania, local farmers receive C payments based on the number of trees they can manage on their lands (Rohit *et al.*, 2008). Here in Ethiopia are the Humbo C Project of World Vision in the Southern part of the country and Bale Eco-Region C Project in South-eastern Ethiopia. Despite the success story of Zongi village regarding the reintegration of trees on agricultural lands, through sustainable land management strategies (Chiemela *et al.*, 2017; Noulèkoun *et al.*, 2017), less focus has been attached to the site by C investors, including the two C projects existing in the country, due to lack of scientific evidence. According to Stringer *et al.* (2012), many of the knowledge gaps in understanding dryland C storage stem from a lack of empirical data and scientific evidence, which limits the utility of scientific knowledge for research users such as policy makers and NGOs. Therefore, quantifying its C potential, which in turn will serve as a baseline for C trading under the CDM, is key to encourage land owners investing in land rehabilitation and sustain the AF systems. Hence, the aim of this paper is to measure the C stock, C sequestration and C trade potential of different land use/land cover (LULC) types in the study area. The paper quantified the amount of C sequestered when a degraded agricultural landscape is converted into small holder AF systems in the drylands, the C trade potential, and also established the relationship between C stock and spectral reflectance of LULC types in satellite imageries using Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) techniques to indirectly predict C status of the LULC types (Aynekulu, 2003).

2. Materials and methods

2.1 Study area description

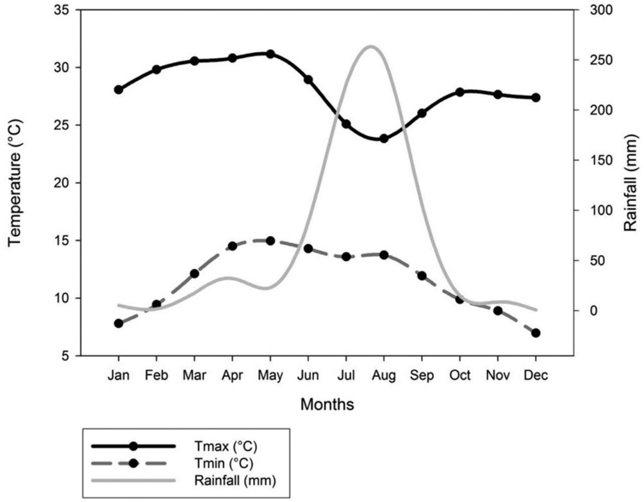
Zongi village is located in Werie Leke District found in the low-lying agroecological zone of Tigray region in the northern part of Ethiopia. The geographical location of the study area lies between 13° 59′-14° 02′N and 38° 59′-39° 02′ E (Chiemela *et al.*, 2017). The area has low to moderate relief with an altitude range of 1,781-2,063 m a.s.l. The topography is characterized by both gentle and rugged slopes with steep hillsides and mountains. The soil types in Tigray region are predominantly cambisols, fluvisols, xerosols, vertisols and luvisols (Hadgu *et al.*, 2011). The mean monthly minimum and maximum temperatures range from

7-15°C and 23.8-30.8°C, respectively (Figure 1). The study area receives an annual rainfall of 600-900 mm year^{-1}; and the maximum monthly rainfall between 2003 and 2012 is about 270 mm (Figure 1).

The farming system of the study area is mainly a combination of crop-tree-livestock system. The most practiced LU type is parkland AF (Chiemela *et al.*, 2017; Noulèkoun *et al.*, 2017). Bee- keeping is also part of the farming system. Agricultural activities in the study area are mainly dependent on the major rainy season extending from July to September. Crops grown in the study area are finger millet (*Eleusine coracana*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), teff (*Eragrostis abyssinica/teff*), chickpea (*Cicer arietinum*), broad bean (*Vicia faba*), linseed (*Linum usitatissimum*), lentil (*Lens culinaris*) and sun flower (*Helianthus annuus*). Agriculture is the most important sector of the economy with their daily livelihood depending on it.

2.2 Land use/land cover of the study area

The total land area of the study site is about 33.1 km^2 (Chiemela *et al.*, 2017). A mix of drought-deciduous and evergreen shrubs and trees characterizes the vegetation of the study site. This vegetation occurs as a secondary re-growth and regeneration. The site is largely dominated by *Vachellia etbaica* (Schweinf.), *Faidherbia albida* (Del.) A.Chev. and *Vachellia seyal* (Delile) P.J.H.Hurter. Various LULC types identified by Chiemela *et al.* (2017) in the area included shrubland (SL), bushland (BL), intensively cultivated land (C1), moderately cultivated land (C2), sparsely cultivated land (C3), bare land and rock-out crop (BarL/RoC) and water course/body (WC/B). In 1984, the study area predominantly consisted of C1 (67.7 per cent) and degraded lands described as BarL/Roc (28.9 per cent) (Chiemela *et al.*, 2017). In the year 2013, there was increased vegetation cover in the study area, portrayed by the decrease in C1 and the emergence of new and less intensively cropped LU types (Chiemela *et al.*, 2017).



Source: Ethiopian Meteorological Office (2013)

Figure 1. Pattern of average minimum and maximum temperature and average rainfall from 2003 to 2012

The drivers of change as identified were extension intervention, increased environmental awareness and byelaws. Here we extend our findings beyond the early report of conversion of degraded arable lands to AF parkland (Chiemela *et al.*, 2017) to include assessing the C stock potentials of the different LULC types and implications for C trading.

2.3 Carbon stock assessment procedures

Sample plots were located randomly on a LULC map of the area, which shows clearly the boundaries of different strata (LU types). This was accomplished with a random function in ArcMap/GIS 10.1 program. To ensure the even distribution of plots among the LULC classes and enable comparisons, five plots were selectively established in each of the LULC type, except in bushland (BL) that had four plots because of its relatively small size.

Nested rectangular sample plots of 2000 m^2, 200 m^2 and 0.25 m^2 was used as recommended in Hairiah *et al.* (2011) for forestry and agricultural lands to account for the variability in age and size of the woody trees. The rectangular plots were also chosen, because they tend to include more of the within-plot heterogeneity, and thus are more representative than the square or circular plots of the same area (Hairiah *et al.*, 2011).

2.3.1 Tree above-ground biomass estimation. Tree sizes were measured in the main plot (Hairiah *et al.*, 2011). The minimum DBH measured was 2.5 cm (Pearson *et al.*, 2007). Tree diameter was measured at breast height (1.3 m above-ground level). For multiple-stemmed trees, individual stem diameter was measured for the trees that stemmed before breast height (Hairiah *et al.*, 2001; Condit, 2008), whereas average diameter was considered for the trees that stemmed from breast height. Diameter at stump height (DSH) for shrubs was measured at 0.3 m from the ground.

The allometric equation developed by Kuyah *et al.* (2012) was adopted for tree biomass estimation:

$$W = 0.1428 \times DBH^{2.2471} \tag{1}$$

where, W = biomass (dry weight, kg tree) and DBH = Diameter at breast height.

It is a mixed species tree size equation developed in Western Kenya for agricultural landscapes. The equation has been found suitable and used in AF systems in Malawi (Kuyah *et al.*, 2014) with relatively the same climatic and topographic conditions as in this study area and in South-eastern Ethiopia (Negash, 2013).

2.3.2 Below-ground biomass estimation. Below-ground biomass was estimated according to IPCC (2003) guidelines by taking 27 per cent of above-ground biomass:

$$Below\ ground\ Biomass = Above\ ground\ Biomass \times 0.27 \tag{2}$$

2.3.3 Undergrowth sampling and litter biomass estimation. Grasses and herbs were harvested in the 0.25 m^2 quadrants (Hairiah *et al.*, 2011). Total wet weight of the various samples was recorded at the field level and composite samples were taken and weighed, oven dried in the laboratory of Mekelle University at 65°C until a constant weight was achieved (Hoff *et al.*, 2002). The dry weight of the materials was recorded afterward. The grass, herb and litter biomass was estimated using equations (3) and (4):

$$B_o = (Bks \times Bbt)/Bbs \tag{3}$$

where Bo is the weight of material (kg), Bks is the dry weight of the sample (kg), Bbt is the total fresh weight (kg) and Bbs is the fresh weight of the sample (kg):

$$Biomass\ \left(tons\ ha^{-1}\right) = \frac{B_o}{1000} \times 5000 \tag{4}$$

where Bo is the weight of material (kg).

The biomass of above-ground, below-growth and undergrowth of each plot was extrapolated to hectare.

To convert biomass to C, 50 per cent (Brown, 2002) of each biomass pool was assumed to be the C stock.

2.3.4 Soil sampling and carbon estimation. Composite soil samples were taken from three different depths (0-10, 10-20 and 20-30 cm) at each corner and center (5 points) of the rectangular subplot 5 × 40 m (Hairiah *et al.*, 2011). Bulk density was estimated by taking undisturbed soil samples using a core sampler of 100 cm^3 volume. Before the collection of soil sample for bulk density and percentage (per cent) of organic C determination, the litter layer was first removed. Seventy-two soil samples were collected for laboratory analysis. Bulk density was determined after drying the core soil samples in an oven at 105°C until a constant weight was observed. The dried soil was sieved through a 2-mm sieve. Soil C was determined by the Walkley–Black oxidation method (Walkley and Black, 1934) in Mekelle Soil Research Centre, Mekelle. Pearson *et al.* (2007) equation was used for calculation of soil organic C:

$$SOC = \%OC \times \rho \times D \times 100 \tag{5}$$

where SOC is the soil organic C (t C ha^{-1}); per cent OC is the C concentration (per cent); ρ is the bulk density (g cm^{-3}); D is the depth of the soil sample (cm) and 100 is the conversion factor from gcm^{-2} to ha^{-1}. The following equation was finally used for the calculation of the total C stock per hectare:

$$C_{ha} = \left(C_{aboveground} + C_{belowground} + C_{litter} + C_{undergrowth} + C_{soil}\right) \tag{6}$$

2.4 Estimation of carbon sequestration potential

The CO_2e of the system was calculated by multiplying the total C stock of the system (TCsystem) by a factor of 3.67 [equation (7), IPCC (2003)].

$$CO_2e = TCsystem \times 3.67 \tag{7}$$

2.5 Carbon trade potential estimation

Complying with the decision of the Conference of the Parties of the Kyoto Protocol (UNFCCC, 2003), we assume that non-permanent certificates are rewarded in the form of temporary credits (tCER), which expire at the end of the commitment period subsequent to the period when they were issued (Olschewski *et al.*, 2005). In the estimation of C trade potential, US$4 per ton as used in the case of Humbo project in Ethiopia was used:

$$Ctrading\ potential = TCsystem\ \left(tons\right) \times Price\ per\ ton\ of\ C \tag{8}$$

The present value of C revenues was determined in accordance with Olschewski *et al.* (2005). Assuming a five-year project and a discount rate (d) of 8.1 per cent for developing countries (Mekuria *et al.*, 2011), the formula used was as below:

$$Discounted\ price = TCsystem \times Price/(1 + d)^5 \tag{9}$$

2.6 Statistical analysis

All the data were first tested for normal distribution and homogeneity of variance. ANOVA was used to check for significant differences of C stock among vegetation pools and different soil depths. Besides, for each of these analyzes, ANOVA was run to assess the effect of LULC types on total C stocks. Gabriel's post hoc test was used when the ANOVA result was significant to compare means as it accounts for the unequal sample size.

2.7 Spectral relationship between spatially explicit sequestered C and vegetation indices

ERDAS Imagine version 9.2 was used to extract spectral signatures of each plot from the Landsat image of 2013. Vegetation indices such as NDVI, which principally demonstrates the strength of vegetation greenness and SAVI that incorporates soil correction factor, were calculated (Aynekulu, 2003; Tutu, 2008) using the following equations:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{10}$$

$$SAVI = \frac{(1 + L) \times (NIR - R)}{(NIR + R + L)} \tag{11}$$

where NIR is the near infrared reflectance; R is the red reflectance and L is the soil correction factor which is 0.5 according to Bastiaanssen (1998).

Spearman linear correlation was used to check the relationship between the dependent variables (vegetation C, soil C and total C) and the independent variables (vegetation indices).

3. Results and discussion

3.1 Vegetation composition of the study area

The most dominant tree species on the cultivated lands were *V. etbaica*, closely followed by *F. albida and V. seyal. V. etbaica* dominated in the SL and BL with other dispersed species. Tree density varied from one LULC type to another (Table I). SL had the highest number of trees (mean = 245 trees ha^{-1}), while C1 had the least (Mean = 7 trees ha^{-1}) compared with the other LULC types. The high tree density in SL could be as a result of little or no human and livestock disturbances, leading to more regeneration (Noulèkoun *et al.*, 2017). The DBH/DSH of trees/shrubs in LULC types varied as well. Cultivated lands (C1, C2 and C3) had the biggest trees both in number and in frequency, whereas SL and BL had trees with the lowest DBH. Similar results were reported by Noulèkoun *et al.* (2017) in Zongi AF systems where higher and taller trees were found in LU types characterized by high land cropping intensity and human interferences such as cultivated lands, as compared to LU types subject to low cropping intensity such as SL. Such observation highlights the importance attached to tree by farmers in AF systems who managed and conserved them on agricultural lands to derive ecosystem goods and services (Noulèkoun *et al.*, 2017). Further, the presence of bigger trees on cultivated land relative to SL and BL may be explained by the prevalence of more intense ecological interactions in terms of light and nutrient competition in the latter LU types due to the high tree density (Fandohan *et al.*, 2011; Noulèkoun *et al.*, 2017). These findings imply that the variations are based on the number of trees and cover types used for the LULC classification. Consequently, DBH would impact on the quantifications of biomass and C stock.

3.2 Carbon stock potential of different vegetation pools in the different LULC types

The C stock of vegetation biomass was significantly different among the different vegetation pool and LULC types ($p < 0.05$) (Table II). The highest vegetation C stock was recorded in C3 (13.13 tons ha^{-1}) followed by SL (12.75 tons ha^{-1}). The least C stock was recorded in C1 (4.41 tons ha^{-1}) (Table II). The results showed that LULC type coupled with the influence of size of trees have a significant effect in its ability to store C. The highest vegetation C stock found in C3 could be the result of higher tree density with relatively large sizes compared to BL and SL.

The above-ground C pool of the different LULC types stored the highest C in the vegetation pools of the LULC types except for SL, which stored more C in the undergrowth pool. C3 had the highest C stock (9.91 tons ha^{-1}), while the least C stock was recorded in BL (1.53 tons ha^{-1}) (Table II). Although there is no significant difference between C3 and SL LULC types (Table II), C3 had a higher above-ground C stock compared to SL with the highest tree density ha^{-1}, indicating the presence of more C in less number of trees of larger size. High tree density and high number of larger diameter trees contribute to high biomass and consequently, higher C accumulation (Kuyah *et al.*, 2014). In addition, studies have shown that above-ground C stored in an ecosystem varies based on several other factors such as vegetation type, age, management practices, human and natural disturbances (Woldemariam *et al.*, 2011; Tilahun *et al.*, 2015). However, the above-ground C stocks of the LULC types were found to be lower (Table II) than those reported in the AF systems in South-eastern Ethiopia (81.6-135.6 tons ha^{-1}) by Negash (2013), but in line with the findings of Henry *et al.* (2009), a study conducted in AFs in the highlands of Kenya. A relatively greater amount of C (+4.61tons ha^{-1}) was found in the dominant undergrowth plants of BL compared to SL (Table II). The amount of C stock in the undergrowth of the BL (5.71 tons ha^{-1}) is slightly close to that reported by Gibbon *et al.* (2010), where grasslands near the tree-line were found to store 7.5 ± 0.7 tons C ha^{-1}. However, the total C stock is lower than the results of Lasco *et al.* (2001) which found that on average, grasslands has a C stock of 12.1 tons ha^{-1}. The total vegetation C stocks of the LULC types are within the range (4.5-19 tons ha^{-1}) accounted for AF systems in Sub-Saharan Africa in Unruh *et al.* (1993) and lower than the range (29-53 tons ha^{-1}) reported in humid tropics of Africa (Albrecht and Kandji, 2003). In general, the disproportionate distribution of biomass and C stocks across the plots evaluated in this study is attributed to the heterogeneity of trees in terms of species diversity, stocking levels and more importantly, tree size.

3.3 Carbon stock potential of soil in the LULC types

The C stock potential was significantly different at different soil depths and LULC types ($p < 0.05$) (Table III). The highest soil C stock was recorded in BL (19.21 tons ha^{-1}), while the

LULC type	Mean tree density/plot	DBH Range (cm)
BL	23	2.5-33
C1	7	3.4-59.24
C2	29	2.9-56.6
C3	74	4.8-45.86
SL	245	2.5-20.6

Table I. LULC types, tree density/plot and DBH range least was recorded in C1 (10.06 tons ha^{-1}) (Table III), indicating that the rehabilitation of croplands through conversion to tree-based systems may result in increased net C sequestration (Hairiah *et al.* (2011). This finding is also sustained in Aynekulu (2003) in that different LULC types have different SOC stocks.

The C stock showed a decrease with increasing soil depth (Table III). According to World Bank (2012), the potential C sequestration is controlled primarily by pedological factors such as soil depth, texture and clay mineralogy that set the physical and chemical maximum limit to storage of C in the soil. The soil C stocks of the LULC types are lower than that reported for a semi-arid woodland dominated with *V. etbaica* in southern Ethiopia (43 tons ha^{-1}) (Lemenih and Fisseha, 2004). It is also found to be lower than the 27 tons ha^{-1} reported in AF systems in Central India (Swamy and Puri, 2005). These differences could be as a result of climate (such as temperature, rainfall pattern and intensity), topography and soil type.

The high soil C potential of BL (comprizing areas dominated by grass and herbs cover) is likely because of a direct proportion of high organic matter resulting from the high dominant undergrowth as observed from the high undergrowth C stock (Table II). High surface cover by grasses and herbs increased the rate of infiltration, and hence reduced runoff production and caused less erosion. Vesterdal and Leifield (2010) found that higher residue inputs and reduced turnover were associated to higher C potential. The least C stock in C1 could be attributed to the low vegetation density and coverage, thus less accumulation of soil C. In addition, bare and tilled soils increase the aeration, alter the temperature and moisture of the topsoil, and, thus, often accelerate soil organic matter decomposition rates (Balesdent *et al.*, 2000). Therefore, the plausible reasons for the variations in soil C could be dominant vegetation species in LU types, age of trees, tree density and quantity of litter fall.

Table II.
Carbon stock potential in tons per hector of different pools and LULC types ($n = 24$)

C pool	BL	C1	C2	SL	C3
Aboveground C	1.53^{b} ± 0.93	3.23^{b} ± 1.85	7.89^{a} ± 0.87	8.47^{a} ± 2.08	9.91^{a} ± 1.52
Belowground C	0.41^{b} ± 0.25	0.87^{b} ± 0.50	2.13^{a} ± 0.23	2.29^{a} ± 0.56	2.68^{a} ± 0.41
Undergrowth C	5.71^{a} ± 0.52	n/a	n/a	1.10^{b} ± 0.16	n/a
Litter C	0.95^{a} ± 0.14	0.31^{c} ± 0.11	0.51^{bc} ± 0.05	0.88^{a} ± 0.23	0.54^{bc} ± 0.18
Total (tons/ha)	8.60^{B} ± 1.37	4.41^{C} ± 2.43	10.53^{AB} ± 1.09	12.75^{A} ± 2.37	13.13^{A} ± 1.84

Notes: Values are mean ± standard deviation C stock per LULC types. Within a row, different lower and uppercase letters are significantly different at $P < 0.05$ among LULC types. Abbreviation: n/a – not available, BL – bushland, C1 – intensively cultivated land, C2 – moderately cultivated land, SL – shrubland, C3 – sparsely cultivated land **–** means that nothing was recorded

Table III.
Soil C stock (ha^{-1}) of different depths and LULC types ($n = 72$)

Soil depth	BL	C1	C2	SL	C3
0-10cm	19.89^{a} ± 5.20	10.59^{a} ± 1.13	13.84^{a} ± 0.94	14.47^{a} ± 2.67	14.75^{a} ± 2.74
10-20 cm	19.35^{a} ± 3.61	10.21^{a} ± 1.54	12.95^{a} ± 0.83	13.54^{a} ± 2.80	14.02^{a} ± 2.47
20-30 cm	18.38^{b} ± 3.30	9.38^{b} ± 1.31	11.47^{b} ± 1.43	12.20^{b} ± 2.10	13.35^{b} ± 1.92
Total	19.21^{A} ± 3.79	10.06^{C} ± 1.35	12.75^{B} ± 1.44	13.41^{B} ± 2.54	14.04^{B} ± 2.30

Notes: Values are mean ± standard deviation C stock per soil depth. Within a column, different lowercase letters are significantly different at $P < 0.05$ between soil depths. Within a row (Total), different uppercase letters are significantly different at $P < 0.05$ between LULC types. Abbreviation: BL – bushland, C1 – intensively cultivated land, C2 – moderately cultivated land, SL – shrubland, C3 – sparsely cultivated land

These opinions are supported by Lal (2004), Montagnini and Nair (2004), Nair *et al.* (2009) and Soto-Pinto *et al.* (2010).

3.4 Total carbon stock potential of the different LULC types

The total C stock of the system (TC_{system}) was significantly different across LULC types ($p <$ 0.05). The TC_{system} ranking of the LULC types followed the order BL (27.81 ± 3.90 tons ha^{-1}) > C3 (27.17 ± 2.46 tons ha^{-1}) >SL (26.15 ± 4.02 tons ha^{-1}) > C2 (23.28 ± 0.78 tons ha^{-1}) > C1 (14.48 ± 3.05 tons ha^{-1}) (Figure 2).

Overall, higher stocking levels of trees (denser stands) enhanced the total C stock. The trend of the total C stock shows that soil C stock contributed more than vegetation C stock (Figure 2). This finding is in line with the result of Negash (2013), where an average of about 66 per cent of the total soil C was recorded at 0-30 cm in three AF systems. As previously stated, the overall C stock of the LU types is found to be a function of tree density, the dominant vegetation species and tree size. According to Hairiah *et al.* (2011), the amount of C that could be sequestered from conversion of a crop land to a tree-based LU would range from 5 to 60 tons ha^{-1} above ground and 5 to 15 tons ha^{-1} in the topsoil over a 25 year period.

3.5 Carbon sequestration potentials of LULC types

The amount of CO_2e sequestered in the study area were 102.06 tons CO_2eq ha^{-1}, 99.71 tons CO_2eq ha^{-1}, 96.01 tons CO_2eq ha^{-1} and 85.44 tons CO_2eq ha^{-1} for BL, C3, SL and C2. C1 had the lowest CO_2eq ha^{-1} recorded (53.14 tons CO_2eq ha^{-1}) (Figure 3). The highest difference in potential C sequestration of the LU types was observed between BL and C1 (48.92 tons).

From the analysis in the study area's AF systems, it can be affirmed that change from a LU with less permanent vegetation cover to one with a substantial permanent vegetation cover has a great potential of C sequestration. Therefore, the development and good management of AF could contribute to enhancing the role of C sequestration which can lessen the negative impacts of climate change and ultimately may have a positive impact on

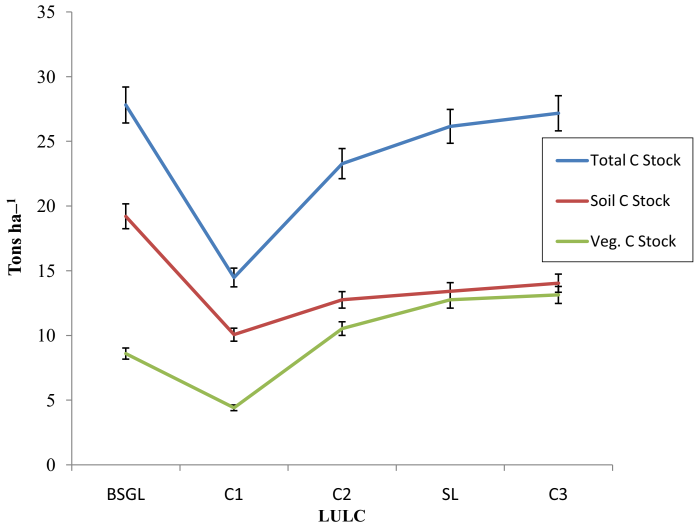


Figure 2.
Total carbon stock in tons ha^{-1} of different LULC types

sustainability of the agroecosystem. Studies like that of Burschel *et al.* (1993) and Woodbury *et al.* (2006) reported that regeneration and afforestation activities have a major C sequestration potential.

3.6 Carbon trading potentials of LULC types

C1 had the least C trade potential (US\$143.48 ha^{-1}), while BL had the highest C trade potential (US\$275.56 ha^{-1}) (Table IV). The difference between the highest and the least potential LULC types was US\$132.08 ha^{-1}.

The intent of CDM is to augment the revenue streams of C sequesters, thereby enhancing the economics of clean projects and incentivizing more such projects to be undertaken. The estimated C trade potential of the AF systems imply that LULC change to AF systems in the study area have resulted in an increased C trade opportunity through C sequestration. This is, therefore, an indication that besides the environmental services, AF systems such as those of Zongi could serve as a source of income from C trading. As opined by Sireh-Jallow (2010), if Ethiopia could reduce the rate of deforestation by about 50 per cent, and engage in C trade, then it stands to enjoy a potential fiscal space of about US\$141 million, which is about 0.63 per cent of GDP. Directly, this would help to diversify the income of the farmers, improve their standard of living and overall sustainability of the system.

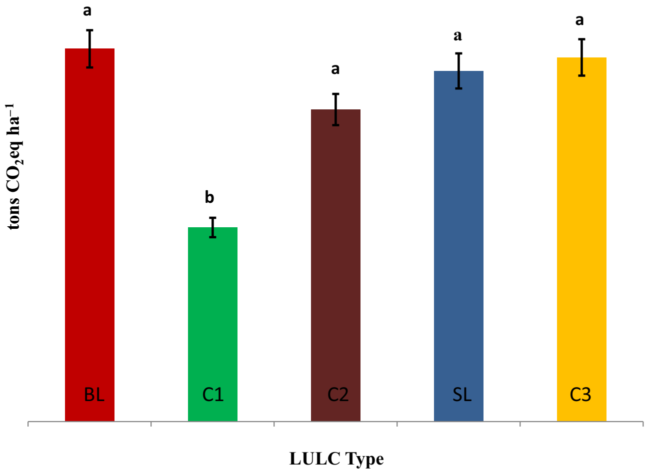


Figure 3.
Showing carbon sequestered (tons CO$_2$eq ha^{-1}) per LULC type

Table IV.
Effect of LULCC on carbon trade potentials and opportunities

Item	BL	C1	C2	SL	C3
Price (US\$/ha)	408.24	212.56	341.76	384.04	398.84
Price[a] (US\$/ha)	275.56	143.48	230.69	259.23	269.22

Notes: [a]Discount given at a rate of 8.1% for 5 years. Abbreviations: BL – bushland, C1 – intensively cultivated land, C2 – moderately cultivated land, SL – shrubland, C3 – sparsely cultivated land, BL/ROC – bare land/rock-outcrop, WB/C – water body/course

3.7 The spectral connection between spatially explicit sequestered carbon and selected vegetation indices

The vegetation indices were significantly correlated with field soil C and total C data (Table V). The values of the NDVI and SAVI varied in magnitude, but the same correlation (r) and p-value results were obtained. The coefficient of correlation (r) of soil and total C was 0.729 and 0.559 ($p < 0.01$), respectively. No significant correlation was observed between the indices and vegetation C. However, this does not imply that there is no relationship. For instance, in BL there existed a relatively higher dense vegetation that contributed to higher spectral reflectance, but the biomass per unit area was relatively smaller.

On the basis of the C indices, the results of the analysis showed that there were meaningful relationships with the soil C and the total C stock of different LULC types of the study area and a positive relationship with vegetation C, although not significant. The main reason for the better correlation observed for the soil C is that the dominant vegetation species and species composition could have contributed to a higher C. Another factor is the presence of higher vegetation C stock in areas with sparse vegetation but with bigger trees compared with more dense areas. These results are in line with the findings of Aynekulu (2003), in which vegetation indices could not explain vegetation biomass stock. A similar result was obtained in Ghana that showed no relationship with total C stock and vegetation indices (Tutu, 2008). This could be because of several factors, which cannot be concluded in this study. However, one of these several factors (including the ones aforementioned above) in Yuhong *et al.* (2012) could be seasonal variations.

4. Conclusion

A transition from intensively cultivated and degraded land to smallholder AF systems led to substantial gains in the C stock. The C stock in different C pools has a potential to decrease the rate of enrichment of atmospheric concentration of CO_2. C3 had the highest vegetation C, and C1 had the least vegetation and soil C. The highest soil C was observed in BL. However, the total amount of C sequestered largely depended on the tree density of the LU type and the vegetation composition. This study concludes that the LULCC to AF systems has significantly improved the vegetation and soil C of the study area. Positive changes in the LULC type of the study area demonstrated the potential of AF systems to offer the environmental service of C sequestration and C trading. The reflectance of the sampled plots showed to be dependent on the greenness of an area irrespective of the vegetation composition. Although vegetation indices NDVI and SAVI could not well explain the vegetation C, soil C and total C showed a relatively higher significant linear relationship with vegetation indices. This result provides useful and practical information for further research in the application of remote sensing data for C accounting. The study recommends that relevant authorities should develop strategies to promote these good practices of AF.

Vegetation index		C pool	*r*	Significance
NDVI	SAVI	Vegetation biomass C	0.133	0.535
NDVI	SAVI	Soil C	0.729	0.000*
NDVI	SAVI	Total C	0.559	0.005*

Note: *Significant at 0.01 level

Table V. Relationship between C stock and vegetation indices (NDVI and SAVI)

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