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“Ecosystem Services of the Indigenous Agroforestry Systems in the South-eastern Rift- valley Landscapes, Ethiopia: Plant diversity, Carbon pools, Soil Fertility and Local Livelihoods’ Support’’

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Submitted by

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Declaration

I, the undersigned, hereby declare that this is my original research work and all the resources and materials used are duly acknowledged. This work has not been submitted to any other educational institutions for achieving any academic degree awards.

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Abstract

The role of agroforestry systems in providing multiple ecosystem services and other socio-economic benefits is very crucial. Despite some studies related with management of AF practices, component interaction and carbon stocks little attention has been paid to plant diversity conservationn, carbon stocks and soil fertility with monocrop as a control and litterfall contribution at stand level of AF systems in the study area. The study was aimed to investigate plant species diversity, carbon pools, compare soil nutrient availability of AF systems versus their adjacent monocrop farms, litterfall biomass production and associated nutrients and the contribution of the system for local livelihoods' support. Enset based, Enset-coffee based and Coffee-Fruit tree-Enset based AF system were the three indigenous AF on which our study was focused. The study was conducted in the South-eastern Rift-Valley landscapes of Ethiopia. 20 farms representative of each AF system were randomly selected and 10 adjacent mono-cropping farms for each AF farm were selected in purposive manner for comparison. Inventory of the floristic diversity, taking of soil, litter and litterfall samples were employed in the 10×10 meter farm plot. Biomass C stocks of trees and shrubs, Enset, Coffee, herbs, fine roots were estimated by adopting different allometric equations. Data needed for the livelihood part were collected through a standard structured questionnaire administered to 160 household heads through face-to-face interviews, key informants' interviews and focus group discussions. A total of 52 perennial woody and non woody plant species belonging to 30 families were recorded. Of all species identified, 63.5% were native and two species were registered as endemic. The highest proportion of native species was recorded in Enset based AF (93.3%) and the least was in C-Ft-E based AF (59%). Acccording to IUCN Red Lists and local criteria, 13 species were recorded as of interest for conservation in all AF systems. Prunus africana was identified as both vulnerable by IUCN Red Lists and rare for 25% of species that least occured. The mean AGB ranged from 81.1 t ha^{-1} to 255.9 t ha^{-1} and for BGB from 26.9 t ha^{-1} to 72.2 t ha^{-1}. The mean above and below ground biomass values of the present study are higher than reported for AF systems of South-eastern Ethiopia and some other tropical AF ssystems. The highest total AF C stock was found in C-Ft-E based AF (233.3±81.0 t ha^{-1}) and the least was in E-C based AF system(190.1±29.8 t ha^{-1}). The C stock values of our AF systems are substantially higher than those of tropical forests and other AF systems. Addition of biomass prunings and root turnover in AF systems have contributed to the development of soil organic matter and nutrient stocks. Withincreasing soil depth an increasing of pH in both H_2O and $CaCl_2$ could be observed while the values of CEC and BS% decreased. The concentration of extractable Ca^{2+}, K^+, Mg^{2+} as well as OM%, SOC and TN under AF systems were significantly higher than the adjacent monocrop farms. The average annual litterfall production was 5.87 t ha^{-1} yr^{-1}. Mean monthly litterfall production was affected by climatic factors such as temperature, rainfall, wind and humidity. C-Ft-E based AF system in the study provided the households with diversified benefits such as source of cash income (from high value crop sale, fruit and timber), household consumption, traditional medicine and employment opportunity. The result of the regression model showed that household income was significantly affected by predictors such as land holding, off-farm income, family size and household expense.

Key words*:* Diversity, Soil fertility, Carbon pool, litterfall, Indigenous agroforestry system, Coffee, Enset, livelihood

Zusammenfassung

Die Rolle von Agroforstsystemen bei der Bereitstellung mehrfacher Ökosystemleistungen und sozioökonomischer Vorteile ist von entscheidender Bedeutung. Trotzdem in einigen Studien der Zusammenhang zwischen dem Management von AF-Systemen, den Wechselwirkungen zwischen ihren Komponenten und den Kohlenstoffvorräten untersucht wurde, ist bisher der Erhaltung der Pflanzenvielfalt, den Kohlenstoffvorräten und der Bodenfruchtbarkeit im Vergleich mit einfachen Feldfruchtmonokulturen ebenso wenig wurde auch der Beitrag des Bestandesstreufalls in der AF-Systeme im Untersuchungsgebiet untersucht. Ziel der Studie war es, die Artenvielfalt von Pflanzen, Kohlenstoffpools, die Nährstoffverhältnisse in den Böden der AF-Systeme im Vergleich zu den angrenzenden Feldfruchtmonokulturen, die Produktion von Streufallbiomasse und die damit verbundenen Nährstoffe sowie den Beitrag des Systems zur Erhaltung der lokalen Lebensgrundlagen zu untersuchen. Enset-basierte, Enset-Kaffee-basierte und Kaffee-Obstbaum-Enset-basierte AF-Systemen waren die drei indigenen AF-Systeme, auf die sich unsere Studie konzentrierte. Die Studie wurde in den südöstlichen Rift-Valley-Landschaften Äthiopiens durchgeführt. 20 Betriebe, die für jedes AF-Systemen repräsentativ sind, wurden zufällig ausgewählt, und 10 benachbarte Monokulturbetriebe für jeden AF-Betrieb wurden zum Vergleich gezielt ausgewählt. Das Inventar der floristischen Vielfalt, der Bodenproben und anderer Parameter (z.B.Biomasse Makrnährstoffe u.a.) wurden auf dem 10×10 Meter großen Probeflächen in den landwirtschaftlichen Betrieben untersucht. Die Biomasse-C-Vorräte von Bäumen und Sträuchern, Enset, Kaffee, Kräutern und feinen Wurzeln wurden unter Verwendung verschiedener allometrischer Gleichungen geschätzt. Die für Untersuchungen des Lebensunterhalts benötigten Daten wurden mithilfe eines strukturierten Standardfragebogens gesammelt, der von 160 Haushaltsvorständen in persönliche Interviews, oder Interviews mit Schlüsselinformanten und Fokusgruppendiskussionen beantwortet wurde.

Insgesamt wurden 52 mehrjährige holzige und nicht holzige Pflanzenarten aus 30 Familien erfasst. Von allen identifizierten Arten waren 63,5% einheimisch und zwei Arten wurden als endemisch registriert. Der höchste Anteil an einheimischen Arten wurde im AF-System auf Enset-Basis (93,3%) und der geringste im Kaffee-Obstbaum-Enset-AF-System mit 59% verzeichnet. Gemäß den Roten Listen der IUCN und lokalen Kriterien wurden 13 Arten in allen AF-Systemen als für die Erhaltung von Interesse erfasst. Prunus africana wurde sowohl nach den Roten Listen der IUCN als gefährdet eingestuft als auch zu den 25% der am seltensten lokal vorkommenden Arten gezählt. Die mittleren oberirdischen Biomassenvorräte (AGB) lagen zwischen 81,1 t. ha^{-1} und 255,9 t. ha^{-1} und für die unterirdischen Biomassenvorräte (BGB) zwischen 26,9 t.ha^{-1} und 72,2 t.ha^{-1}. Die mittleren ABG- und BGB Biomassewerte der vorliegenden Studie sind höher als für andere AF-Systeme im Südosten Äthiopiens und einige andere tropische AF-Systeme. Der höchste Gesamt-AF-Kohlenstoff-Vorrat wurde in Kaffee-Obstbaum-Enset-basiertem AF (233,3 ± 81,0 t.ha^{-1}) und der geringste in Enset-Kaffee-basiertem AF-System (190,1 ± 29,8 t.ha^{-1}) gefunden. Die Kohlenstoff-Vorräte der untersuchten AF-Systeme sind wesentlich höher als die von manchen Tropenwäldern und anderen AF-Systemen. Der Eintrag von Biomasse aus dem Baumschnitt und der Wurzelumsatz in den AF-Systemen haben zur Steigerung der organischen Substanzen und der Nährstoffbeständen im Boden beigetragen. Mit zunehmender Bodentiefe steigen die pH-Werte, sowohl in H_2O als auch in $CaCl_2$, während die Werte für CEC und BS% abnehmen. Die Konzentrationen von austauschbarem Ca^{2+}, K^+, Mg^{2+} und auch OM%, SOC und Gesamtstickstoff (TN) waren im Vergleich zu den Böden unter den Feldfrucht-Monokulturen signifikant höher. Der durchschnittliche jährliche Streufall betrug 5,87 t ha-1 $Jahr^{-1}$. Die Masse des durchschnittlichen *monatlichen Streufalls wurde durch klimatische Faktoren wie Niederschlag, Wind und Luftfeuchtigkeit beeinflusst.*

Das auf Kaffee-Obstbaum-Enset basierende AF-System in der Studie bot den Haushalten vielfältige Vorteile wie Einnahmequellen (aus dem Verkauf hochwertiger landwirtschaftlicher Produkte, sowie Obst und Holz), Deckung des Haushaltskonsums, Heilmittel für traditionelle Medizin und Beschäftigungsmöglichkeiten. Das Ergebnis des Regressionsmodells zeigte, dass das Haushaltseinkommen signifikant von Prädiktoren wie Landbesitz, Einkommen außerhalb der Landwirtschaft, Familiengröße und Haushaltskosten beeinflusst wurde.

Schlüsselwörter: Biodiversität, Bodenfruchtbarkeit, Kohlenstoffpool, Streufall, indigenes Agroforstsystem, Kaffee, Enset, Lebensunterhalt

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1. INTRODUCTION

1.1 Background and justification

It is impossible to find a land on earth where plants do not exist. Some reports showed that there are about 1 million plant species in the world out of which 20% are threatened with extinction (Davis *et al*. 2014). People know the importance of plants in depth because of their daily interrelationship with them (Omer, 2010). It is a well-known fact that the oxygen that human beings breath in comes from plants and life without plant is impossible (Hooper and Vitousek, 1997). In most cases there is damaging and destruction of plant resources without considering for future generations although there are some initiatives to plant and grow plants in degraded areas (Kenrick and Crane, 1997). As scholars mentioned the consequences of the destruction of plant resources in our planet are extremely complex and harming human lives (example: global warming and climate change (Parmesan and Yohe, 2003; Lau and Tiffin, 2009).

In the atmosphere the concentration of CO_2 and other greenhouse gases (GHGs) has considerably risen over the last century and further increase can be expected. The accumulation of carbon dioxide in the atmosphere has been with a rate of 3.5 Pg (Pg = 10^{15} g or billion ts) per annum and from this, burning of fossil fuels and the conversion of tropical forests to agricultural lands accounting the largest proportion (Paustian *et al*. 2000). Increasing levels of atmospheric `greenhouse gases' (CO_2, CH_4, N_2O, water vapor, HFCs, O_3) are generally accepted to be a main contributer to global warming; which is changing the Earth's weather patterns and could raise ocean levels substantially in the next 100 years. These climatic changes can impact environmental conditions and human populations, causing serious disturbance to ecosystems, livelihoods and the economy. Land use changes through especially deforestation and land degradation have often contributed substantially to the rising level of CO_2 in the earth's atmosphere (IPCC, 2007; Nair *et al*., 2009).

One of the best strategies for mitigation of CO_2 concentration in the atmosphere is increasing the size of the global terrestrial sink. Shifting from land-use systems with less biomass stocks (for example, grasslands, agricultural fallows) to tree-based systems such as forest conservation, sustainable forest management, afforestation/reafforestation and agroforestry systems which could bring a significant increase in biomass and consequently in higher C storage. This is because tree-based systems have a higher biomass lifespan than grass-based systems. Under the Kyoto Protocol's Article 3.3, A and R (afforestation and reforestation) with agroforestry as a part of it has been recognized as an option for mitigating greenhouse gases (Nair *et al*., 2009). For funding organizations who are looking for certified emissions reductions' having the Clean Development Mechanism (CDM) of the Kyoto Protocol is a good opportunity. Because of this, CDM offers golden opportunity for funding organizations and supporters to make investments in emerging countries. The objective of this investment in developing countries is to reduce greenhouse gas emission and to contribute something that brings sustainable development. Zomer *et al*. (2016) reported that, the earth's area that is appropriate for practicing agroforestry is approximately 222×10^7 ha and if agroforestry systems are turned into effect on these suitable areas more than 55.3 billion t C could be stored in the terrestrial ecosystems over the next 50 years.

Extended rotation agroforestry systems such as agroforests, homegardens and boundary plantings can sequester considerable quantities of C in plant biomass and in long-lasting wood products. Agroforestry also contributes to emission reduction through provision of goods and services. This could help to reduce pressure on natural forest since practitioners tend to use goods and different services from their farm instead of harvesting from the natural forest (Gupta *et al.*, 2009). Carbon sequestration potential of agroforestry systems differes among different agroecological landscapes. As a result, carbon storage potential of agroforesty is estimated to 9, 21, 50, and 63 t C ha^{-1} in semiarid, sub humid, humid, and temperate regions (Montagnini and Nair, 2004). Extensive reviews by Luedeling and Neufeldt (2012) for West African sahel countries (from arid Sahara desert to humid region Guinea) showed biomass C stocks ranging from 22.2 to 70.8 t C ha^{-1}.

Species composition of agroforestry systems, age, geographical location (Jose, 2009), previous land use (Mutuo *et al.*, 2005; Sauer *et al*. 2007), climate, soil characteristics, crop-tree mixture, and management practices (Pandey, 2002; Dossa *et al.*, 2008; Schulp *et al.*, 2008) are some of the factors that drive for variation in C sequestration potential of these systems. In addition to accumulating C in the biomass agroforestry systems have a potential to store carbon in the soil. The amount of soil organic carbon (SOC) in agroforestry systems differs with region, agroforestry system and soil depth (Nair *et al.*, 2011). Litterfall also contributes to C stock accumulation in the soil. It is the most important known pathway connecting vegetation and soil, and is a good indicator of aboveground productivity (Köhler *et al.*, 2008). Breymeyer *et al. (*1996) and Liu *et al.* (2004)

revealed, litterfall amount and quality varies with stand characteristics (tree size, species, foliar biomass and age), geographic location (climate), site, season, management practice, pest and pathogens

Agroforestry may not only be considered for its potential to sequester greater amounts of carbon but it can also often increase biodiversity through the integration of trees, shrubs, crops and/or animals into the system. It contributes to biodiversity conservation through: arranging and providing additional supportive habitats for species that do not tolerate high levels of disturbance (Jose, 2009); by conserving gene pools of native tree species in fragmented landscapes (Das and Das, 2005; Harvey and Gonzalez-Villalobos, 2007); playing an important role in increasing microbial, avian and faunal diversities (Gillespie *et al*., 1995; Schultz *et al*., 2000); soil conservation and allowing water to recharge, thereby preventing habitat degradation and habitat loss; protecting against the pressure on forest degradation and deforestation in the surrounding natural habitat; and construction of a corridor and stepping stones for perseverance of floral and faunal species through connecting different fragmented habitats in the landscape (McNeely and Schroth, 2006; Bhagwat *et al.*, 2008; Jose, 2009). Therefore, the definition given by ICRAF (2000) confirms the above mentioned main points which is, "Agroforestry is an ecologically based natural resource management system that integrates trees (for fibre, food and energy) with crop and/or animal on farms with the aim of diversifying and sustaining income and production while maintaining ecosystems".

It is known that, agroforestry systems have components that make up the system and perennial woody tree species are the pillar. Woody tree species have extensive root systems that enable them to accumulate large quantities of above and belowground biomass compared to seasonal and/or annual crops. Decomposition and nutrient release, addition of litter, biological nitrogen fixing, pumping of nutrients from deeper soil layers and protecting from nutrient loss are some of the vital processes that have significant contribution for sustainable farm production (Sarvade *et al*., 2014). Integrating cash crops in an agroforestry system additionally also gives an opportunity for better utilization of land, maintaining the health of tropical soils in terms of biological property, chemical property and physical property (Arevalo-Gardini *et al.*, 2015). Studies conducted by Yadav *et al.* (2011) reaveled that, under different agroforestry systems there is a significant and substantial improvement in soil biological activity in terms of nitrogen, phosphorus, microbial biomass carbon, dehydrogenase and alkaline phosphatase activity as compared to cropping with out incorporating trees and shrubs.

Communities around the world have developed diverse agroforestry practices to meet their household needs by combining trees, crops and livestock in their farming practices. The effective farm activities could be based on research findings gained by different scholars or it could be from indigenous knowledge (Walker *et al.*, 1995; Miller and Nair, 2006). Comparing agroforestry systems and subsistence agriculture, agroforestry systems provide more benefits than the subsistence agriculture. This could be in terms of generating cash income from selling of multiple products gained from the system (Kalaba *et al.*, 2010). Agroforestry systems also provide multiple products for smallholder farmers such as fruit and nuts, fuel wood, timber, medicine, fodder for livestock, green manure, gum, resins, spices and other additional/diversified products (Raj and Chandrawanshi, 2016). These are believed to improve the livelihoods of small marginal farmers (ICRAF, 2013).

Agroforestry practices in the tropics and sub-tropics are an old aged activity by the farming communities. Although it is difficult to know the exact year when agroforestry practices were started, some scholars reported that it could be probably as old as agriculture itself (Atta-Krah *et al.*, 2004; Kumar and Nair, 2004; McNeely and Schroth, 2006). In Ethiopia, the integration of trees and shrubs into agriculture emerged some 7000 years ago (Brandt, 1984; Edmond *et al.*, 2000) and the practice has developed into a number of distinguished indigenous agroforestry systems during subsequent millennia (Getahun, 1974; Kanshie, 2002).

The area of agroforestry systems in Ethiopia is not well documented, but some 2.32 million ha are considered as agroforestry landuse according to some estimates and based on satellite imagery for the base year 2006 (Brown *et al.*, 2012). The figure did not include scattered trees on crop and grazing lands. The latest estimate by Franks *et al*. (2017) puts the agroforestry area cover to 6 million ha and is projected to increase to 16 million ha by 2020.

1.2 Rationale of the study

Agroforestry practice in Gedeo zone of southern Ethiopia is known as old aged and indigenous in nature. Gedeo agroforests are also a well-known land-use system and it is believed to have selfsustaining and self-regulating attributes compared to other land-use system in the area (Kanshie, 2002). Since the Ethiopian government has recognized agroforestry as an important land use practice it has been included as extension package in the rural development strategy for the country (MoARDE, 2005). Under this strategy, the main focus is on sustainable utilization of natural resources and maximizing the resource base, diversifying sources of income and lessening the risk of production failure, enhancing land productivity on a sustainable basis and protecting the environment in such a way that it is integrating working on the ecological aspect of the landscape as whole.

Studies have been conducted by different scholars in Ethiopia (Kanshie, 2002; Negash *et al*. 2005; Asfaw and Agren, 2007; Negash, 2007; Abebe, 2013) on the area of management of indigenous agroforestry practices, component interaction of agroforestry systems and determinants for diversity and composition in agroforestry and additional ecosystems services of agroforestry systems in Gedeo zone and in other locations. Besides, a study was conducted by Negash (2013) and Seta and Semssew (2014) on carbon stocks of indigenous agroforestry systems and litterfall production of selected woody tree species. However, the study conducted by Negash (2013) on litterfall was concentrated on species effects while the present study opted to investigate stand level litterfall contribution and associated macro nutrient inputs of Enset based, Coffee-Enset(C-E) based and Coffee-Fruit tree-Enset (C-Ft-E) based agroforestry (AF) systems. Moreover, this study evaluated carbon stocks for monocropping systems as control, which was lacking in the previous study in the same site (Negash *et al*., 2013). A study of soil physico-chemical properties of the three agroforestry systems and comparing with monocropping farms as control was also conducted, which was lacking in the prevous study in the same site. The study on the contribution of Coffee-Fruit tree- Enset based agroforestry system in enhancing the livelihood of the community was also limited and remains unexplored in the study area despite a study conducted by Adane *et al*. (2019) in neighboring Sidama zone of Ethiopia. Therefore, studying the role of these three indigenous agroforestry systems for biodiversity conservation and carbon sequestration, soil fertility improvement and livelihood enhancement of the community is very important for proper management and sustainable production of the system.

2. LITERATURE REVIEW

2.1 Three indigenous agroforestry systems as concern of the study

2.1.1 Enset based agroforestry

Enset (*Ensete ventricosum*) based agroforestry systems are common in central, south-western and southern Ethiopia (Asfaw, 2003; Abebe, 2005; Tesemma, 2007). The area share of Enset in this systems could be approximately with range of 60-70% depending on the composition of other plant species. Enset is one of the species under the category of the Musaceae family, which is also commonly known as false Banana. This perennial species is native and domesticated as one of the important crops in Ethiopia. Because of having an edible pseudo stem and an starchy underground corm, the households use Enset as staple food and it is consumed as food only in Ethiopia. The community not only used it for food but also as fooder for their livestock , wrapping material and fibre. The growth habit of the plant could be either monocrop plantation or mixed with other crops with a rotation period of 3 to 15 years (Brandt *et al.*, 1997; Zewdie *et al.*, 2008). The rotation age to bear flowers and then set seed could be 9 or more years (Bizuayehu, 2008). Brandt *et al.*(1997) reported that, it is not well known when domestication of enset was exactly started in Ethiopia but it is believed that it has been used in the Ethiopian highlands for more than 5000 years. An estimated area of Enset cover in Ethiopia to nearly 300,000 ha, yielding approximately 4.4 million metric ts per annum and feeding approximately 20% of the total population of the country (Shank and Ertiro 1996; Tsegaye and Struik, 2001; Negash and Niehof, 2004).

Enset is among homegarden crops known for its high energy content (Abebe and Bongers, 2012). Enset makes a great contribution to food security and stability of the community. This is because Enset products could be stored for long time and the plant itself could be maintained on farm until it is needed and harvested (Negash, 2001; Tsegaye, 2002). As a result of this, Enset producing areas could be less exposed to famine (Rahmato, 1995).

Enset not only provides economic benefits to the farmers but it gives also a significant environmental services. For instance micro-climate amelioration, addition of nutrients through litterfall and hence improving the soil fertility, protection of the soil from water erosion and runoff hazard are some of the environmental services. One of the good things related with nutrient addition to the soil is, when Enset is harvested most of the biomass remains in the system because the leaves and all the other unedible part of the Enset corm returned directly to the soil as left over (Negash, 2001; Tsegaye, 2002). A study conducted on Enset based agroforestry system in the Gedeo by Negash and Starr (2015) revealed that, in its above and below ground biomass including herbaceous plants, litter and soil, the total carbon stock of the system was 232.8 t C ha^{-1}. Enset production also has sociocultural values and plays a role for ritual offerings, medicine, compensation for payment, as part of farmers' cultural heritage and for claiming ancestoral lands in southern Ethiopia (Goldthorpe, 1967; Negash, 2001).

Several studies were conducted on production and the management of Enset in Southern Ethiopia (Negash, 2001; Tsegaye, 2002; Bizuayehu, 2008). One of the important attributes of Enset within the agroforestry system is, it enables sustainable agricultural production with low inputs and high quantity yields. For instance, it supports as high as 1300 persons/km^2 in Gedeo, Southern Ethiopia (Negash and Achalu, 2008). In addition, the plants hardly demand external inputs and thus, saves production costs in general.

2.1.2 Coffee-Enset based agroforestry

The Coffee-Enset based agroforestry (C-E based AF) system is one of the traditional agroforestry homegardens in Southern Ethiopia (Abebe, 2005). The system is suitably practiced in an altitude range between 1,500 and 2,300 meter above sea level. In this altitude moisture and temperature conditions are expected to be conducive for these agroforestry practices. The two dominant native perennial crops, namely Enset and Coffee together cover more than 60% area share of the agroforestry systems in Southern Ethiopia (Abebe, 2013). Enset is a staple food crop and Coffee serves as cash crop. Coffee also contributes more than 60% of export income in Ethiopia (Muleta *et al*., 2007; Labouisse *et al*., 2008). Owing to their great socioeconomic and ecological benefits in the farming system of the study area. Enset and Coffee can be considered as "key-stone" species in Southern Ethiopia agroforestry.

C-E based AF systems harbour several native woody species (*Cordia africana*, *Millettia forginea*, roots (Ginger, Sweet potato) and annual crops (Maize) favourably growing in intimate association with Enset and Coffee. The perennial woody species are growing in spatial and vertical configurations in this agrforesty system. Generally, these indigenous C-E based AF are all inclusive farm systems from which households get almost all their subsistence as well as cash needs (Abebe *et al.*, 2006). The average size of C-E based AF as homegarden in Southern Ethiopia is estimated to approximately 0.7 hectars per farmer. The systems can support a population of 500-1000 persons per km^2 (Abebe *et al*., 2010). Like other agroforestry systems, this system also maintains high species diversity which combines crops, trees and animals having different uses and production cycles. The perennial nature of major components helps in the recycling and efficient use of nutrients and thus contributes a vital role for successful sustainable agriculture. Maximazing the net benefits gained from agricultural production and from ecosystem services are the main goals of sustainable agriculture (Cassman, 1999; Tilman *et al.*, 2002; Fiorella *et al.*, 2010).

Sustainability of the indigenous C-E based AF mostly have three dimensions (Social, economic and ecological sustainability) that are integrated and have a meaningful importance for rural societies. To maintain the existing components of the agroforesty system and their productivity in a ready states is essential for its ecological and socioeconomic sustainability. For instance, conservation of the natural resource base in such a way that the farming of the agroforestry system can be possible and continued is more of the ecological sustainability. Whereas socioeconomic sustainability shows how the agroforestry system is suitable to provide products, goods and/or income for the livelihood of the people in a lasting way and its level of economic feasiblitiy and viability. (Pretty *et al*., 2003; Ojiem *et al.*, 2006; Peyre *et al.*, 2006; Holden and Linnerud, 2007; Olson and Neher, 2018).

Researchers tried to evaluate the ecological and socioeconomic sustainability features of the Enset-Coffee agroforestry and they give explanation about how their system needs to be scrutinized to guarantee sustainability. Some of features of the indigenous C-E based AF that are important for the ecological and socioeconomic sustainability include: i) Ensuring the diversity of species which in turn contribute to the conservation of genetic resources and species which are native to the area, ii) discouraging the application of inputs like chemical fertilizer and pesticides and instead encouraging the use of organic fertilizers like manure or compost, iii) soil conservation and soil maintenance and iv) further self-sufficiency and using materials that can be easily attained locally (Abebe *et al*., 2006). Generally, when indigenous C-E based AF systems are compared with other agricultural systems, it is strongly believed that the former are more ecologically sustainable (Trenbath, 1999; Pretty *et al*., 2003; Holden and Linnerud, 2007; Tesfaye and Bongers, 2012).

The other important feature of the C-E based AF system is its potential for sequestration of CO_2. As the study done in Gedeo zone of Southern Nations and Nationalities Regional State revealed that the mean C stock of total biomass (above- and belowground, and including herbaceous plants and litter) was the highest for the C-E system followed by the Fruit-Coffee base agroforestry system and the lowest for the Enset system (Negash and Starr, 2015). The area of C-E homegardens in Southern Ethiopia is not precisely known although there are some reports on the land areas where Coffee and Enset are grown in association with other plant species (such as fruits and vegetables, root and tuber crops and pulses).

2.1.3 Coffee-Fruit tree-Enset based agroforestry system

Multipurpose tree/shrub species, Coffee (*C. arabica L.*), Enset (*E. ventricosum)*, several fruits, annual crops, vegetables, medicinal plants and animal species are components of this agroforestry system. Under this type of indigenous agroforestry system, the Coffee, Fruit tree and Enset have the greater share and the remaining components such as vegetables, spices and livestock are still included (Asfaw *et al*., 2015). The proportion of Coffee, Fruit tree and Enset is estimated approximately from 20-25% for each species. In C-Ft-E based AF system the fruit trees (e.g. *Persea americana Mill., Mangifera indica L. Casimiroa edulis Lal Llave and Lex.*), Coffee and Enset are shaded by tree species such as *Cordia africana, M. ferruginea, Ficus Vasta* and *Ficus sur.* The understory consists of herbaceous crops, including *Zea mays L., Musa spp., Brassica oleracea L.* and *Ipomoea batatas (L.) Lam* (Mulugeta and Mabrate, 2017). A study conducted in Dilla Zuria district of the Gedeo zone of Southern Ethiopia in a specific study site called “Chichu” revealed that, total of 48 plant species were recorded in the C-Ft-E based AF. On average, about four to six plant species served as source of income and dietary diversification in one season of the year. Communities practicing such type of agroforestry system were self-sufficient in wood for energy and the fruit trees and Coffee accounted for 47% and 45% of their annual income respectively (Asfaw *et al*., 2015).

Like the other agroforestry systems Coffee-Fruit tree- Enset based agroforestry systems also has greater contribution in sequestering CO_2. A study conducted by Negash and Starr (2015) revealed that 256.3 t C ha^{-1} of total carbon stock was reported in the Fruit tree-Coffee agroforestry system of Gedeo zone, Ethiopia. Fruit tree-Coffee agroforestry systems have very less number of Enset but with several number of fruit trees and it is a bit similar to agroforestry systems selected for our study. Comparing with other reports of carbon stock of agroforestry systems this value was 17-36% higher than reported for six agroforestry systems in Chiapas, Mexico (Soto-Pinto *et al.*, 2010) and 50% higher than the highest C stocks reported for coffee system in Guatemala (Schmitt-Harsh *et al.*, 2012). Therefore, from the figure mentioned, one can understand that the C-Ft-E based AF system stores significant quantity of carbon. The contribution of trees and shrubs to the total biomass carbon stock differs across AF systems of the study area. For example, trees and shrubs contributed 80% in the Fruit-Coffee AF system whereas Fruit trees alone accounted for 68% of the total biomass C stock. The contribution of Coffee to the total biomass carbon stock under Fruit tree-Coffee system was 12% (Negash, 2013).

2.2 Agroforestry as refuge for biodiversity

Different agroforestry systems show different diversity status based on their richness, abundance and frequency of plant species (Kumar and Nair, 2004). Gedeo indigenous agroforestry systems are composed of an assemblage of diverse, closely growing trees, shrubs, and annuals that form a seemingly unbroken vegetation cover. These agroforestry practices stand in lush, beautiful contrast to the treeless farmlands of much of the remaining Ethiopian agricultural landscape. The practice is known to be an exemplary land-use system in the region (Kanshie, 2002; SLUF, 2006). Considering the number of plant species as measure to categorize the species richness status in different agroforestry systems of tropical and sub stropical countries, indigenous agroforestry systems have the highest number of species and followed by coffee systems, tree-crop systems and cocoa systems. Therefore, it could be suggested that indigenous agroforestry systems like the agroforestry systems of Gedeo zone of Ethiopia could be considered as a good system for conservation of plant species rather than non-traditional systems. Different management practices in each agroforestry system may result in differencing in species richness among these mentioned agroforestry systems (Negash, 2013). The four tropical agroforestry systems with the highest recorded number of plant species are: (1) homegardens in west Java, Indonesia, (2) homegarden of

Chagga, at the border of Tanzania and Kenya, (3) trees on agricultural land on Mount Kenya, and (4) traditional homegardens, in South-west Bangladesh (Kumar and Nair, 2004; Hemp, 2006; Kabir and Webb, 2009; Kehlenbeck *et al.*, 2011). A study conducted in south-western Bangladesh showed, out of 419 plant species recoreded in homegardens from six regions, 59% were native and six were Red List species from the International Union for Conservation of Nature (IUCN) (Kabir and Webb, 2009).

There are some studies conducted in Ethiopia which assess how agroforestry systems are serving as refuge for plants species. These reports indicated that, there are between 17 (These are mainly Fruit tree systems) and 429 plant species (which includes various agroforestry systems) growning in agroforestry systems and therefore, the systems are very important in biodiversity conservation of native species (Negash, 2013). Moreover, a research conducted by Asfaw (2003) showed that, there was a total of 123 tree, 146 shrub, 25 climber and 135 herbaceous species in various agroforestry systems. Species richness in Ethiopia showed a variation among the different AF practices and regions of the country. For instance, the highest plant species richness was reported in Southern Ethiopia which is from 50-198 plant species (Abebe *et al.*, 2006; Tamrat, 2011; Negash and Achalu, 2008; Asfaw and Woldu, 1997), followed by South-west Ethiopia which is reported 149 plant species (Woldeyes, 2011), in central Ethiopia which ranges from 27-114 plant species (Tolera *et al.*, 2008; Duguma and Hager, 2010; Mengesha, 2010; Kebede, 2010) and the least was recorded in north Ethiopia which is 17-40 plant species (Fentahun and Hager, 2009; Haileselasie and Hiwot, 2012).

Focusing on research conducted in Southern Ethiopia, there are relevant reports that deal with the potential of agroforestry to support and conserve plant species. For instance, a research inventory of plant species in 144 sites in four districts of Sidama zone was conducted. The inventory was carried out in coffee based homegarden agroforestry systems and found a total of 198 plant species. Out of the total 78 plant species were cultivated crops and the remaining 120 were tree species (Abebe *et al.*, 2006). Luckily, the Southern part of Ethiopia is rich withindigenous agroforestry practices that have developed gradually over years and the different tasks done by the communities have facilitated the conservation of plant species in the region. This is also coupled with the significant contribution towards environmental benefits, securing the issue of food safety and other economic benefits (Alemu, 2016). Scholars who conducted research in South-eastern and South-western Ethiopia reported that, the indigenous agroforestry systems of the region are rich in plant species diversity. Accordingly, Mengesha (2010) reported that 90 woody species in south-eastern Ethiopia including native tree species such as *Juniperus procera* Hochst. ex Endl**.**, *Olea europaea subsp. cuspidata* (Wall. ex G. Don) Cif., *Podocarpus falcatus* (Thunb.) R. Br. ex Mirb., *Acacia tortilis* (Forssk.) Hayne, *Acacia etbaica* Schweinf. and *Hagenia abyssinica* J.F. Gmel. And another study in the same part of the country by Debessa (2011) recorded a total of 165 plant species comprising 31% tree, 18% shrub and 45% herbaceous plants growing in homesteads, farms and pasturelands. Parellel to this study, Kebede (2010) identified 114 plant species in south-western Ethiopia comprising 30% trees, 23% shrubs, 40% herbs and 7% climbers etc. Woldeyes (2011) identified 149 species in the same part of the country comprising 30-32% tree, 23-25% shrub, 39-42% herbs and 3-6% climber plants.

2.3 Carbon stocks and C-sequestration of indigenous agroforestry systems versus monocropping

The modification of natural fluxes of carbon compounds between the atmosphere and the oceans, the atmosphere and terrestrial ecosystems and the exchanges among all these systems is influenced by the activity of human beings. The changes are mainly resulting from burning of fossil fuel more significantly in the Northern hemisphere of our planet and the clearing and conversion of forests to agricultural land and degradation of forests (in the tropics) (Paustian *et al*., 2000; Oelbermann *et al*., 2004). Over the past 150 years the atmospheric carbon dioxide concentrations have risen by 28% due to the human drivers (Schlesinger, 2013), and thus resulted in annual accumulation rate of 3.5×10^9 t of carbon (Paustian *et al*., 2000). In fact, the annual deforestation contributes about 5.9 Gt CO_2 in the world (IPCC, 2014). If the rate of deforestation in the tropics continuously increases at the same trend, it could emit an additional 87 to 130 Gt CO_2 to our globe by 2100 (Gullison *et al.*, 2007).

The removal of CO_2 from atmosphere and deposition or storage of this carbon in long-lived pools is called carbon sequestration. The reservoirs for carbon sequestration include oceans, the aboveground plant biomass; belowground biomass such as fine and course roots, soil microorganisms, and those organic and inorganic carbon compunds found in the soil which are believed to be comparatively in a fixed form, and deeper subsurface environments, and the longlived products obtained from biomass (e.g., timber) (Kirby and Potvin, 2007; Jose, 2009). It is possible to decrease the change of CO_2 concentration in the atmosphere by decreasing the emissions that are released from different sources or by increasing the carbon sequestration capacity of different land use systems or primary production. For instance, carbon sequestration can be augmented by increasing the volume of standing biomass and/or extending the rotation period of trees and shrubs, and/or changing the biomass into long lived products. As a land use systems agroforestry practices are believed to sequester more carbon than field crops and pasture lands because tree incorporation in croplands and pastures would bring in higher carbon storage above and belowground (Sanchez, 2000; Sharrow and Ismail, 2004; Kirby and Potvin, 2007; Roshetko *et al*., 2007; Nair *et al.*, 2009).

There are many factors that determine the quantity of carbon sequestered by agroforestry systems. According to Albrecht and Kandji (2003), the carbon sequestered by an agroforestry system mainly depends on the type of agroforestry system implemented, the structure of the components and the practice, the type of species, and at large it is affected by environmental and socio-economic factors and system management. Different species have different carbon sequestration potential because of differing photosynthetic efficiency and capacity. In addition to this, the availability of resources such as water, nutrients etc are also decisive. Generally, there is slow carbon sequestration rate in species that grow slower than those species growing fast (Mandal *et al.*, 2016), resulting in lower carbon stocks in the former species than the later ones. Carbon sequestration potential of soils under agroforestry systems depends on plant characteristic including (trees species, growth, age, crop species, stand characteristics, biodiversity and planting density) (Nair *et al*., 2009). Besides, agro-ecological factors such as altitude, climate, soil characteristics (texture, structure, fertility status, physical, chemical and biological conditions), system characteristics (structure: nature and arrangement of components, function: products stability) and management factors such as tillage, fertilization and harvesting regime affect carbon accumulation (Takimoto *et al*., 2008; Haile *et al*., 2010).

There are quite many studies on the C sequestration potential of agroforestry systems in different regions of the world (Dixon *et al*., 1994; Siyum and Tassew, 2019; *Dossa et al*., 2008; Van-Noordwijk *et al*., 2002). In addition, there are a differences in carbon stock distribution between biomass and soils among ecosystems. There are also a variations among ecosystems because of difference in latitude. As reports showed globally the total biomass carbon stock for agroforestry systems ranged between 12 and 228 t C ha^{-1} (Dixon, 1995; Albrecht and Kandji, 2003). Another study by Nair *et al*. (2003) reported that, agroforestry systems stored carbon ranging from 0.29 to 15.21 t C ha^{-1} yr^{-1} in their aboveground biomass and from 30 to 300 t C ha^{-1} in their soil down to one meter depth. The authors added, other studies which were conducted under various agroforestry systems and in various ecological region. The results of the studies confirmed that, tree-based agricultural systems stored higher amounts of carbon than systems which did not incorporate trees thus more carbon was stored near the tree than further away from the tree. Greater soil organic carbon content was associated with higher species richness and tree density.

Aboveground components of agroforestry systems have different carbon sequestration potential in tropical and temprate regions. For example as Oelbermann *et al*. (2004) reviewed, the carbon sequestration potential of aboveground components of agroforestry systems was estimated 2.1×10^9 t C yr^{-1} for tropical and 1.9×10^9 t C yr^{-1} for temperate biomes respectively. However, there is still variation among the different agroforestry systems globally in terms of potential to sequester carbon. Some authors computed the carbon stock of above ground biomass of agroforestry systems at farm level. For example, a research conducted by Nair *et al.*, (2010b) showed, the average above ground standing biomass carbon stock was estimated with a range of 16 to 36 Mg C ha^{-1}. The study was carried out in Central Kerala, India of homegarden trees (>20cm DBH). Similarly, a study conducted by Seta and Demissew (2014) in the Gedeo zone of Southern Ethipia reported that the average above ground biomass carbon stock estimated for indigenious agroforestry systems found in Sugale, Mokonisa, Dedero and Jememo peasant associations was 4.6 t C ha^{-1}, 10.38 t C ha^{-1}, 11.34 t C ha^{-1}, and 10.99 t C ha^{-1} respectively. Another study in same zone was also conducted by Negash and Starr (2015) and above ground biomass carbon stock (trees, coffee, enset, herbs and litter) of three agroforestry systems (Enset based, enset-coffee based and fruit-coffee based) was estimated and thus the results was 34.9 t C ha^{-1}, 59.2 t C ha^{-1} and 58.3 t C ha^{-1} for the three systems mentioned above respectively. A comparison in terms of above ground biomass carbon stock between food crops and homegarden agroforestry was studied by Henry *et al.* (2009). They found that changing a given system from food crops to homegardens agroforestry in Vihiga district, Western Kenya would result in an increase of 0.5–0.6 t C ha^{-1} yr^{-1} in the above ground biomass carbon stock. Additionally, they reported that the average stock of aboveground C in homegardens was three times larger than in food crops, cash crops and pasture plots in that district.

One of the main carbon pools in agroforestry systems is the soil.There are many data in the literature on carbon sequestration potential of agricultural soils although information on the potential of agroforestry systems to sequester carbon is not adequate. Nair *et al.* (2009) compared the carbon sequestration potential of soils under agroforestry and other land-use systems and noted a trend of increasing soil organic carbon (SOC) and ranked it in the following order: forests > agroforests (complex multistrata systems, similar to homegardens in structural complexity, but larger in size) > tree plantations > arable crops.

Reports on the soil organic carbon stock showed that for a given 0-30 cm layer the soil organic carbon stock around the world was in the average of 41 t ha^{-1}. Besides to this, for 0–60 cm soil layer the carbon stock was 121-123 t ha^{-1} for tropical forests and 110-117 t ha^{-1} for tropical savannahs (Lal, 2004). However, the results were lower for semi-arid *Acacia etbaica* woodlands 43 t $ha^{–1}$ which was investigated in southern Ethiopia (Lemenih and Itanna, 2004). Research also conducted on the potential of agroforestry systems in sequestering soil organic carbon and agroforesty systems of the Gedeo zone of South-eastern Ethiopia showed significant soil organic carbon stock with values 186.4 t ha^{-1}, 177.8 t ha^{-1} and 178.8 t ha^{-1} for Enset based, Enset-coffee based and fruit-Coffee based agroforestry systems respectively (Negash and Starr, 2015). However, a study conducted by Swamy and Puri (2005) showed that the soil organic carbon stock in agroforestry systems of Central India was very low with a value of 27 t ha^{-1}. Negash and Starr (2015) also estimated the total carbon stock of small AF holdings in South-eastern Ethiopia and thus reported 232.8 t ha^{-1}, 255.2 t ha^{-1} and 256.3 t ha^{-1} for the Enset based, Enset-Coffee based and fruit-Coffee based agroforestry respectively. Under these agroforestry systems, 75% the proportion of total biomass C stock to total agroforestry carbon stock was 25% in average across the three agroforestry systems. In other words the remaining 75% carbon stock was stored in the soil within the AF systems.

2.4 Soil nutrient status of indigenous agroforestry systems versus monocropping

It is evident that tree based systems like AF are giving several ecosystem services and ecological benefits at local as well as at a wider scale (Jose, 2009; Yadav *et al.*, 2011). The roles of agroforestry in reduction of soil erosion, conservation of water and organic matter is significant. Conservation and enrichment of organic mater in the system can increase the activitiy of microbs in the soil which assists for better nutrient recycling and thus enhancing soil fertility under AF production. Beyond that, AF systems can also reduce problems related with acidification and salinization by ameliorating the physio-chemical properties of the soil (Young, 1989; Nair, 1998; Sarvade *et al.*, 2014). The cost of inputs like chemical fertilizer can be reduced by planting nitrogen fixing leguminous trees thus increasing agricultural production (Steppler and Nair, 1987; Harterreiten-Souza *et al.*, 2014; Rosenstock *et al.*, 2014; Komicha *et al.*, 2018).

The threat of decreasing soil fertility under AF systems can be considered not too imminent despite of the persistent harvest of wood, crops and other products.The cumulative effects where by the dieback of roots and fall of litter and/or pruning biomass are returned to the soil and thus it contributes to the enhancement of soil physical and chemical properties by thisway soil organic matter and nutrient stocks in the soil are kept up (Lehmann *et al.*, 1998; Rao *et al*., 1998; Khanna, 1997; Komicha *et al*., 2018). For instance a study conducted in homegardens of cocao complex agroforestry in Costa Rica by (Beer *et al.*, 1990), revealed that, there was an increase of soil organic matter content over 10 years within the 0-45 cm soil layer. The organic matter content increased over the period by 42 t ha^{-1} in the cacao (*Theobroma cacao*)–Poro (*Erythrina poeppigiana)* homegarden agroforestry systems and by 16 t ha^{-1} in the cacao (*Theobroma cacao*)–Laurel (*Cordia alliadora)* homegarden agroforestry systems. The amount of carbon sequestered by the above mentioned two agroforestry systems was calculated as 21 t ha^{-1} for cacao–*E. poeppigiana* and 8 t ha^{-1} Cacao–*C. alliadora*.

Land use systems like agroforestry which incorporate tree, crops and pastures within their system play a crucial role in enhancing fertility of the soil and its quality. This is assisted by having the soil organic matter and biological nitrogen fixation by leguminous trees in the system. Trees/shrubs in agroforestry system also play a great role in recycling of nutrients but in monoculture systems especially cereal crop fields such as Sorghum sole cropping the recycling of nutrient is not as such since trees/shrubs are missing (Lehmann *et al*., 1998; Sarvade *et al.*, 2014). Litter decomposition and rate of decomposition under agroforestry has substantial contribution in conserving the soil fertility. Following the production of litter from standing trees/shrubs and other herbaceous species fragmentation and degradation of this litter is expected in order to release nutrients out of it. The soil fauna plays a great role in the decomposition and mineralization of litter because having more floral diversity in the agroforestry system fosters good conditions for the existence of soil fauna and microbes (Zheng *et al*., 2006; Takimoto *et al*., 2009; Kumar, 2011).

Studies showed that the composition of soil decomposer communities may differ distinctly with diverse plant species, or specific functional plant groups such as legumes. Investigations were conducted to compare the total biomass of decoposers between mixed (agroforestry systems) versus mono cultured and they have demonstrated that plant mixtures can produce greater diversity in decomposer communities than the mono cultured systems (Forrester *et al*., 2004). As Steinauer *et al.* (2015) reported the increase in plant biomass in the mixture may have strong effects on the soil microbial community. In addition the authors reported that, in most terrestrial ecosystems microbial biomass and growth have been shown to increase withincreasing carbon input.

In the last couple of decades many studies were conducted in various tropical and temperate regions, comparing aspects and factors of mineral nutrient in agroforestry as well as specific traditional agricultural systems. As Gama-Rodrigues (2011) mentioned, these studies were focused on nutrient cycling of different agroforestry types which includes soil organic matter fractions, biological fixation of nitrogen by leguminous trees and issues of soil quality improvement. Accordingly, the researchers found a significant and greater improvement in soil biological activity in terms of microbial biomass carbon, nitrogen, phosphorus, dehydrogenase and alkaline phosphatase activity occurring under agroforestry systems withincorporation of different multipurpose tree species (like *Prosopis cineraria*, *Dalbergia sissoo*, *Acacia leucophloea* and *Acacia nilotica*), compared with the corresponding values in systems where cereal monocropping alone occurred (Yadav *et al.*, 2011).

There are evidences that revealed agroforesty systems have greater nutrient availability than monocropping. For example, a research conducted by Kaur *et al.*(2000) in Northern India showed that the microbial biomass carbon was higher under soils of agrisilvicultural systems with *Acacia spp.* (133.80-153.40 mg g^{-1} soil) compared to rice–berseem crops (96.14 mg g^{-1} soil) and soils under tree plantations (109.12-143.40 mg g^{-1} soil). Following this, higher microbial biomass carbon (by 42%) and microbial biomass nitrogen (by13%) was observed in tree-based systems compared to monocropping. The author addtionally reported, incorporation of trees in crop land for 6-7 years increased soil organic carbon by 11-52% and the level of mineralization of nitrogen as well as soil inorganic nitrogen got augmented by 12-37% and 8-74% respecitively when it is compared with monocropping (Kaur *et al.*, 2000).

There are also reports on the contribution of tree based systems like agroforestry in improving soil nutrient status and thus their ability to show a positive impact on soils as compared to monocropping systems. A study conducted by Komicha *et al*. (2018) in the Central Rift-valley of Ethiopia revealed that "Soil organic matter, total nitrogen, available phosphorus, exchangeable calcium, exchangeable magnesium and cation exchange capacity were significantly higher under the canopy of trees in park land agroforestry as compared to open land which is without tree". Noticing greater soil organic carbon, total soil nitrogen and available phosphorus under the canopies of *Faidherbia albida* and *Acacia tortilis* tree species in the parkland agroforestry system which might be due to more organic matter accumulation as a result of litter fall and decomposition of fine roots of the trees. Therefore, it could be understood that, availability of nutrients in the soil is as a result of existence of trees on farms and thus it has a positive relation. Generally, improving the soil physical and chemical properties, keeping up the organic matter of the soil and stimulating nutrient cycling in a given locality depends on intervention of the appropriate agroforestry systems (Steppler and Nair, 1987)

2.5 Litterfall production and associated nutrient fluxes of indigenous agroforestry systems

Production of litter from standing trees/shrubs and other herbaceous species under agroforestry has substantial contribution in conserving the soil fertility. Litter decomposition and mineralization is affected by soil fauna. Presence of more floral diversity in the agroforestry system fosters good conditions for the existence of soil fauna and microbes and hence release of nutrient as a result of decomposition (Zheng *et al.*, 2006; Takimoto *et al*., 2009; Kumar, 2011). Land use change which has been observed in tropical areas amongst others has important implications for biogeochemical cycles at both regional as well as global levels. As it already known most of the forests in tropics are changed to other land use systems due to different reasons. One of them is the clearing for agricultural uses. As a result, generally there is disruption of ecosystem services and change of functions (Scholes and Van Breemen, 1997). To minimize the risk of forest degradation and thus low nutrient cycling in agricultural land uses considering effective agroforestry practices as an option is a best possible scientific approach (Tripathi *et al*., 2009). Litter decomposition that induces a continous release of nutrients represents a major biological pathway for essential element transfer from vegetation to soils, and plays a major role in adjusting the nutrient cycling (Dawoe *et al*., 2010; Triadiati *et al*., 2011).

Different authors summarized variation in litterfall quality and quantity to be produced by plants is affected by various factors. For example: season of the year, type of soil in the site, climatic condition in the specific location, stand characteristics which includes size of the tree, foliar biomass and age; and management practice (Ulrich *et al*., 1981; Breymeyer *et al*., 1996; Liu *et al.*, 2004; Starr *et al.*, 2005; Dawoe *et al.*, 2010). A study conducted by (Negash and Starr, 2013) in the indigenous agroforestry systems of Gedeo zone of South-eastern Ethiopia revealed that, high litterfall production would be linked to the high productivity of these systems. Köhler *et al.* (2008); Silva *et al.* (2011) also mentioned that, litterfall production is one of the indicators for a good agroforestry biomass productivity and this is linked to high leaf mass.

Agroforestry systems produce litter and the itterfall has different amounts and different composition which is dependent mainly on species diversity, structus of the AF system (Tangjang *et al.*, 2015). The type of species and their growth pattern, age of the plant species, density and canopy characteristics have also an effect to show variation in terms of the quantity and pattern of litterfall (Bray and Gorham, 1964). In addition, climatic factors such as extreme weather, pests and disease could affect litterfall production (Murovhi *et al*., 2012). The nutrient input-output system of agroforestry systems is derived from the litter that is accumulated on the ground as result of litterfall from the standing tree/shrub biomass. The degraded materials then contribute to the primary productivity, enhance the nutrient cycling and sustain the fertility of the soil. Therefore, understanding the quantity and pattern of litterfall in agroforestry systems is crucial in order to know how the system is running with the issue of nutrient availability and sustainable management (Berg, 2000; Lebret *et al.*, 2001; Ranger *et al.*, 2003; Wang *et al.*, 2008). The main source of organic matter and energy to soil comes from a litter produced by plants, specifically trees. A research conducted in traditional agroforestry systems of Northeast India showed, from the total litterfall the leaves contributed the highest biomass (64.22%) and most of the contribution came from trees (76.06%)(Tangjang *et al.*, 2015).

For soils which are found in agroforestry systems, litterfall that comes from the trees is the main contributor for the humus layer formation and thus litterfall and litter decomposition from these systems may be a principal factor contributing to the quality of the soil as the soil micro-organisms decompose the litterfall and deliver mineral nutrients (Luizao and Schubar, 1987). Litterfall could develop a litter layer on the topsoil and accumulation of this litterfall depends on various factors like the decomposers population and their activities, land use types, type of plant species and climatic condition (Aerts, 2006). Moreover, besides climatic and external factors differences in quality and type of organic input from the contributing components lead to a variation among agroforestry systems and other land use systems like natural forest and agricultural systems (Mafongoya *et al*., 1998).

There are some reports on litterfall production from various parts of the world. Triadiati *et al*., 2011) studied three different Cocoa agroforestry systems and found an annual litterfall of 6.93, 4.98 and 8.23 t ha^{-1} for a system under a remaining forest cover (CF1), system under local shade trees (CF2) and systems without forest cover, but with planted *Glyricidia sepium* as shade trees respectively. Another study conducted by Dawoe *et al*. (2010) in Cocoa agroforestry systems of lowland humid Ghana found litterfall amounts from 5.0-10.4 t ha^{-1} yr^{-1} depending on the age of the agroforestry stand. In addition, more studies were conducted by Isaac and Nair (2006) and Owusu-Sekyere *et al*. (2006) in similar moist semi-deciduous and shaded cocoa systems and they reported different litterfall rates. The reason for variation in litterfall rates among the agroforestry systems was due to difference in tree management, soil and climatic conditions prevailing at different sites (Dawoe *et al*., 2010). Tangjang *et al.* (2015) mentioned, most litterfall in tropical forest based systems have demonstrated a strong seasonality of peak litterfall during the dry season and in times of windy conditions. Therefore, it could be understood that an important determinant for litter production in these regions is the climatic condition. Another study conducted by Dawoe *et al*. (2010) on natural forest and Cocoa agroforestry systems of lowland humid Ghana revealed that high litterfall was recorded during the the time of low air humidity and high temperature. The seasonal pattern of litterfall production of the primary forest and Cocoa agroforestry systems in the similar study site showed also an increase in the dry season. This is because, litterfall production may be influenced by physiological responses of the plants to environmental changes or physical drivers such as windly condition or the mechanical action of rain (Santiago and Mulkey, 2005; Dawoe *et al.*, 2010). In addition to this, disturbances caused by biotic factors such as insect and/or pests and disease may affect the changes in litterfall within one agroforestry system (Pitman *et al.*, 2010).

Under ecosystems it is usual to see a relationship between nutrient flow and nutrient storage and the balance between litter deposition and decomposition within an ecosystem is a determinant factor for the status of organic matter (Singh *et al*., 2004). Biological and non-biological factors derive litterfall decomposition and reduce this litter into different compounds like CO_2, water and mineral nutrients after passing chemical as well as physical actions (Lavelle *et al.*, 1993; Lambers *et al.*, 1998; Kavvadias *et al.*, 2001). Availability and amount of nutrient in the soil (Verhoeven and Toth, 1995; Fioretto *et al.*, 2005), external factors such as climatic condition, mostly temperature and humidity, and soil (Fioretto *et al.*, 2001), type of plant growing (Lambers *et al.*, 1998), the quantity and performance of decomposers to degrade the litter (Knoepp *et al.*, 2000) and quality of the litter in terms of chemical properties such as C:N ratio, lignin and polyphenol content, and quantity of litter (Sariyildiz and Anderson, 2003) are the main biological and non-biological factors that interact to affect rate of decomposition.

2.6 Role of agroforestry systems in enhancing local community livelihoods

The concept of 'livelihoods' is mainly defined as the activities, allocation and benefit by which people make a living in agiven situation. Related with this, the definition of "sustainable livelihoods" is also given by the International Institute for Sustainable Development (IISD) and explained, sustainable livelihoods is concerned with people's abilities to produce and maintain their means of existence, improve their well-being, and considering also the needs of future generations' (Singh and Titi, 2001). The role of agroforestry in enhancing livelihood of people and its significant ecosytem services have increased recognition in rural areas in recent times. It is believed that, when agroforestry system are compared with subsistence agriculture, the former provide more benefits to the community by additional cash incomes generated from selling of multiple products (Kalaba *et al.*, 2010). Agroforstry plays as a bridge between agricultural land use and forestry and it is considered as one of the sustainable land-use systems where by agricultural productivity could be increased and maintained (Malla, 2000; Neupane and Thapa, 2001).

Forests and trees have been integral parts of subsistence farming systems in developing countries to add diversity to the farming system and to sustain the rural household economies (Arnold, 1997; Neupane *et al*., 2002). Lately, the positive benefits of agroforestry practices to the producers (i.e. farming households) and to the environment have been increasingly recognized, e.g. agroforestry, carbon sequestration and biodiversity conservation (Nair *et al*., 2009). The contribution of agroforestry in enhancing the livelihood of the rural household could be also seen in terms of improving food and nutritional needs and in mitigating environmental degradation by integrating tree component, crop or/and livestock component either in different time arrangemnts or stratified ways (Sinclair, 1999).

Implementing agroforestry in a given farming system could potentially enhance the livelihoods of farmers because of increasing the agricultural productivity of the landscape (Mbaga-Semgalawe, 2000). Under agroforestry small marginal farmers produce fruit and nuts, fuel wood, timber, medicine, fodder for livestock, green manure, gum, resins, spices and vegetables etc and as a result they enjoy a diversified income from their products (ICRAF, 2013). In addition, there are other opportunities in which agroforestry could enhance the livelihood of the community. For instance, practicing apiculture, sericulture and growing of suitable trees for gum and resin could help to generate better economic returns thus ensuring livelihood security in rural areas. In line with this, it may also helps to check the migration of rural youth towards urban areas (Handa *et al.*, 2016).

Households who adopt agroforestry have got positive impacts on their livelihoods. Some of the major impacts identified by the rural community are showing increament in crop yield, increment in household cash income and better nutrition and health related issues (Ndalama *et al.*, 2015). Micro-climate amelioration and enhanced physical-chemical properties of the soils (Buresh and Tian, 1998); rising of nutrient inputs drived from biological nitrogen fixation of plants (Kang and Akinnifesi, 2000); and increased availability of nutrient assisted by improved activity of biological resources in the soil and high nutrient turnover rate (Akinnifesi *et al.*, 2006) are the main drivers for increased crop yield in agroforestry.

The second major impact of agroforestry intervention is increased household cash income. For example, corroborating these findings, various studies have shown that household cash income has increased due to agroforestry intervention in the hills of Nepal (Neupane *et al.*, 2002). The authors also assessed how or which sources of income complemented the food shortage of poorer households in the hills of Nepal and they confirmed that the dependency on the income from agroforestry was significant. Complementary, the income from tour guiding and other wage labor declined slightly. The income from the sale of agroforestry products such as fruits, cash crops, vegetables and livestock and livestock products has reduced the frequency of borrowing and loans from relatives/neighbors and wage labour. The sale products from agroforestry trees have a significant role in improving financial status of the households by increasing the revenue (Pandit *et al.*, 2013; Ndalama *et al*., 2015).

The third major impact of agroforestry intervention is improved health and nutrition. Household get indispensable nutrition and diet from fruits that are produced in agroforestry systems. For example: a study conducted in Balaka communities of Malawi revealed that fruit trees are mostly served for food especially during difficult times of drought, thus bridging nutrition gaps. Agroforestry systems have also the potential grow medicinal plants and communities who live in remote rural areas depend very often on these plants for most of their health treatments (Ndalama *et al.*, 2015). As a result, many people who live in rural sub-Saharan Africa depend mainly on medicinal plants. The report added at least 80% of communities enjoyed the benefit of medicinal plants to garantee their health needs and generate income out of it (Garrity, 2004).

Agroforestry intervention and adoption by farmers has also a great contribution to food security. Food sufficiency is measured by quantifying the amount from own farm produce and purchase with cash income generated from sale of other household-level farm produce (Pandit *et al.*, 2013). A study conducted in Lushoto district of Tanzania revealed that the level of the household's farm production and net income was greater among farmers practicing agroforestry. In comparison, the farm production and net income of the farmers who did not practice agroforestry system was low. This could tell us that increased yield and income is significantly contributed by these agroforestry practices and thus helps to reduce poverity at household levels. The trees and crops in such systems have benefits beyond subsistence food and source of cash income. They could help in reducing soil degradation and water shortage, derived decomposors, enhancement of soil structure and a solution to household source of enery by providing firewood. The livestock was mostly stall-fed with fodder and contribute to the household's nutrition and income through sale of their products like meat, eggs and milk (Namwata *et al.*, 2012*)*.

Promoting AF systems and rehabilitation of degraded forest and agricultural lands through area exclosures are priorities in the current natural resource management agenda of the Ethiopian government. Smallholder farmers are expanding their woodlot plantations. Farmers in central and southern Ethiopia are intensifying their traditional agroforestry systems (Asfaw *et al*, 2015).

3. OBJECTIVES OF THE STUDY

3.1 General Objectives

The overall objective of the present study is to investigate the potential of indigenous agroforestry on biodiversity conservation, carbon sequestration and livelihoods support in the south-eastern Rift Valley landscapes of Ethiopia.

3.2 Specific objectives

- To evaluate and compare the plant species diversity, composition and structure of the three indigenous agroforestry systems
- To determine and compare the biomass and soil carbon pools in agroforestry systems and adjacent mono-cropping system;
- To determine and compare the litterfall biomass production and associated nutrient fluxes among the three agroforestry systems
- To determine and compare the soil macro nutrients (N,P,K) and soil fertility indicators of the three agroforestry systems and adjacent mono-cropping system
- To assess the contribution of agroforestry systems for livelihood improvement of the community

3.3 Research questions

The research questions of this study are a) Could carbon stocks among the three indigenous agroforestry systems differ because of having different management system? b) Do the three indigenous agroforestry systems have different content of macro-nutrients (Nitrogen, Phosphorus, Potassium etc in the soils)? c) How different are soil organic carbon stocks in comparison of these three agroforestry systems with monocropping? d) How Coffee-Fruit tree- Enset agroforestry system can enhance the livelihood of the rural households in the study area?

3.4 Significance of the study

The significance of this study is that it offers an opportunity for the evaluation of the agroforestry systems and to contribute to the conservation of this unique agroforestry systems and to assess carbon stocks of tree and shrub species in these agroforestry systems, Thus important data are gained to evaluate the potential of AF systems to contribute the the reduction of atmospheric CO_2 and to mitigate climate change. It may also render essential information as to which tree species store more carbon during its growth and development in the agroforestry systems. It further contributes to the development of a national policy concerning the conservation of biodiversity, the mitigation of climate change, and the implementation of international mechanisms such as REDD+ (Reducing Emission from Deforestation and Forest Degradation) and CDM (Clean Development Mechanism).

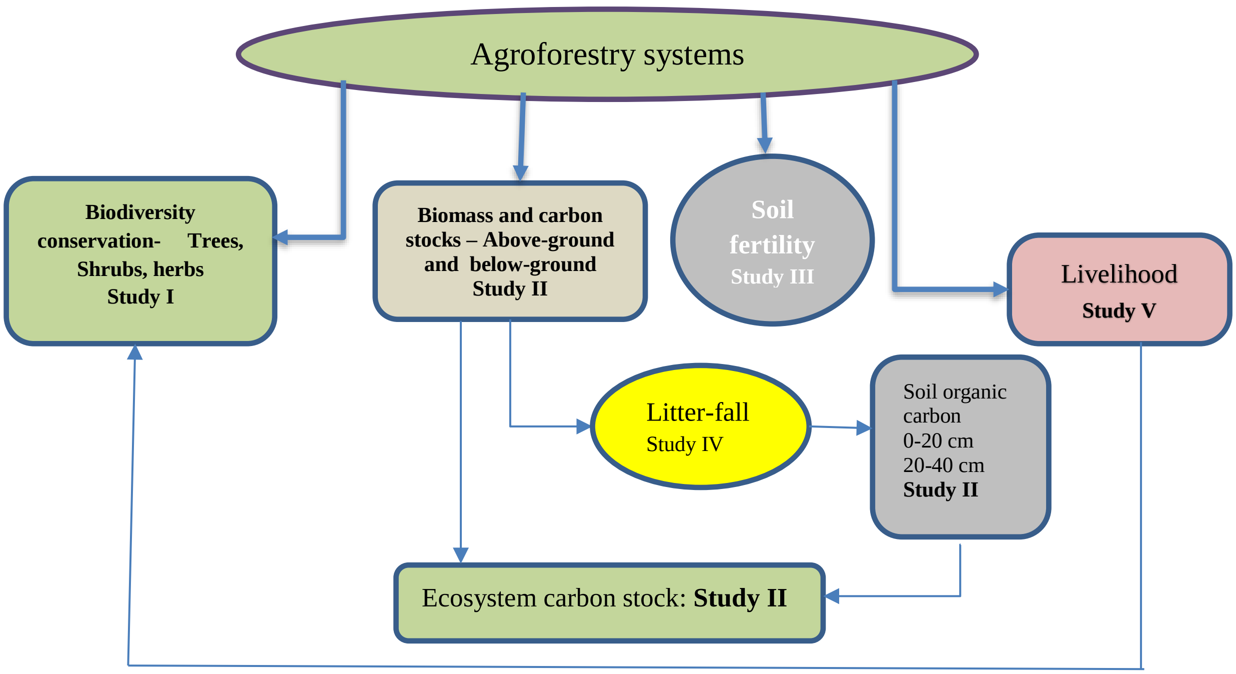


Figure 1. Links among the different components of the study (study framework)

4. METHODS AND MATERIALS

4.1 Study area and sites

4.1.1 Location of the study area

The study was conducted in the South-eastern Rift-Valley landscapes in the Gedeo zone of the Southern Nations', Nationalities' and Peoples' Regional State (SNNPRs) of Ethiopia, (5°50' 26"–6° 12' 48" N, 38° 03' 02"–38° 18' 59" E). Elevation in the study area ranges between 1300 and 3064 m asl. Gedeo is one of the most densely populated administrative zones in Ethiopia, averaging 627 *persons* km^{-2} with a range of 122 to 1300 persons km^{-2} (Negash, 2007; Mebrate, 2007; Bishaw *et al*., 2013). The specific study sites are located in Dilla Zuria district of the zone.

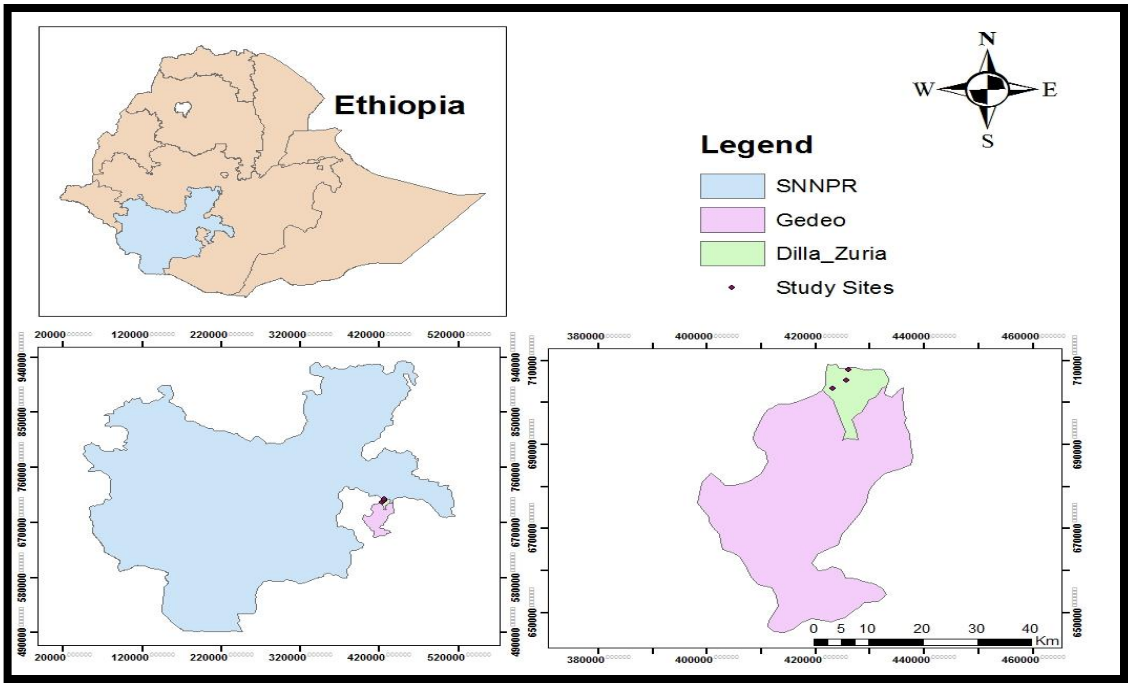


Figure 2. Map of the study site

4.1.2 Climate of the study area

Climate data was obtained from meteorological station located in Dilla town which is an average 4 km away from the study sites (National Meteorology Agency, 2019). The mean maximum and minimum air temperature were calculated from 9 years (2010-2018) recorded climate data. The meanthly mean maximum ranges from 26.1 ^{0}C in August to 31.2 ^{0}C in February and the mean monthly minimum temperature ranges from 9.7 ^{0}C in January to 14.9 ^{0}C in July (Figure 3). The general trends of 9 years mean maximum and minimum annual temperatures was almost stable. This might be due to effect of the well managed agroforestry systems in the study area which have a positive impact on the microclimate amelioration. However, there is variability in mean monthly air temperature across the months of the year.

The mean annual rainfall for the 9 years in the study sites is 1392.7 mm ranging from 1127 mm in 2015 and 1624 mm in 2018 (National Metreology Agency, 2019). The total annual rainfall amount showed a bit flattening in the first consecutive 5 years and and falling in 2015 and again started rising after the year 2016. There is also variability in monthly rainfall across the months of the year (National Metreology Agency, 2019). The area receives bimodal rainfall. The first rain season is

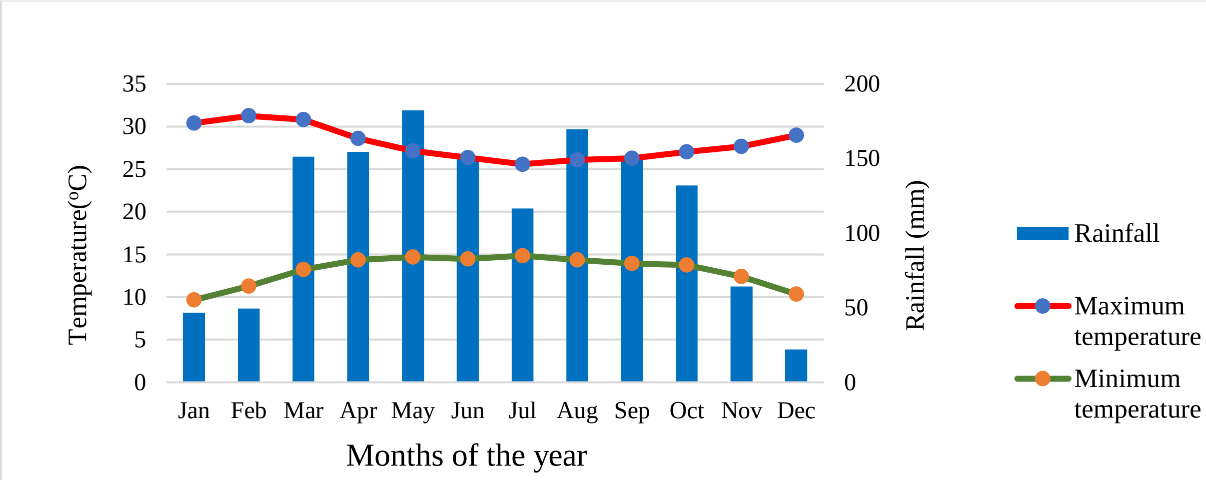


Figure 3. Mean monthly rainfall and temperature distribution for the study area (2010-2018) (National Metreology Agency, 2019).

July- Oct and the second rain season is from March-June. The remaining four months are dry season. All the climatic information was sourced from National Metreology Agency Hawassa branch (2019). The climate between 1300 and 1500 m asl is classified as hot tropical (locally known as ‘Kolla’), between 1500 and 2300 m asl is classified as sub-tropical (‘Weynadega’), and between 2300 and 3100 m asl is classified as mid-altitude (‘Dega’) (Negash, 2007; Mebrate, 2007; Bishaw *et al*. 2013).

4.1.3 Land use types of the study area

The total area of the Gedeo zone is 134700 ha, comprising agricultural land (agroforestry- perennial and annual crops land) (94.5%), grassland (1.4%), wetland (0.8%), natural forest (0.5%), plantations (0.1%) and others (2.7%) (Mebrate, 2007). As the figure shows the largest share is taken by agroforestry- perennial and annual crops land followed by very small area grass lands. According to our assessment the texture of the soil in the studied three agroforestry systems was dominantly clay. A range of soil types are found in the study zone, but the dominant soil type in the studied three agroforestry systems are Nitisols and those soils were developed from volcanic rocks specifically from rhyolite type. These soils are deep, reddish-brown, clayey soils with a relatively high organic matter content and a crumb and/or subangular blocky structure, and are therefore well-drained and fertile (FAO, 2001).

4.1.4 Farming system

The main economic activity of farmers in the study area is agroforestry practice in which they used mixed farming, including non-fruit trees, fruit trees, crops, vegetables, spices production and very limited animal husbandry focused on fattening of oxen, goats and sheeps. The three main agroforestry systems practiced in the study area are: 1) Enset based agroforestry system (mainly

Table 1 Characteristics of the three studied agroforestry sites in the Rift Valley landscapes of south-eastern Ethiopia

Characterstics	Study sites		
	Sisota	Golla	Chichu
Location	Dilla zuria district, SNNPRs	Dilla zuria district, SNNPRs	Dilla zuria district, SNNPRs
Altitude	1760-1830 m asl	1665-1732 m asl	1544-1587 m asl
Topography	Steep slope land feature, azimuth: north, west and south facing	Slightly steep to medium, azimuth: north, west and south facing	Gentle slope, azimuth: north, west and south facing
Annual rainfall range	1127 - 1624 mm	The same	The same
Annual temperature range	13-28 ^{0}C	The same	The same
Soil texture	Little silt- clayey	Predominantly clay	Predominantly clay
Soil type	Predominantly Nitisol	Predominantly Nitisol	Predominantly Nitisol
Plant species coverage	Enset dominated	Coffee and Enset dominated	Fruit tree, Coffee and Enset dominated
AF management practice	Tree pruning, lopping, thinning, slashing of weeds. Enset leaves and foliage of *Millettia sp*. used for composting and mulching	Pruning, lopping, pollarding, thinning, slashing of weeds. Enset leaves, herbaceous plants and foliage of *Millettia sp*. used for composting and mulching	Tree pruning, pollarding. Farm house waste, ash and Coffee husks used as manure
Major food and cash crops, vegetables	Enset, Taro, Yam, Kale	Coffee, Enset, Banana, Taro, Yam, Sweet potatoes	Fruit, Coffee, Enset Maize, Haricot bean, Sweet potatoes
Average distance from the next town (market)	10 km	8 km	5 km

practiced in Sisota site), 2) Enset-Coffee based agroforestry system (practiced in Golla site) and 3) C-Ft-E based AF system (practiced in Chichu site) see table 1 for detail information. These agroforestry systems are primarily aimed at meeting household food needs (Negash, 2007) and also at generating income to boost the economic status of the family (Kanshie, 2002; Asfaw, 2003). Practitioners obtain different products and benefits from practicing agroforestry such as timber, pole, firewood, fruits, vegetables, crops, medicinal plants, honey, meat and others.

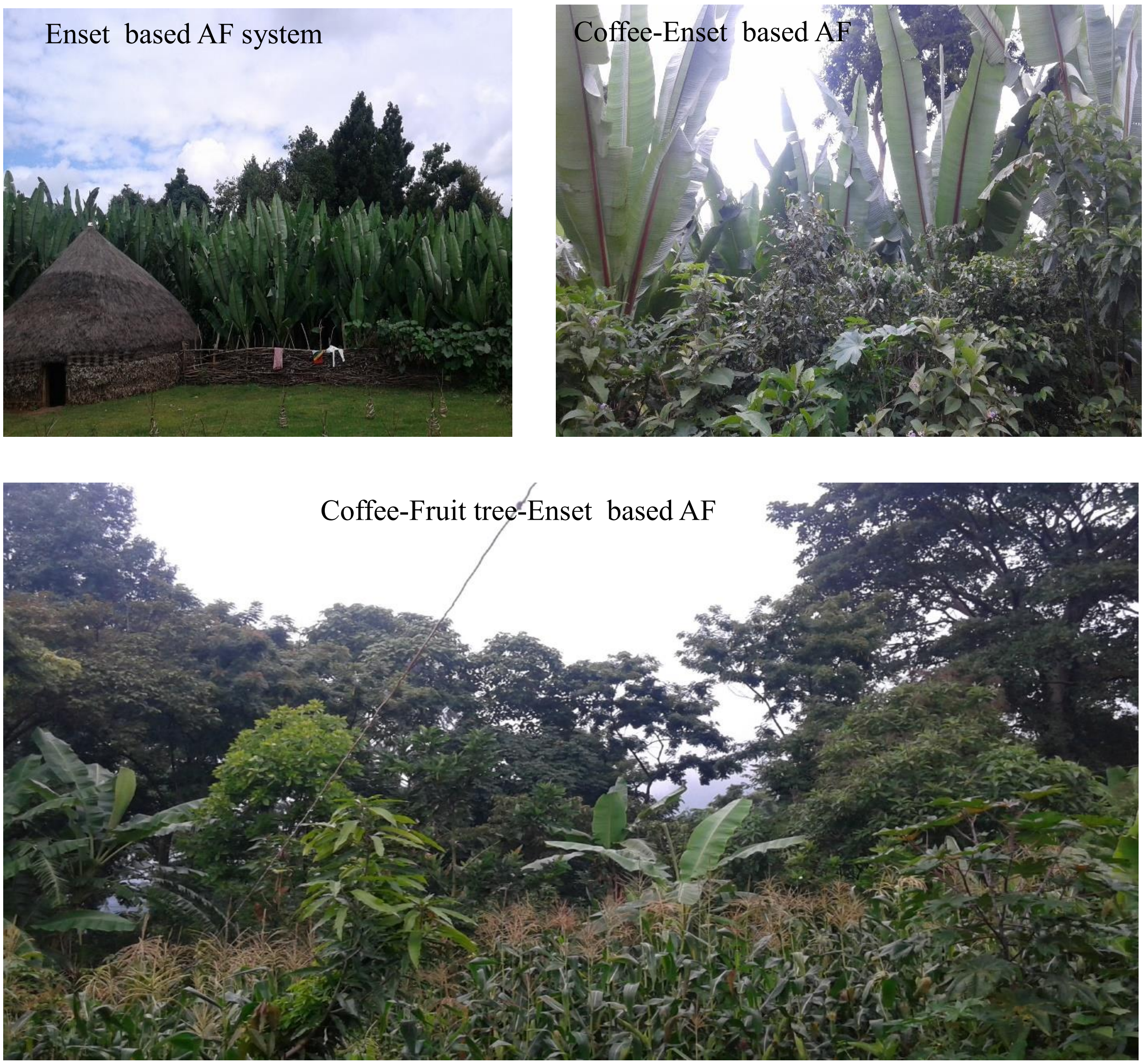


Figure 4. The three dominant agroforestry systems practiced in the study area

4.2 Methods

4.2.1 Sampling design and data collection

Out of the different agroforestry systems practiced within the zone, the three agroforestry systems which are the objective for this study were identified using satellite imagery and aerial photographs. In addition, ground observations were carried out to validate the identification. The agroforestry systems were selected at similar altitudinal locations gradient of the landscape to minimize variation in climatic variables, slope and aspect. Within each agroforestry study site 20 agroforestry farms (60 farms intotal) were randomly selected and 10 adjacent mono-cropping farms (30 farms intotal) were selected in purposive manner. The altitude, slope, GPS location, agroforestry type, age of each agroforestry farm and mono-crop farm and site history were also recorded.

A nested quadrat with 10×10 m size was established in each agroforestry farm for the inventory of trees/shrubs, Coffee and Enset. Within each quadrant three 0.5×0.5 m small plots for litter sampling were laid out. In addition five circular plots at four corners of the quadrant and one in the center were determined for soil sampling. To locate the central position of a quadrat on the farm, ocular

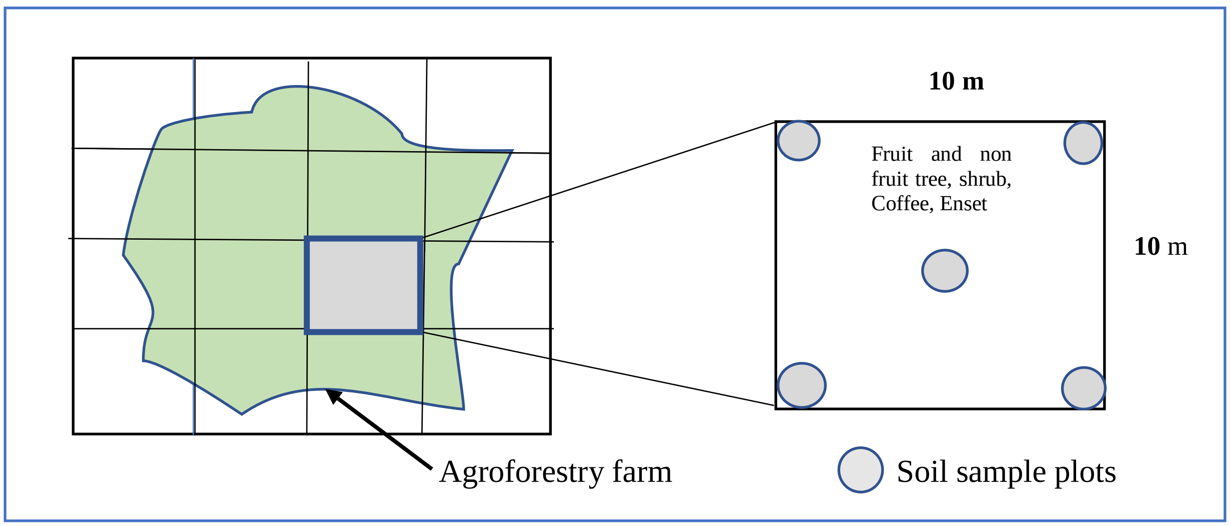


Figure 5. Sample plot layout for inventory of trees, shrubs, Coffee and Enset plants (10 × 10 m) and soil sample points (circular points). See 4.2.2, 4.2.3 and 4.2.4 for detail description.

estimation was first used to divide the farm into ten equal parts. Second, a number was assigned to each part. Third, a data collection plot was selected by generating random numbers. The size of the quadrats and sampling size coincide with recommended practice in literature for similar agroforestry farms by (Negash *et al*., 2013). In some cases the size of the quadrant might occupy the whole farm. Due to the above reason and cost and time related issues we limited the size of our quadrant to 100 m^{-2} rather than 400 m^{-2} or more.

4.2.2 Plant species inventory (Study I)

To assess the plant species diversity and composition an inventory of all the trees (fruit and non-fruit), Coffee and Enset plants was carried out. The inventory was conducted on the 10×10 m quadrants on each agroforestry farm. Measurements such as diameter at breast height (DBH, cm ±0.1), total height (h, m ±0.1) of all trees and shrubs (single and multi-stemmed) having a breast height diameter ≥ 2.5 cm and height ≥ 1.5 m was made. For Coffee plants (in Enset-Coffee and C-Ft-E based AF systems), the stem diameter at stump height (40 cm), d_{40}, was also measured. For Enset based agroforestry systems, the basal diameter of the pseudostem (height of 10 cm, d_{10}) of plants one year old or older was measured. Stem diameter measurements (d, d_{10} and d_{40}) was taken using Caliper in two perpendicular directions and the average value was used in subsequent calculations. In the studied agroforestry systems biodiversity analysis was done by counting all woody species above 20 cm height and species identification was performed by using identification keys and local informants. For those species that could not be identified in the field, specimens were taken to the national herbarium for identification.

Figure 6. Inventory of plant species in agroforestry systems

4.2.3 Biomass and biomass C stocks (Study II and IV)

Estimation of total above-ground biomass (AGB) and belowground biomass (BGB) (t ha^{-1}) of non-fruit trees and shrubs, fruit trees, Enset and Coffee plants was done for the 60 farms (20 farms from each of the three agroforestry systems). For the determination of biomass C stocks (t C ha^{-1}), 30 of the farms (10 farms from each of the three agroforestry systems) were randomly selected and estimated. The C stocks of the tree and shrub, Enset, Coffee, and litter fall biomass and soil to 40 cm depth were determined. However, the C stocks of fine roots and herbs were not included in our calculation. Researchers in all parts of the world have developed a tradition of applying allometric equations developed for tree species of the natural forest to estimate AGB of trees in agroforestry. This is due to the fact that destructive harvesting of trees is too costly, labor intensive, and time consuming for both AGB and BGB determination. Further on farmers may demand compensating payments for the sampled trees because it may be harvested at wrong time and/or production is less due to premature cutting.

To estimate the above and below ground biomass and their respective carbon stocks a plant species inventory followed by the application of allometric equations were perfomed. These equations were developed by different authors. The reason for adopting these allometric equations is because the study site in which the equation was developed had similar environmental conditions (climate and soils) to our study sites and showed highest R^2, lowest error of prediction values and used only breast height diameter for trees (Kuyah *et al*., 2012a; Kuyah *et al*., 2012b; Negash *et al*., 2013b; Negash *et al*., 2013a). For instance, Kuyah *et al*. (2012a) developed an equation to estimate AGB of trees grown in agroforestry systems in western Kenya.

$$AGB= 0.225 \text{ x } d^{2.341} \text{ x } \rho^{0.73};\ R^2=98;\ n=72 \text{ .... } (1)$$

Where AGB (kg dry matter /plant) = aboveground biomass, d (cm) = diameter at breast height and ρ is species wood density (g cm^{-3}).

But, to estimate the aboveground biomass (AGB, kg dry matter/plant) of the Coffee and Enset plants, an allometric equation which was developed for Coffee by (Negash *et al*., 2013a) and Enset (Negash *et al*., 2013b) was adopted.

$$AGB_{Coffee} = 0.147 \text{ x } d_{40}^2 \qquad R^2 = 0.80,\ n = 31 \text{ .... } (2)$$

$$\ln(AGB_{Enset}) = -6.57+2.316\ln(d_{10}) + 0.124\ln(h); \quad R^2= 0.91,\ n= 40 \text{ ....}(3)$$

Where d_{40} (cm) = stem diameter of the coffee plant at 40 cm height, d_{10} (cm) = the basal diameter of the Enset pseudo stem at 10 cm height and h (m) = total height

Total aboveground biomass is defined as the sum of tree, Coffee, Enset and litter biomass.

For estimating the belowground biomass (stump plus coarse roots (>2 cm)) for trees and shrubs, including Coffee, the following allometric equation by Kuyah *et al*. (2012b) was used.

$$BGB= 0.490\ AGB^{0.923} \qquad R^2 = 0.95,\ n = 72 \text{ ....} (4)$$

Where BGB (kg dry matter/plant) = belowground biomass, d (cm) = diameter at breast height.

However, to estimate the belowground biomass of Enset (corm plus attached proximal roots), the allometric equation developed by (Negash *et al*. 2013b) was adopted.

$$BGB_{Enset} = 7\ x10^{-6}\ x\ d_{10}^{4.083};\ R^2 = 0.68,\ n = 40 \text{ ....}(5)$$

Where BGB Enset (kg dry matter/plant) = Enset belowground biomass, d_{10} (cm) = the basal diameter of the Enset pseudostem at 10 cm height

Note: n (in all the formulas) is the number of individual plants that were taken for development of allometric equation

Total belowground biomass is defined as the sum of BGB and roots (stump plus coarse roots, >2 cm diameter). The biomass of litter was determined from collected samples taken from the three 50×50 cm plots; within the 10×10 m inventory quadrant. Three samples were taken from each quadrant and later one composite sample was taken for measurement and further analysis.

The BGB and AGB carbon stocks of non-fruit trees and shrubs, fruit trees, Enset and Coffee plants and litter was determined by using content C% in each component. It was calculated from organic matter contents determined as loss-on-ignition (LOI; ignition at 550 °C for 2 hours) and an assumed C content of organic matter of 44 %. (Negash and Starr, 2015). Accordingly for the different biomass fractions the following C-contents were used: 48% for non-fruit trees and shrubs, fruit trees, 43 % for Coffee, 41 % for Enset, 32 % for and 29 % for litter. Total biomass C stocks are defined as the sum of total aboveground and belowground biomass C stocks.

4.2.4 Soil sampling for soil organic carbon stocks and macro nutrients (OM, N, P, K, Ca, Mg, C:N ratio) (Study II and III)

Soil samples of 0-20 cm and 20-40 cm layers were taken for determination of SOC, OM, N, P, K, Ca and Mg contents from the four corners and centre of each 10 × 10 m inventory quadrant and composited by layer. It was assumed that taking samples down to 40 cm soil depth might be sufficient. The sampling depth was chosen with regard to cost for soil analysis and to have uniform and compelete sampling procedure since the method shoul be used for our agroforestry farms and monocrop farms. The sampling was employed for all three agroforestry systems as well as the adjacent mono-cropping farms. Both gravimetric and volumetric soil sampling methods were employed in the same place to get soil for further soil organic carbon determination. The volumetric soil sampling was employed in the middle of each 10×10 m inventory quadrant. A gouge-type Auger (8 cm diameter) soil sampler was used for the gravimetric method. For the volumetric sampling a Core sampler (7.2 cm dia. ×10 cm tall, 406.9 $^{-3}$) was used for Enset based AF and C-E based AF systems. A Core sampler (5.6 cm dia. × 10 cm tall, 246.2 cm^{-3}) was used for C-Ft-E volumetric soil samples were taken for determination of bulk density separately. After soil sampling using gravimetric method one composite soil sample was formed for each layer by mixing the five samples properly. This was done at the field before the soil samples were air-dried at room temperature and sieved. Similar way of composite soil samples preparation were employed for soil samples taken from the AF as well monocrop farms. Then, the composite sampls were taken to Hawassa University, Wondo-Genet College of Forestry and Natural Resources soil laboratory for preparation.The soil C stocks (t C ha^{-1}) were calculated as the product of C content (%), bulk density (g cm^{-3}) and layer thickness (cm). The C stocks for the two layers (0-20 cm and 20-40 cm) was summed to obtain the C stock for the 0-40 cm layer. It was also used a similar procedure to calculate nutrient stocks of N, P, K, Ca and Mg which is product of the element content (%), bulk density (g cm^{-3}) and layer thickness (cm). The soils that were sampled using the gravimetric method was for the purpose of determining the content of soil nutrients, pH and texture.

Soil laboratory procedure

Some part of the laboratory work such as preparation of soil samples, analysis of bulk density was done in Hawassa University, Wondo-Genet College of Forestry and Natural Resources soil laboratory. The composite soil samples which were collected and needed for nutrient analysis were

120 (20 samples from each agroforestry system and 20 from their adjacent monocropping farm; 0-20 cm, 20-40 cm soil depth for the three agroforestry systems). The soil was air-dried at room temperature and then passed through a 2 mm sieve and finally transported to Vienna for determination of the remaining parameters. The whole analysis was done in the University of Natural Resources and Life Sciences (BOKU), soil laboratory of the Institute of Forest Ecology. soil texture, Soil pH, organic matter percent (OM%) organic carbon (OC), total nitrogen (TN), soil total nutrients (Ca, Mg, Na, K, P), available phosphorous (P_{avail}), cation exchange capacity (CEC) and base saturation percentage (BS%) were determined for the respective soil depths following the standardized soil laboratory procedures. For detail see methods on the following pages.

The soil samples for bulk density were oven-dried at 105 °C for 48 hours until we get constant weight and then immediately weighed. We did the analysis for 120 soil samples from both the agroforestry and monocropping farms.

Figure 7. Soil sample preparation and filtration in laboratory

For the soil texture analysis a fine soil with <2 milimeter diameter was used. Sixty (60) out of the 120 soil samples were taken randomly from all the AF farmsys and their adjacent monocropping farms; 0-20 cm, 20-40 cm soil depth. The texture was determined by a combination of wet sieving and sedimentation analysis with a micromeritics SediGraph III Particle Sise Analayzer. The wet sieving was done by a vibrating sieve having a mesh sizes 630µm, 200µm, 63µm and 20µm. The grains on each sieve were dried at 105°C and weighed. Particles smaller 20µm that pass through the sieve were collected in a glass and put into the waterbath to reduce the volume of the suspension. The sedimentation was done by mixing the sample on a magnetic stirrer properly and then 50 ml were pipetted out and mixed with 5 ml 0.5% Na-polyphosphate to prevent coagulation. The analysis was performed after the soil pH was determined. The texture classes sand, clay and silt were categorized using textural triangle developed by USDA (1987).

Soil pH was determined in a suspension of 1:2.5 (soil:water) in deionized water and 0.01 molar of $CaCl_2$ solution using a potentiometric pH meter. The measurement was conducted based on Austrian standard (ÖNORM L 1083). The temperature is assumed to be constant during the determination. 5 grams of airdried soil was used for each pH determination and this was performed for the 120 soil samples.

For SOC and N content calculation later 10 grams of soil were prepared and oven-dried at 105 °C for 24 hours to get airdried weight to oven-dry weight proportion before we started determination. 200-250 mg soil from each of the 120 samples was weighed and the SOC and N contents were determined by a LECO TruSpec CN analyzer. The analysis process involved dry combustion at 950 °C in pure O_2 atmosphere and infrared detection of evolved CO_2 and thermal conductivity detection of N_2 (ÖNORM L1080).

Extraction of 7 elements (exchangeable cations) namely Na^+, K^+, Mg^{2+}, Ca^{2+}, Mn^{2+}, Al^{+3} iron and Fe^{2+} were determined by Barium chloride extraction. 50 ml of 1M barium chloride solution and 5 gm of air-dried soil was used. After letting the samples to stay 24 hours and shaking on shaker machine the filtration was done. Following filtration, the exchangeable cations were determined by using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) measurement based on Austrian standard (ÖNORM L 1085). Finally, the result was converted into oven dried soil bases using the moisture percentage of air dried soils. Cation exchange capacity was determined by summing the charge concentration of cations, and the base saturation percentage (BSP) was determined using the following formula:

$$BSP = \left(\frac{Ca+Mg+Na+K}{CEC}\right) \times 100 \quad \text{..} (6)$$

Acid digestion was used to determine the total nutrient of the soil samples. For the analysis 600 mg of oven dried soils were prepared and digested by aqua-regia. Under a fume hood, 15 ml of 37% HCl and 5 ml of 65% HNO3 (in 3 to 1 ratio) were added into a tube with the soil samples. The solution was digested for two hours period, shaked and stayed in micro-wave for 30 minutes at 210 °C and then 40 ml deionized water (almost twice of the existing volume) was added. After filtration using whatman filter paper, the total nutrients were determined by using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) measurement based on Austrian standard (ÖNORM L 1085).

Available phosphorus was determined using the Olson method (Olsen and Sommers, 1982). 2 grams of airdried soil in 25 ml of 0.5 molar of sodium bicarbonate solution was used for extraction. The extraction was done only for 105 soil samples. This is because the remaining 15 samples had higher concentration of Al and were omitted from the list. Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) measurement based on Austrian standard (ÖNORM L 1085) was used for analysing the phosphorus content.

4.2.5 Litterfall biomass and associated C, N, P, K, Ca and Mg fluxes (Study IV)

To assess and determine the litterfall and associated C, N, P, K, Ca and Mg contributed by woody and non woody tree species and shrubs into the system five farms were selected randomly from each agroforestry system. In each AF farm there were three replications. These three litterfall traps were assigned randomly in each agroforestry farm. These traps were fully exposed under the

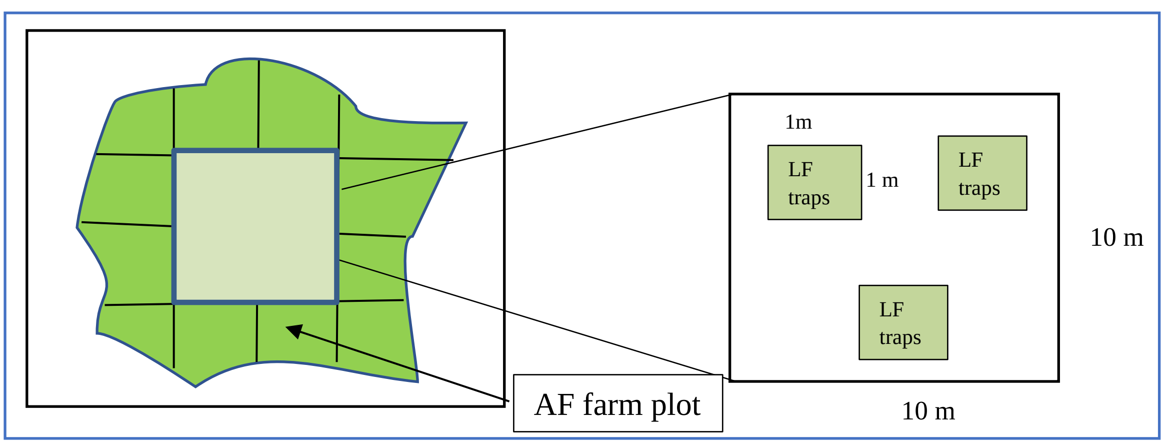


Figure 8. Sample plot layout for litterfall sample collection (three 1 m× 1 m plots) from the 10 × 10 m inventory plot

canopy. The litterfall trap consisted of four 1.5 m tall wooden poles forming a 1×1 m space over which nylon netting (1 mm mesh diameter) was draped and a stone placed in the centre to weigh the netting down. An agreement was attained with the farmers to place the litterfall traps inside their farm and approval of the farmers to set out the litterfall traps. Litterfall collection was carried out for one year (Feb, 2018 - Jan, 2019) and the samples were collected at the end of each month. Litterfall was collected from 15 traps in each agroforestry system (45 intotal) every month successfully.

Laboratory procedure for analysis of plant material

The litterfall samples collected from the 45 traps were air-dried for a day and then oven-dried for 24 h at 65 °C until maintained constant weight. A total of 540 samples were collected throughout the year. The samples were weighed (±0.01 g) following their dry biomass was recorded and then stored for further chemical analysis. By mixing the litterfall samples collected from each trap within each month 3 composite samples were prepared. This was done for the three agroforestry systems. Therefore, finally we prepared 108 composite litterfall samples (3 composite samples from the 5 agroforestry farms × 3 agroforestry systems × 12 Months). The samples were ground to a fine powder in a rotary grinder and then transported to Vienna for the determination of organic carbon (OC), total nitrogen (N) and total nutrients (Ca, Mg, Na, K, P, Mn, Fe, Al and S). Acid digestion method with 10 ml of Nitric acid (HNO3) mixed with 150 µl Octanol (CH3(CH2)7OH) was used for the determination of the parameters. Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) measurement based on Austrian standard (ÖNORM L 1085) was used for analysing all te above parameters. The whole chemical analysis was done in the University of Natural Resources and Life Sciences (BOKU), soil laboratory of the Institute of Forest Ecology.

Figure 9. Litterfall collection and sample preparation in laboratory

Model development and selection

A multiple linear regression model was developed in order to predict whether the dependent and independent variables were significantly related and to measure the strength of their relationship. To select the final model that predicts with statistically significant value, it was used a backward fitting method. During the development of the regression model the dependent variable, monthly litterfall of the three AF systems were predicted by the independent variables (temperature, rainfall, wind speed and relative air humidity). To find the standard regression coefficient, the beta weight (ß) of each independent variables, the multiple correlation, R, and the multiple coefficient of determination, R^2 were taken into account. These four independent variables were included because they were thought to be able to account for more of the variation in the dependent variable. Before the data was analyzed using IBM SPSS software it was standardized. The general model notation used in the multiple linear regression was:

$$Y_i = a + b_1x_1 + b_2x_2 + \ldots\ldots\ldots\ldots\ldots + b_jx_j + e_i$$

Where: Y_i = the ith observed value of the monthly litterfall of the AF systems (dependent variable).

a = Intercept

b_1 to b_4 = Independent variable coefficients

X_1 = Temperature

X_2 = Rainlfall

X_3 = Wind speed

X_4 = Relative air humidity

e_i = Residual error

4.2.6 Role of agroforestry systems in enhancing local community livelihoods (Study V)

4.2.5.1 Sampling and data collection methods

To study the role of agroforestry systems in enhancing the livelihoods of the local community one site out of the three study sites was selected in purposive manner. The farmers in the selected site were practicing mainly C-Ft-E based AF system and the site have four villages. Both primary and secondary data sources were used in this study. The primary data were collected through household survey, focus group discussions, field observation, and key informants interview and market survey.

4.2.6.1.1 Primary data

A) Household survey

Data were collected by using structured and semi-structured questionnaires administered to various respondents of the households at specific village level. During this survey socio-economic data such as occupation, education, household composition, land use activity, agricultural crops, livestock types and productivity, fruit types and productivity, cost of production, revenues, market prices, and sources of income were assessed. Direct field observations were also conducted to support the information generated from the households.

Table 2. Distribution of respondents across the villages

Village name	Number of agroforestry practitioners
Chito	40
Gumata	40
Sharo	40
Tuba	40
Total	160

B) Household Sampling

To get the **primary data/information** from the household, random sampling procedure was used. A list of farmers obtained from the site extension office was used as a sample frame and the total male and female households were recorded. The sample size of households in which an interview was employed was 160. In addition to the household survey, **key informants interview** and **focused group discussion** were employed to collect primary data regarding the role of agroforestry systems in enhancing local community livelihoods. This was intended to gather supporting information and verify the data collected from the households.

4.2.6.1.2 Secondary data

The secondary data were collected from publications, reports, other documents from the district agriculture and natural resource office, district finance and economic development office, regional agriculture and natural resource bureaus and Ministry of Agriculture and Natural Resources, Forest, Environment and Climate Change Commission.

4.2.6.2 Model development and selection

A multiple linear regression model was developed in order to predict whether the dependent and independent variables were significantly related and to measure the strength of their relationship. To select the final model that predicts with statistically significant value, we used a backward fitting method of the R-statistical software. During the development of the regression model the dependent

Figure 10. Photo showing focused group discussion with practitioners in the study site

variable, revenue of household's from C-Ft-E based AF system was predictedby the independent variables (age, land holding, family size, farming experience, off-farm income and household expense) to find the standard regression coefficient, the beta weight (ß) of each independent variables, the multiple correlation, R, and the multiple coefficient of determination, R^2. These six independent variables were included because they were thought to be able to account for more of the variation in the dependent variable. Before the data was analyzed using R-software it was standardized. To get best fitted model with acceptable residual standard error and AIC (akaike information criterion) log transformation was employed for the six explanatory variables. The general model used in the multiple linear regression was:

$$Y_i = a + b_1x_1 + b_2x_2 + \ldots\ldots\ldots\ldots\ldots + b_jx_j + e_i$$

Where: Y_i = the i^{th} observed value of the revenue of the household's farm production (dependent variable).

a = Intercept

b_1 to b_6 = Independent variable coefficients

X_1 = off-farm income

X_2 = Land holding

X_3 = House hold expense

X_4 = Family size

X_5 = Age

X_6 = Farming experience

e_i = Residual error

4.3 Data analysis

4.3.1 Stand characteristics of plant species and diversity analysis (study I and II))

Stand characteristics of the woody species and Enset were calculated for each agroforestry farm and agroforestry system using different formulas. Parameters such as relative frequency, relative abundance, relative dominance, mean diameter at breast height (DBH), height, basal area and stem numbers were calculated one by one and displayed in tables. ANOVA was carried out to test differences among the three agroforestry systems in terms of stand characteristics (abundance, mean dbh, height, basal area, and stem numbers), diversity indices (Shannon diversity index, Simpson's evenness index and Margalef's diversity index) followed by Post hoc testing by means of the LSD test (Fisher's LSD test). This comparison has helped to evaluate differences between one agroforestry system and the another one (Dytham, 2003). Levene's test was also conducted to check homogeneity of variances. To see the relationship between some parameters regression analysis was also employed for multi-stemmed plants mainly in the case of Coffee plant (2 to12 stems per plant) and Mango plant (2-4), each stem was measured and the equivalent diameter of the plant was calculated as the square root of the sum of squared diameters of all stems per plant (Snowdon *et al*., 2002).

$$\mathrm{de\ or\ de40} = \sqrt{\sum_{i}^{n} \mathrm{di}^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Where d_e (cm) = equivalent diameter at breast height, d_{e40} (cm) = equivalent diameter at 40 cm height, di= sum of all squared diameters up to the ith stem

The Shannon diversity index (Shannon and Weaver 1949; Kent and Coker, 1992), Pielou's evenness index (J) and Margalef's diversity index (Dmg) (Magurran, 2004) was calculated for each plot. Sorensen's similarity coefficient was to determine the similarity/dissimilarity between agroforestry systems. species richness and abundance followed by Mann–Whitney U test for multiple comparisons. The following formulas were used for the diversity indices.

$$H' = -\sum_{i=1}^{s} \text{pi lnpi} \qquad \text{...} (8)$$

Where, H' = Shannon Diversity Index, Pi = the abundance of i^{th} species expressed as a proportion of total cover (Shannon and Weaver, 1949; Magurran, 2004). As Negash and Luukkanen (2012) mentioned, the Shannon diversity index is more preferred to know plant species diversity due to its sensitivity to sample size. It also gives more weight in assessing rare plant species.

$$J = \frac{H'}{H'max} \qquad \text{..} (9)$$

where: J = Pielou's evenness (Equitability) (Pielou, 1966), H' = Shannon-Wiener diversity index and H'max = ln S where "S" is the number of species. J has values between 0 and 1.0, where 1.0 represents a situation in which all species are equally abundant.

$$D_{\text{Mg}} = \frac{(S-1)}{\ln(N)} \qquad \text{..} (10)$$

Where D_{Mg} is Margalef's richness index, S = species richness, N= the total number of individuals in the plot

$$Ss = \frac{2a}{2a+b+c} \qquad \text{...} (11)$$

Where: S_s = Sorensen's similarity coefficient, a =number of species common to both samples, b =number of species in sample 1 but not in 2, c =number of species in sample 2 but not in 1

Another very important index which is used to investigate the structural role of each plant species in the sampling plots is important value index (IVI). It was calculated using the percentage of relative abundance (R.A.), relative dominance (R.D.) and relative frequency (RF). Therefore, to investigate the importance value index (IVI) of each species we used the following formulas

IVI (%) = Relative abundance + Relative dominance + Relative frequency, Where

$$\text{Relative abundance} = \frac{\text{Number of individual s of woody species}}{\text{Total number of woody individual s}} \times 100 \quad \text{..............................} \ (12)$$

$$\text{Relative dominance} = \frac{\text{Basal area of each species}}{\text{Basal area of all species}} \times 100 \quad \text{.......................................} (13)$$

$$\text{Relative frequency} = \frac{\text{Chance to find each species}}{\text{Chance to find all species}} \times 100 \quad \text{...} (14)$$

Analysis of species conservation concern

It is very important to assess the conservation concern of species for sustainable maintainance of the plant species in our AF landscapes. Species conservation concern (rare, threatened, vulnerable, least concern) of each studied AF types were analysed. Geographical distribution, habitat preference and population size are the main factors to take into account and then to classify species as rare (Martins, 2010). To analyse species conservation concerns in our study three approaches were used: (i) those woody or non-woody species retained in the different agroforestry systems and listed as of least concern, threatened/vulnerable by IUCN Red Lists (Edwards and Kelbessa 1999; Vivero *et al*., 2005); (ii) 25% of species that have the least occurrence in each AF type (Magurran, 2004); and (iii) based on local criteria (Bekele *et al*., 1999; Gebremariam *et al*., 2009). The local criteria might be based on the information from published and unpublished documents. Under this species conservation concern categorization approach it was used the classes made by the Woody Biomass Inventory and Strategic Planning Project (Bekele *et al*., 1999). The above study has covered about 60% of the area in Ethiopia and the classification includes those species with a population density below 100,000 individuals in the country.

4.3.2 Differences in dry biomass and biomass C stocks (study II)

By using the allometric equations the biomass of the trees and shrubs, Coffee and Enset was estimated for all 60 farms (plots). However, the ecosystem C stocks (in biomass and soil) were calculated only for the 30 farms (plots), implying 10 farms from each agroforestry system. This was because the soil and litter samples were only taken from randomly selected 30 agroforestry plots. In addition, C stocks in the litter from the 10 farms were also calculated. The biomass, biomass carbon stocks for each agroforestry system were described using the mean, minimum, maximum and standard deviation statistics. To test for differences in the dry biomass between the three agroforestry systems a one-way ANOVA followed by post-hoc testing (Fisher's LSD test) was used used. Levene's test was conducted to check homogeneity of variances. Linear regression analyses was also performed to analyse the relationship between some parameters.

4.3.3 Differences in soil organic carbon stocks and soil nutrient relations (OM, N, P, K, Ca, Mg, C:N ratio) (study II and III)

The soil carbon stocks of each agroforestry system and their adjacent monocropping farms were calculated layer by layer and the means were compared. On top of this, the soil macro nutrients and fertility indicators such as OM, N, P, K, Ca and Mg were calculated their content layer by layer for the same farms. The C:N ratios for agroforestry farms as well as their adjacent monocrop farms were also calculated. To test for differences in the above mentioned parameters between and among the three agroforestry and their corresponding adjacent mono-cropping farms a one-way ANOVA followed by post-hoc testing (Fisher's LSD test) was used. For comparison of agroforestry systems with adjacent monocropping farms pairwise 2-tailed T-test was conducted. Levene's test was conducted to check homoginity of variances. Pearson correlation analyses was also performed to see the relationship among soil nutrients.

4.3.4 Differences in litterfall and associated C, N, P, K, Ca, and Mg fluxes (Study IV)

Litterfall production per unit area of the three agroforestry systems was calculated on monthly and annual bases. The monthly litterfall biomass (g m^{-2}) was calculated by dividing the average of combined litterfall mass by the combined surface area of the traps. The annual litter fall production was also calculated by summing up the values of 12 months and then extrapolated to tonnes per hectare. The annual carbon flux and associated nutrients (N, P, K, Ca, and Mg**)** was calculated by multiplying the annual litterfall production (kg ha^{-1} y^{-1}) by the content (%) for C and N, and the nutrient concentrations for P, K, Ca, and Mg. The monthly flux of nutrients was also calculated in the same manner. Descriptive statistics such as mean and standard deviations were used to show the monthly and annual litterfall production, C and N contents, C:N ratio and the other nutrient fluxes for each agroforestry system. The inter-monthly variation of litterfall production per unit area for each agroforestry system was also calculated.

Inter-monthly variation (%) = (max - min/max) × 100 ....(15)

Where max = maximum monthly litterfall production, min = minimum monthly litterfall production (Silva *et al*., 2011).

A multiple linear regression analysis was also conducted to develop model for litterfall and climatic factors that affect the litterfall production.

4.3.5 Role of agroforestry systems in enhancing local community livelihoods (Study V)

The data that were collected during the survey generated both qualitative and quantitative data. The survey primary assessed the contribution of agroforestry in enhancing livelihood of the community. The focus group discussion and farm survey data were analyzed by using descriptive and econometric procedures. All the qualitative responses were summarized, categorized and coded into numeric values and then entered into IBM SPSS software version 22 (SPSS Inc.2010), R-software and Microsoft window excel (2010). Descriptive statistics of the data such as frequency, mean, percentile was analyzed and the results were displayed in tables, bar graphs, box plots etc. The production cost and benefit data obtained from the household survey were analyzed by employing Cost Benefit Analysis. In the Cost Benefit Analysis economic performance indicator benefit cost ratio (BCR) was used.

The statistical analyses in all parts of the thesis were done using Statistical Package for Social Sciences -IBM SPSS version 26 (SPSS Inc. 2019), R-software, Microsoft Window Excel (2016).

5. RESULTS AND DISCUSSION

5.1 Plant diversity and conservation in indigenous agroforestry systems

5.1.1 Perennial plant species composition

Agricultural landscapes practicing agroforestry (AF) systems are nowadays maintaining perennial woody and non-woody plant species diversity. Conservation of these biological resources should not be restricted to forest areas alone since these are endangered by the encroachment in an increasing way (Kasa *et al*., 2015). A total of 52 perennial woody and non woody plant species belonging to 30 families were recorded (Appendix 1). Out of this number the 31 plant species were recorded from the 60 inventoried quadrants while the remaining 21 plant species were recorded out of the 60 quadrants. The highest number of species was recorded in C-Ft-E based AF system (22) (Table 3) whereas the least was in Enset based AF system (15) (Table 4).

The cumulative species richness in our study sites (52 species) was within the range of woody and non-woody species recorded in AF systems of Southern Ethiopia (50-120 plant species) (Abebe *et al*., 2006; Tamrat, 2011; Negash and Achalu, 2008; Asfaw and Woldu, 1997) and in central Ethiopia which ranged from 27-114 species (Tolera *et al.*, 2008; Duguma and Hager, 2010; Mengesha, 2010; Kebede, 2010). However, the species richness of the present study was higher than in north Ethiopia which ranged from 17-40 species (Fentahun and Hager, 2009; Haileselasie and Hiwot, 2012). In addition, our results showed higher richness over three agroforestry practices in Wolayta zone of Southern Ethiopia with 32 woody species belonging to 19 families (Bajigo and Tadesse, 2015); 39 woody species belonging to 25 plant families recorded by Tefera *et al*. (2016) in the same district of South-eastern rift-valley landscapes in which our study was conducted but different specific sites. It was also tried to compare the woody and non woody species richness in our study sites with other East African countries. Accordingly, species richness of the present study was also a bit higher than reported in Coffee based AF system, Eastern Uganda (50 woody species; Negawo and Beyene, 2017). Therefore, the AF systems in our study sites somehow seemed to have fairly high plant species richness.

Higher plant species richness than in our study were also recorded in different study areas of the country as well as other tropical countries: 55 woody species for traditional agroforestry practices of Dellomenna district of South-eastern Ethiopia (Molla and Kewessa, 2015), 58 wood species for

Gedeo Zone of Southern Ethiopia (Negash and Luukkanen, 2012), 69 for the compound farms of Nigeria (Okafor and Fernandes, 1987), 77 woody species for Kandy in Srilanka (Perera and Rajapakse, 1990), 83 species for Nicaragua (Mendez *et al*., 2001), 100 species for Yem special district of Southern Ethiopia (Kasa *et al*., 2015) 129 species for Kerala in India (Kumar *et al*., 1994), 168 species for Peruvian Amazon (Padoch and Jong, 1991) and 179 species for West Java (Soemarwoto, 1987), 289 woody plants from sub-urban areas in Sri Lanka (Kumari, 2009) and 459 tree and shrub species around Mt. Kenya in central and eastern Kenya (Oginosako *et al*., 2006). The higher species richness in these study sites might be related to the scale of areal coverage included in the study and the range of agro-climatic zones. Because, some authors argued that the wider the scale of the study in terms of areal coverage (Abebe, 2005) and wider altitudinal range (Nogue´s-Bravo, 2008), the better probability of getting more additional woody species adapted to different agroecology. For instance, our study was conducted in three sites. But, had it been in more than three sites there would be a possibility of getting more than 52 woody plant species. Abebe (2005) reported that the variation in plant species richness in different study areas could be also related with the difference in site characteristics (farm size, altitude), management strategy of the practitioner and socioeconomic factors. O'Neill *et al*. (2001) and Demissew (2014) added that trees and shrubs preference of farmers to plant for different functions could also contribute for the variation in species richness in a particular AF system. In general, owning such number of woody species richness under agroforestry systems of the present study showed a good potential to serve as a haven for biodiversity conservation.

Out of the 30 families recorded, three families had highest number of woody species Fabaceae (represented by 5 species), Myrtaceae (4) and Euphorbiaceae (3). While Francoaceae, Rhizophoraceae, Rubiaceae, Anacardiaceae, Lauraceae, Boraginaceae, Rhamnaceae, Asteraceae, Dracaenacea, Caricaceae, Annonaceae, Solanaceae, Cupressaceae, Salicaceae and Phyllanthaceae were only represented by one species either from woody or non-woody species (Appendix 1). In general, the small number of families (10%) were represented by 5, 4 and 3 perennial woody and non-woody plant species while the majority of the families (50%) were represented by a single species. The remaining 40% of the families were represented by two species. The highest number of perennial woody or non-woody plant species in our study was represented by the family Fabaceae. Similar studies conducted in different AF systems by Kasa *et al*. (2015), Negash *et al*. (2012), and Bajigo and Tadesse (2015) found also that the family Fabaceae scored with highest number of species compared to other families. The assessment regarding the origin of the woody and non woody species across the three agroforestry systems (n=60) showed that, 33 of 52 (63.5%) were native while the remaining 19 of 52 (36.5%) were exotic.

The highest native perennial woody and non-woody plant species number was registered in Enset based AF system with 14 out of 15 species (93.3 %) while the least was in C-Ft-E based AF system with 13 out of 22 species (59%).The average native plant species percentage in the present study (63.5%) was higher than in a study reported from homegardens of six regions in South-western Bangladesh with 247 out of 419 (59%) (Kabir and Webb, 2009). However, it was lower than the one study reported in similar study zone with different sampling sites where 50 out of 58 (86%) were native species (Negash *et al*., 2012). In general, maintaining such quite significant number of tree and shrub species in our study sites, both native and exotic in origin implies a great role of these indigenous AF systems in the conservation of plant genetic resources. This was reported by Michon, *et al*., (1983) and Kessy (1998) who conducted a research on homegarden agroforestry systems of west Java and East Usambara of Indonosia.

As the plant species inventory results under tables 3, 4 and 5 displayed, more native plant species were registered in Enset based and C-E based AF systems than the C-Ft-E based AF systems. This might be due to practitioners established these AF systems by thinning the previous existing natural forests. It has been also a common practice to deliberately kept native trees for the purpose of shading for Coffee or/and soil fertility and other ecosystem services. For instance, *Millettia ferruginea (Hochst.) Baker* and *Cordia africana* Lam. have been used as shade for Coffee because of their less dense crown and scattered branches. In addition, the practitioners believed that *M. ferruginea (Hochst.) Baker* has the ability to improve soil fertility and enhance the productivity of crop and vegetables that grow beneath them (Hailu *et al*., 2000). However, in the case of C-Ft-E based AF systems the plots were dominated by exotic fruit species such as *Persea americana, Musa acuminata, Psidium guajava, Carica papaya* and *Mangifera indica.* The dominance of exotic species in this type of AF might be due to high number of fruit tree species which were more or less introduced by development missionaries and domesticated for the lower altitude areas (Negash and Ashalu, 2008). In lower altitude areas warmer temperatures are mostly refelected. This situation in turn may assist better litter decomposition and thus soil fertility, which favours growth of variety of plants. Introduction of these exotic species might affect the existence of native species implying that they could be replaced by the exotic ones due to shortage of space for proper growing. These exotic species may be also attractive for the farmers because of their vaues for consumption and in the market.

5.1.2 Plant species endemism and conservation concern

Biodiversity conservation of plant species usually focuses on conserving either endemic, threatened, vulnerable or economically, ecologically and culturally useful plants for the human beings (Berhanu and Afaw, 2014). We have assessed the potential of the three AF systems in conservation of native and endemic woody and non-woody perennial species. According to our results, *M. ferruginea (Hochst.) Baker* and *Erythrina brucei* were some of the common woody species found across the three agroforestry systems in our study area and they are registered as native and endemic. However, because of anthropogenic drivers it has been argued that the species distinctiveness expressed in terms of their presence as rare species or endemic species of AF systems is low compared to forest areas (Bhagwat *et al*., 2008). Therefore, the reason for small number of endemic woody and non-woody perennial species in the present study might be related with anthropogenic activities such as removal of native trees and replacing with some cash crops and exotic fruit trees.

Species conservation concerns of AF systems is also one of the important issues to deal with. As our inventory from the three agroforestry systems showed that a total of 13 species were listed as species of conservation concern according to the IUCN Red Lists and local criteria. *M. ferruginea, Erythrina brucei, Dracaena steudneri, Senna siamea, Trichilia dregeana, Melia azedarach L., Azadirachta indica var., Albizia grandibracteata Taub., Bridelia micrantha (Hochst.) Baill*. were listed under the least concern by IUCN red lists (Vivero *et al*., 2005). *Rhamnus prinoides* was listed as both rare for 25% of species that least occurred (Magurran, 2004) and as least number of individuals (\100,000 individuals in the country) as per local criteria (Bekele *et al*., 1999). *Prunus africana* was listed as both vulnerable by IUCN red lists (Vivero *et al*., 2005) and rare for 25% of species that least occurred (Magurran, 2004). *Albizia gummifera* and *Ficus vasta* were listed as rare for 25% of species that least occurred (Magurran, 2004). The number of species listed under IUCN Red List in the present study (10 out of 52) were higher than reported in South-western Bangladesh

(6 out of 419) (Kabir and Webb, 2009). In terms of proportion from the total species, the number of Red List species in our study (25%) was by far higher than the reported in South-western Bangladesh (1.4%). This difference may be due to the physiogeographic situation of Ethiopia (East African highland) as compared to Bangladesh.

The assessment of species in terms of rarity within the inventoried 60 agroforestry smallholdings showed that the occurrence of five native species was very limited to certain plots. According to the result displayed in figure 11, woody species such as *Combretum sp., P. africana*, *Ficus sur Forssk, S. siamea (C. siamea) and T. dregeana* occurred only in one plot, implying that these are rare species which demand conservation and need to be maintained by the practitioners.

5.1.3 Plant species frequency and important value index

Frequency of perennial woody and non woody plant species across the three agroforestry systems (60 plots) in our study sites were checked. It was found that, 4 of the most frequent species occurred in over 25 plots out of the 60 AF plots. *E. ventricosum* was the most frequent species occurring in 60 plots. It was followed by *M. ferruginea (*in 46 plots), *Coffea arabica L.* (in 39 plots) and *C. africana* (in 29 plots) (figure 11). A study conducted in similar zone but under different site conditions reported that *C. arabica, C. africana* and *M. ferruginea* were the most frequent woody species (Tefera *et al*., 2016). On the other hand, 5 woody species were very rare each occurring only in one of the AF plots. These four most frequent species are native species by origin. The reason for more frequency and abundancy of *E. ventricosum* is due to its greater economic importance for the community. In addition, all the three indigenous AF systems also contained this very important food plant. The plant has been used as source of staple food by the community and the leaves, stem and left over from the main product are used as source of fodder for their livestock during drought season. This idea depicts the result reported by Molla and Kewessa (2015) who mentioned plant species with a greater economic or/and ecological value were found to be more frequently distributed across the smallholdings. *M. ferruginea* also showed higher frequency. This might be mainly due to the fact that this multipurpose tree is used as shade for *C. arabica* and finally it is better adapted the area, and propagation and management of the species is easy (Negash *et al*., 2012). It has also the ability to increase productivity of crops planted beneath because of its improvement of soil fertility (Hailu *et al*., 2000). The third most frequent species was *C. arabica*.

The reason why coffee has higher frequency might be related to its economic importance in bringing cash income for the household and thus in enhancing the livelihood (Kanshie, 2002; Abebe, 2005; SLUF, 2006).

Table 3. List of perennial woody and non woody plant species and their important value index under C-Ft-E based AF system, South-eastern rift-valley landscapes, Ethiopia

Scientific name	Family	Fre n	RF (%)	Tot Dom	RD (%)	AB	RA (%)	IVI (%)
*Ensete ventricosum (*Welw. Cheesman*)*	Musaceae	20	15.4	16.9	58.6	363.0	29.4	103.4
Coffea arabica L.	Rubiaceae	19	14.6	2.0	7.0	310.0	25.1	46.7
Mangifera indica L.	Anacardiaceae	16	12.3	0.9	3.1	108.0	8.8	24.1
Spathodea campanulata	Bignoniaceae	3	2.3	0.4	1.5	5.0	0.4	4.2
Millettia ferruginea (Hochst.) Baker	Leguminosae	12	9.2	0.6	2.1	64.0	5.2	16.6
Persea americana Mill.	Lauraceae	16	12.3	1.3	4.5	59.0	4.8	21.6
Prunus africana	Rosaceae		0.0	0.0	0.0	0.0	0.0	0.0
Carica papaya	Caricaceae	8	6.2	0.1	0.2	22.0	1.8	8.2
Musa acuminata	Musaceae	15	11.5	3.4	11.8	234.0	19.0	42.3
Psidium guajava	Myrtaceae	1	0.8	0.0	0.0	1.0	0.1	0.9
Cordia africana Lam.	Boraginaceae	5	3.8	0.1	0.5	16.0	1.3	5.7
Ficus vasta Forsk.	Moraceae	1	0.75	1.5	5.15	1.0	0.1	6.0
Rhamnus prinoides L. Herit.	Rhamnaceae	1	0.8	0.0	0.0	4.0	0.3	1.1
Albizia gummifera (J.F. Gmel.) C.A.Sm	Fabaceae	1	0.8	0.0	0.0	4.0	0.3	1.1
Annona chrysophylla	Annonaceae	2	1.5	0.0	0.2	22.0	1.8	3.5
Casimiroa edulis Lal lave and Lex	Rutaceae	4	3.1	0.0	0.0	11.0	0.9	4.0
Solanum betaceum	Solanaceae	1	0.8	0.0	0.0	1.0	0.1	0.9
Ficus sur Forssk.	Moraceae	1	0.75	1.5	5.15	1	0.1	6.0
Leucaena leucocephala	Mimosoideae	1	0.8	0.0	0.0	2.0	0.2	0.9
Erythrina brucei Schweinf.	Leguminosae	1	0.8	0.0	0.2	2.0	0.2	1.1
Maytenus senegalensis	Celastraceae	1	0.8	0.0	0.0	2.0	0.2	0.9
Trichilia dregeana	Meliaceae	1	0.8	0.0	0.0	1.0	0.1	0.9

Fre: frequency; RF: relative frequency; Tot Dom: total dominance; RD: relative dominance; AB: abundance; RA: relative abundance; IVI: important value index

Table 4. List of perennial woody and non woody plant species and their important value index under Enset based indigenous AF, South-eastern rift-valley landscapes, Ethiopia

Scientific name	Family	Fre n	RF (%)	Tot Dom	RD (%)	AB	RA (%)	IVI (%)
Ensete ventricosum (Welw. Cheesman)	Musaceae	20.0	30.3	61.3	96.1	743.0	78.2	204.6
Millettia ferruginea (Hochst.) Baker	Leguminosae	19.0	28.8	0.9	1.3	102.0	10.7	40.9
Prunus africana	Rosaceae	1.0	1.5	0.0	0.0	4.0	0.4	1.9
Cordia africana Lam.	Boraginaceae	11.0	16.7	0.9	1.4	39.0	4.1	22.2
Rhamnus prinoides L. Herit.	Rhamnaceae	1.0	1.5	0.0	0.0	6.0	0.6	2.1
Albizia gummifera (J.F. Gmel.) C.A.Sm	Fabaceae	2.0	3.0	0.2	0.3	6.0	0.6	3.9
Solanum betaceum	Solanaceae	1.0	1.5	0.0	0.0	3.0	0.3	1.9
Erythrina brucei Schweinf.	Leguminosae	3.0	4.5	0.0	0.1	14.0	1.5	6.1
Senna siamea (Cassia siamea)	Fabaceae	1.0	1.5	0.0	0.0	4.0	0.4	2.0
Combretum sp.	Combretaceae	1.0	1.5	0.0	0.0	4.0	0.4	1.9
Vernonia amygdalina Delile	Asteraceae	1.0	1.5	0.2	0.3	4.0	0.4	2.2
Dracaena steudneri Schweinf. ex Engl	Dracaenaceae	1.0	1.5	0.0	0.0	11.0	1.2	2.7
Crot macrostachyus	Euphorbiacee	2.0	3.0	0.2	0.4	6.0	0.6	4.0
Maytenus senegalensis	Celastraceae	1.0	1.5	0.0	0.0	1.0	0.1	1.6
Dovyalis abyssinica	Salicaceae	1.0	1.5	0.0	0.0	3.0	0.3	1.9

Fre: frequency; RF: relative frequency; Tot Dom: total dominance; RD: relative dominance; AB: abundance; RA: relative abundance; IVI: important value index

Table 5. List of perennial woody and non woody plant species and their important value index under C-E based indigenous AF system, South-eastern rift-valley landscapes, Ethiopia

Scientific name	Family	Fre n	RF (%)	Tot Dom	RD (%)	AB	RA (%)	IVI (%)
Ensete ventricosum (Welw. Cheesman)	Musaceae	20.0	20.8	41.3	89.8	594.0	48.6	159.2
Coffea arabica L.	Rubiaceae	20.0	20.8	1.3	2.7	400.0	32.7	56.3
Spathodea campanulata	Bignoniaceae	1.5	1.55	0.1	0.2	4.0	0.3	2.1
Mangifera indica L.	Anacardiaceae	1.5	1.55	0.1	0.2	4.0	0.3	2.1
Millettia ferruginea (Hochst.) Baker	Leguminosae	15.0	15.6	0.9	2.0	76.0	6.2	23.9
Persea americana Mill.	Lauraceae	1.0	1.0	0.0	0.0	0.0	0.0	1.0
Psidium guajava	Myrtaceae	2.0	2.0	0.0	0.0	10.0	0.4	1.6
Cordia africana Lam.	Boraginaceae	13.0	13.5	1.7	3.8	48.0	3.9	21.3
Ficus vasta Forsk.	Moraceae	1.0	1.0	0.1	0.2	1.0	0.1	1.4
Rhamnus prinoides L. Herit.	Rhamnaceae	2.0	2.1	0.0	0.0	16.0	1.3	3.4
Albizia gummifera (J.F. Gmel.) C.A.Sm	Fabaceae	5.0	5.2	0.1	0.3	14.0	1.1	6.7
Leucaena leucocephala	Mimosoideae	1.0	1.0	0.0	0.0	5.0	0.4	1.5
Erythrina brucei Schweinf.	Leguminosae	3.0	3.1	0.0	0.0	13.0	1.1	4.2
Jacaranda mimosifolia	Bignoniaceae	1.0	1.0	0.0	0.1	5.0	0.4	1.5
Vernonia amygdalina Delile	Asteraceae	1.0	1.0	0.0	0.0	4.0	0.3	1.4
Dracaena steudneri	Dracaenaceae	1.0	1.0	0.0	0.0	8.0	0.7	1.7
Crot macrostachyus	Euphorbiacee	2.0	2.1	0.0	0.1	8.0	0.7	2.8
Ficus sur Forssk.	Moraceae	1.0	1.0	0.1	0.3	2.0	0.2	1.5
Dovyalis abyssinica	Salicaceae	1.0	1.0	0.0	0.0	2.0	0.2	1.2
Clausena anisata (Willd.) Benth.	Rutaceae	2.0	2.1	0.0	0.1	8.0	0.7	2.8
Euphorbia abyssinica	Euphorbiaceae	2.0	2.1	0.0	0.0	6.0	0.5	2.6

Fre: frequency; RF: relative frequency; Tot Dom: total dominance; RD: relative dominance; AB: abundance; RA: relative abundance; IVI: important value index

The important value index (IVI%) of each perennial woody or non woody plant species in each of the studied AF systems was calculated to determine the significance of each species in the system. According to the results, five plant species with the highest important value index in Coffee-Fruit tree- Enset based indigenous agroforestry system were *E. ventricosum*, *Coffea arabica L.*, *M. acuminata*, *M. indica L.* and *P. americana Mill.* respectively (Table 6). In comparison to the first and third AF system the Enset based AF system exhibits a higher IVI% for the species Enset. Besides the lead species, the system includes four more different tree species which are important multipurpose species, namely *M. ferruginea (Hochst.) Baker*, *C. africana Lam.*, *Erythrina brucei Schweinf.* and *Crot macrostachyus*. In the C-E based AF system there is besides the lead species Coffee and Enset a certain species overlap with the second AF system.

Table 6. The five woody species and Enset with the highest important value index across the three indigenous AF systems in South-eastern rift-valley landscapes, Ethiopia

Agroforestry system	Species Scientific name	Important value index (IVI %)
C-Ft-E based AF system	*Ensete ventricosum (Welw. Cheesman)*	103.4
	Coffea arabica L.	46.7
	Musa acuminata	42.3
	Mangifera indica L.	24.1
	Persea americana Mill.	21.6
Enset based AF system	*Ensete ventricosum (Welw. Cheesman)*	204.6
	Millettia ferruginea (Hochst.) Baker	40.9
	Cordia africana Lam.	22.2
	Erythrina brucei Schweinf.	6.1
	Croton macrostachyus	4.0
C-E based AF system	*Ensete ventricosum (Welw. Cheesman)*	159.2
	Coffea arabica L.	56.3
	Millettia ferruginea (Hochst.) Baker	23.9
	Cordia africana Lam.	21.3
	Albizia gummifera (J.F. Gmel.) C.A.Sm	6.7

C-Ft-E based AF: Coffee-Fruit tree- Enset based indigenous AF system; Enset based AF: Enset based agroforestry system; C-E based AF: Coffee-Enset agroforestry system

The important value index of *E. ventricosum* was recorded the highest across the three AF systems. This was due to the species showed a high relative frequency, relative abundance and relative dominance in each agroforestry system. The variation in important value index for various woody or non woody species among the AF systems might be related to farmers' species preference, growth performance and may be also related to original stocking density in the sample quadrants (Bajigo and Tadesse, 2015).

Under C-Ft-E based AF system the majority of the plant species with the highest IVI% were exotic species specifically fruit trees whereas in Enset based and C-E based AF system all the species with highest IVI% were native ones. These results coincide with the report on plant species inventory (part 5.1.1) of this study which found a higher percentage of native species under Enset based and C-E based AF system while the C-Ft-E based AF system had lower numbers of native species.

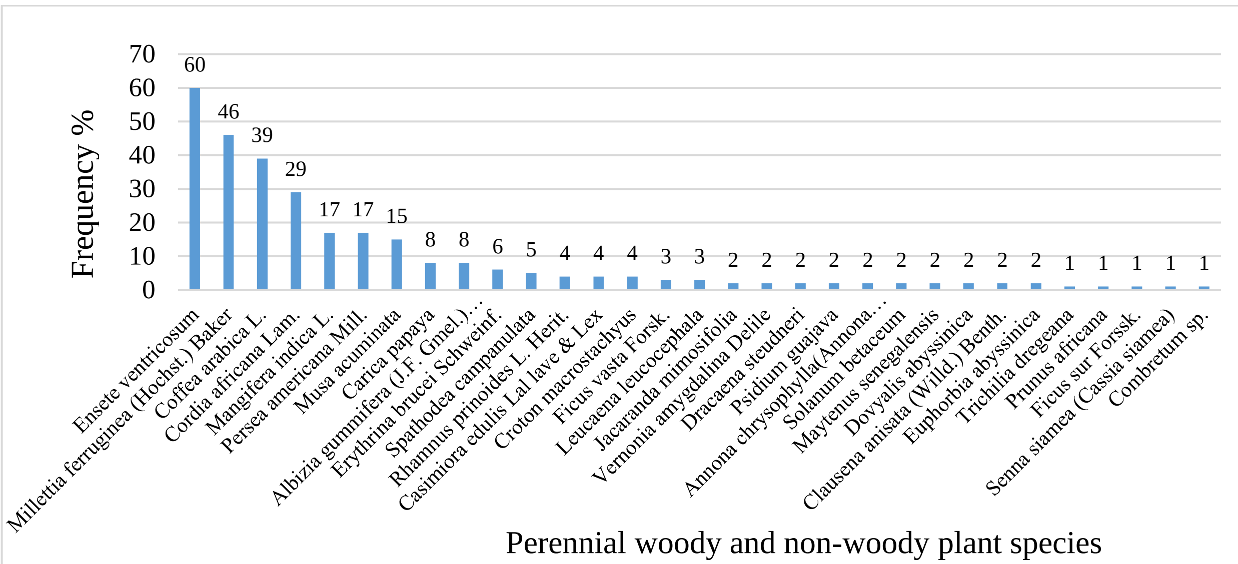


Figure 11. Frequency of woody species and Enset across the three AF systems (60 plots) of the study sites, South-eastern rift-valley landscapes, Ethiopia

5.1.4 Stand structure, diversity and richness status of agroforestry systems

The average number of stems in each quadrant, mean basal area, diameter at breast height (DBH) and height of the perennial woody and non woody plant species was computed. Dealing with these variables could help to determine and compare the stand structure of the three studied AF systems. The inventory was carried out in the 10×10 m farm plots which constitute 20 farm plots from each AF system. Out of the three AF systems, Enset based AF system showed the highest stem number, basal area, height and diameter at breast height (DBH) for Enset species isolately (Table 7). Whereas the lowest value for these parameters was found in C-Ft-E based AF system (Table 7). The mean stem number, basal area and DBH of woody species isolately were higher under C-Ft-E based AF system. Whereas Enset based AF system showed the highest in terms of woody species mean height (Table 8). The least mean values for the woody species in terms of stem number and basal area were recorded under Enset based AF system (Table 8). The computation of these four parameters were also carried out for the mixture of woody and Enset species for each AF system. The highest mean stem density was recorded in C-Ft-E based AF system (71.2 stems) while the least was in Enset based AF system (44.6 stems) (Table 9). The highest average height of the plant cover was recorded in Enset based AF system (4.59 m) and the least was in C-E based AF system (4.3 m). The combined mean stem density (57.3 per 100 m^2 or 5730 ha^{-1} when extrapolated to hectare basis) for all 60 farm plots in the present study was much higher than that was reported by Negash *et al*. (2012) who found stem density of woody species in Enset based AF (625 ha^{-1}), Enset-Coffee based AF (1240 ha^{-1}) and Fruit-Coffee AF (1505 ha^{-1}) systems of South-eastern Ethiopia. Similarly, Abebe (2005) and Jensen (1993) also reported 636 trees ha^{-1} in Enset-Coffee-Maize AF systems of Southern Ethiopia and 1833 trees ha^{-1} in homegardens of west Java respectively which is lower than the mean values of the present study. The greater difference in mean value of our results and those reported by other authors could be explained that Enset was included in the calculation. As the result in tables 3, 4 and 5 displayed, Enset is the most dominant and abundant species across all three AF systems and thus affect the stem density.

The one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=20) showed that the mean stem density, basal area, height and DBH of Enset species for Enset based AF system was significantly different at ($P<0.05$) from C-Ft-E based AF system (Table 6). In addition, Enset based AF system has showed significant difference from C-E based AF only for mean basal area (Table 7). The computed values of woody species under the three AF systems showed that C-Ft-E based AF system was significantly different at ($P<0.05$) from Enset based AF for their mean stem density, basal area and height (Table 8). In addition, the stem number, height and DBH of Enset based AF was significantly different from C-E based AF systems. Under table 9 , the computation for their mean stem density, basal area, height and DBH were conducted for all the woody and Enset species as mixure for the three AF systems. C-Ft-E based AF system was significantly different at ($P<0.05$) from Enset based for their mean stem density, basal area and DBH. In addition, C-Ft-E based and Enset based AF system were significantly different from C-E based AF system for their basal area and DBH. But, for the height of the species there was no significant difference between the AF systems (Table 9). The density of plant species in AF systems is related to ecological (altitude, rainfall and temperature issues) (Abebe, 2005) and socioeconomic conditions (marketing, size of land holding) (Abebe, 2005; Wiersum, 1982; Jensen, 1993). The highest mean basal area and mean DBH of plant species in Enset based AF system was found to be 317.7 m^2 ha^{-1} and 26.7 cm respectively. The least mean basal area and mean DBH of species in C-Ft-E based AF was found be 149.2 m^2 ha^{-1} and 15.7 cm respectively.

The mean basal area and mean DBH of all species significantly differed ($P<0.05$) between the three agroforestry systems (Table 8). According to the computed mean basal area values for each species, *E. ventricosum* (58.6%), *Musa acuminate* (11.8%) and *C. arabica* (7.0%) in C-Ft-E based (Table 3) and *E. ventricosum* (96.1%), *C. africana* (1.4%) and *C. macrostachyus* (0.4%) in Enset based (Table 4) had the highest relative dominance. Under C-E based AF system *E. ventricosum* (89.8%), *C. africana* (3.8%) and *C. arabica* (2.7%) showed highest relative dominance (Table 5). The share of native perennial woody and non woody plant species in terms of relative dominance was 80%, 99.9% and 99.5% in C-Ft-E based, Enset based and C-E based AF systems respectively. Therefore, the above results revealed that native species almost fully dominate the horizontal space especially in Enset based and C-E based AF systems. The average stem number (2083.3 stems ha^{-1}) and basal area (29 m^2 ha^{-1}) of woody species recorded in the present study was higher than that reported in other indigenous AF systems of south-eastern Ethiopia (Negash *et al*., 2012), in Coffee-based agroforests in Guinea (Correia *et al*., 2010) and in Cocoa agroforest and mixed food agroforest in South-eastern Ghana (Asase and Tetteh, 2010). The greater difference in stem number and basal area of this investigation and those reported by other authors might be related to the tendency of the farmers to maintain more native trees from previous forest land and planting of more exotic Fruit trees and Coffee.

To see the relationship between basal area and DBH, and basal area with stem number for mixture of woody and Enset species a regression graph was constructed. Our result displayed in figure 14 (A) showed that the mean basal area was increased withincreasing mean DBH with a correlation of (r^2 =0.6). The correlation between basal area and DBH by separate computing of woody species and Enset was from very low to low respectively (Figure 12 A and 13A). The mean basal area of Enset and woody species separately within the AF systems was some how affected by stem number although the correlation was low with values of r^2 =0.31 and r^2 =0.23 respectively (Figure 12 B and 13 B). However, ignoring some outliers, the mean basal area was not affected by the mean

Table 7. Mean stem number, basal area (BA), height and diameter at breast height (DBH) of Enset species for each AF system, followed by SE in parenthesis.

Agroforestry system	n	Stem number (No/100 m^2)	Basal area (m^2 ha^{-1})	Height (m)	DBH (cm)
C-Ft-E based AF	20	13.1(2.0)$^{(a)}$	81.2(9.3) $^{(a)}$	3.6(0.2) $^{(a)}$	24.2(1.4) $^{(a)}$
Enset based AF	20	34.7(2.7)$^{(b)}$	306.4(28.8) $^{(b)}$	4.4(0.2) $^{(b)}$	31.0(1.7) $^{(b)}$
C-E based AF	20	29.3(2.8)$^{(b)}$	207.0(15.1) $^{(c)}$	4.1(0.2) $^{(b)}$	28.8(1.8) $^{(ab)}$
P-value		<0.05	<0.05	<0.05	<0.05

C-Ft-E based AF: Coffee-Fruit tree-Enset based AF; C-E based AF: Coffee-Enset based AF

Table 8. Mean stem number, basal area (BA), height and diameter at breast height (DBH) of woody species for each AF system, followed by SE in parenthesis.

Agroforestry system	n	Stem number (No/100 m^2)	Basal area (m^2 ha^{-1})	Height (m)	DBH (cm)
C-Ft-E based AF	20	31.2(3.5)$^{(a)}$	53.8(10.4) $^{(a)}$	4.2(0.2) $^{(a)}$	11.8(0.5) $^{(a)}$
Enset based AF	20	9.3(1.7)$^{(b)}$	11.3(2.5) $^{(b)}$	6.0(0.8) $^{(b)}$	11.2(1.3) $^{(a)}$
C-E based AF	20	22.0(1.1)$^{(c)}$	21.9(4.1) $^{(bc)}$	3.6(0.2) $^{(ac)}$	8.1(0.3) $^{(b)}$
P-value		<0.05	<0.05	<0.05	<0.05

C-Ft-E based AF: Coffee-Fruit tree-Enset based AF; C-E based AF: Coffee-Enset based AF

Table 9. Mean stem number, basal area (BA), height and diameter at breast height (DBH) of woody and Enset species for each AF system, followed by SE in parenthesis.

Agroforestry system	N	Stem number (No/100 m^2)	Basal area (m^2 ha^{-1})	Height (m)	DBH (cm)
C-Ft-E based AF	20	71.2(3.2)$^{(a)}$	149.2(17.6) $^{(a)}$	4.3(0.1) $^{(a)}$	15.7(0.7) $^{(a)}$
Enset based AF	20	46.9(3.0)$^{(b)}$	317.7(28.1) $^{(b)}$	4.6(0.1) $^{(a)}$	26.7(1.5) $^{(b)}$
C-E based AF	20	53.8(2.6)$^{(b)}$	228.5(14.8) $^{(c)}$	4.3(0.2) $^{(a)}$	18.9(0.7) $^{(c)}$
P-value		<0.05	<0.05	NS	<0.05

Note: similar letter shows not significant difference and different letters indicate significance differences between groups according to LSD multiple test (Fisher LSD test) at $P<0.05$; NS: not significant

C-Ft-E based AF: Coffee-Fruit tree-Enset based AF; C-E based AF: Coffee-Enset based AF number of stems for the mixture of woody and Enset species. As a result, the correlation between them was r^2=0.00 which indicates no correlation at all (Figure 14 B). The no correlation between stem number and basal area might be because of mixing the woody and Enset together.

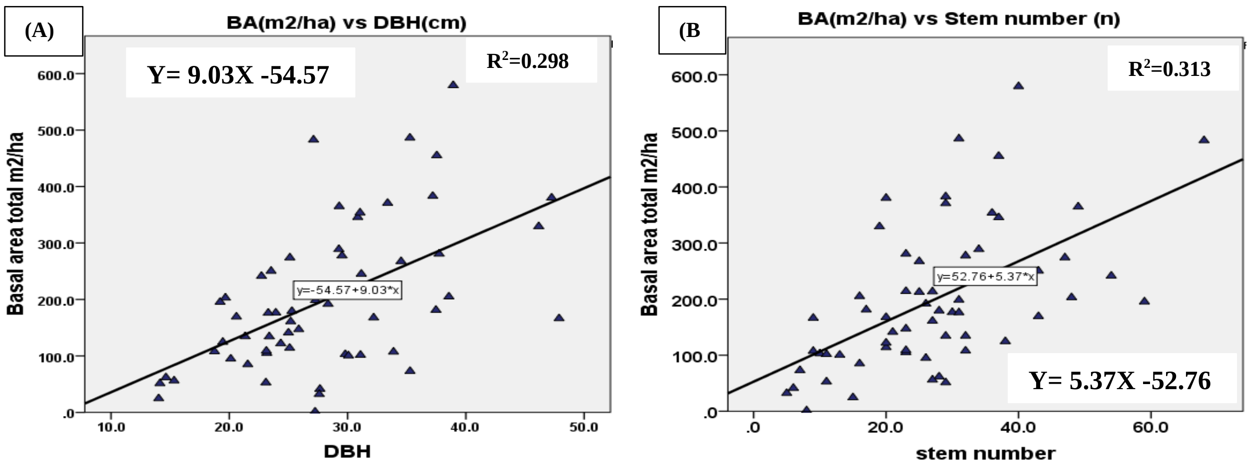


Figure 12. Relation between diameter at breast height (DBH) and basal area (A); stem number and basal area (B) for the Enset species of the three studied AF systems.

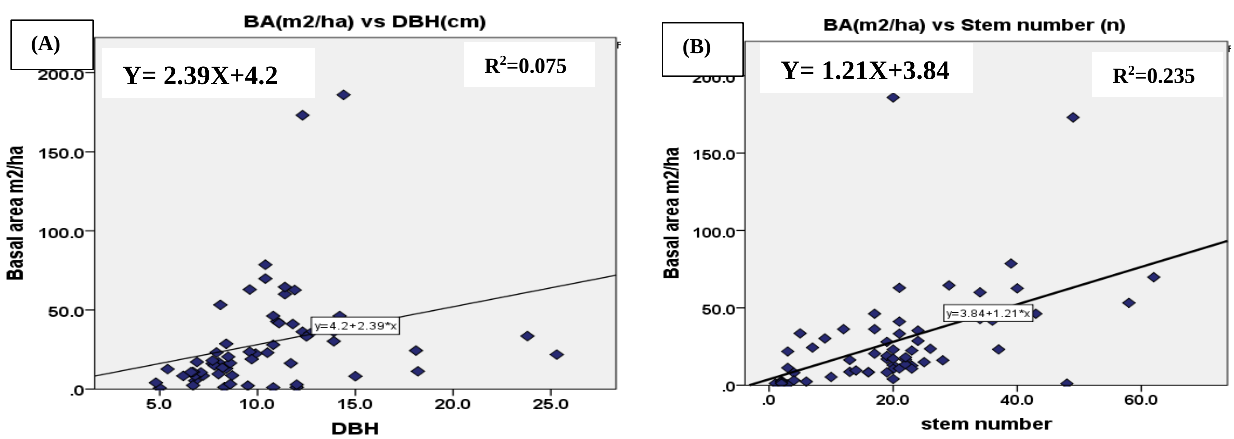


Figure 13. Relation between basal area and diameter at breast height (DBH) (A); basal area and stem number (B) for the woody species of the three studied AF systems.

Diversity indices such as Shannon diversity index, Margalef's richness index and Pielou’s Eveness index helped us to analyse and evaluate the relationships of species distributed among the three studied AF systems. According to our results, C-E based AF system showed higher species abundance and the least was recorded in Enset based AF. The greater diversity index and richness index was observed in C-Ft-E based AF systems. Whereas the least was in Enset based systems.

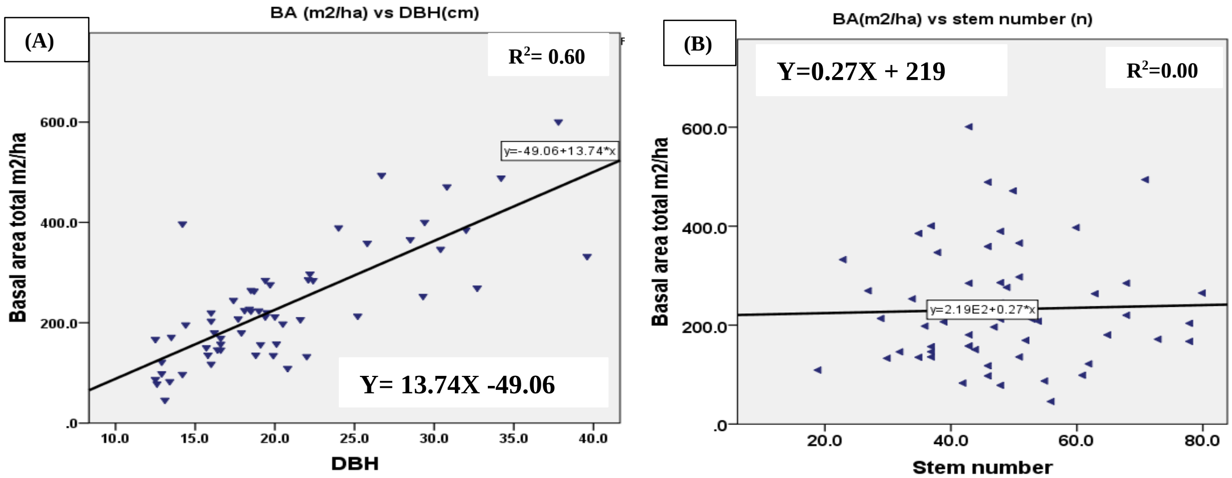


Figure 14. Relation between diameter at breast height (DBH) and basal area (A); stem number and basal area (B) for the woody and Enset species of the three studied AF systems.

The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=20) showed that species mean abundance and Pielou's Eveness index values between the AF systems were not significantly different (Table 10). Whereas, the Shannon diversity index and Margalef's diversity index of species richness was significantly different (P<0.05) between the three AF systems. The high richness index in C-Ft-E based AF might be related with proximity to main roads (Asfaw, 2003; Abebe, 2005) and favourable environmental conditions like temperature (Negash *et al.*, 2012). Because, the temperature under C-Ft-E based AF was a bit warmer compared to the two systems. This warmer air condition coupled with high rainfall amount might bring favorable condition for plants to survive easily and grow faster. Negash and Achalu (2008) also reported greater species richness in C-Ft-E based AF might be related with the incorporation of various native and non-native woody species along a vertical stratum. The above mentioned reasons might motivate the practitioners to incorporate more woody and non woody species (in our case mainly high value Fruit trees and Coffee, Enset and other native species) to get more benefits out of them.

In general, the native and exotic perennial woody and non woody plant species in our study site provide several functions: economical benefit such as source of firewood, timber, wood for different purposes (local construction, farm implements, household utensils), fodder, food, medicine; environmental benefits such as erosion control and soil fertility improvements and finally ecological imrovements such as biodiversity conservation. The Shannon diversity index values in the present study for C-Ft-E based (1.1) and C-E based AF (1.0) were comparable with studies conducted in Enset-coffee-maize-chat AF (1.15) in Sidama region of Southern Ethiopia (Abebe, 2005) and in Kerala homegarden agroforestry (1.2) in India (Kumar *et al.*,1994). However, our results were lower than values reported by Molla and Kewessa (2015) in traditional AF practices (2.2) of the Dellomenna district of South-eastern Ethiopia; Abreha and Gebrekidan (2014) in homegarden AF (1.8) of Southern Gonder of Ethiopia and Bajigo and Tadesse (2015) in homegarden AF (2.23) of Wolayitta Zone, Ethiopia. Lower diversity index values of the present study compared to above mentioned reports was due to the medium evenness index values across

Table 10. Mean ±SD. of woody and non-woody species abundance, Shannon diversity index (H′), Margalef's richness index (D_{mg}) and Pielou's evenness (J) of study plots under the three AF systems

Agroforestry system	N	Abundance Per 100 m^2	Shannon diversity index	Margalef's richness index	Pielou's Eveness index
C-Ft-E based AF	20	48.5(3.2) [(a)]	1.1±0.2[(a)]	1.2±0.3[(a)]	0.6±0.1[(a)]
Enset based AF	20	44.6(3.0) [(a)]	0.7±0.2[(b)]	0.6±0.2[(b)]	0.6±0.1[(a)]
C-E based AF	20	51.3(2.6) [(a)]	1.0±0.1[(c)]	1.0±0.3[(c)]	0.6±0.1[(a)]
P-value		NS	<0.05	<0.05	NS

Note: Same letter shows not significant difference and different letters indicate significance differences between groups according to LSD multiple test (Fisher LSD test) at P<0.05; NS: not significant

C-Ft-E based AF: Coffee-Fruit tree-Enset agroforestry; Enset based AF: Enset based agroforestry and C-E based AF: Coffee-Enset based agroforestry

all smallholdings of the investigated AF plots. This implies species diversity is affected by abundance and equitability of the species within the sample plots. The results of our study in terms of Pielou's Eveness index (with a mean value of 0.6) was also comparable with other study reports elsewhere: in homegarden AF (0.6) of similar study zone like ours but with different study sites (Teferea *et al*., 2016), in Enset-Coffee-Maize-Chat-Pineapple AF (0.55) in Sidama area of Southern Ethiopia (Abebe *et al*., 2006) and in homegardens of Kerala (from 0.24 to 0.71) of Southern India (Kumar *et al*., 1994).

The equitability of the woody species was almost the same across all the AF systems. The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=20) showed that the difference in mean Pielou's Eveness index between the studied AF systems was not statistically significant. The mean Pielou's Eveness index value of 0.6 implies a situation in which species are moderately distributed in each plot of the AF systems or in other words the relative homogeneity of the species in the sample plots was 60% of the maximum possible even population across all smallholdings. According to the anysis of Sorensen's similarity index for the three AF systems, highest species similarity was observed between C-Ft-E based AF and C-E based AF with a value of 67% (14 woody species out of 28) while the least was between C-Ft-E based AF and Enset based AF with a value of 48% (9 woody species out of 28). The species similarity between Enset based AF and C-E based AF was a little higher than the later relatively with a value of 57 % (10 woody species out of 25).

5.1.5 Relationship of altitude with species richness and species abundance

Altitude is one of the important variables that could exert an effect on habitat quality and thus influence species richness, composition and diversity. This is because, altitude affects changes in the availability of relevant resources for plant growth for instance heat and water (Korner, 2000; Tefera *et al*., 2016). Regression analysis was performed to evaluate the relationship between altitude versus species richness and altitude versus species abundance. The graphs representing all the three studied AF systems are displayed in figure 15 A and B. Our results showed that both the mean Margalef's species richness index and the mean species abundance were decreasing as mean altitude increased. The correlation between mean Margalef's species richness index and mean altitude reached a value of r^2=0.33 while the correlation between mean species abundance and mean altitude was r^2 =0.31. From the results we could understand that altitude was a little more related to species richness than species abundance although both have very low correlation values.

The results of the present study are in line with other reports else where: Wang *et al*. (2006) who observed a decreasing trend of plant species richness as altitude increases in Northeastern Tibetan Plateau China. Similar results were also found by Tefera *et al*. (2016) and Negash *et al.* (2012) in indigenous homegarden AF of southern Ethiopia. However, contradicting results were reported by Shimono *et al*. (2010) and Abebe (2005) in which an increasing trend of species richness with increasing altitude. The studies were conducted in Qinghai-Tibetan Plateau China and Southern Ethiopia respectively. The reason for increasing species richness with altitude in these studies might be related with different factors. For instance, the study conducted by the first author included all altitude ranges (from 320-5200 m asl). The reason for increasing species richness with altitude was because in the higher altitudes impact of livestock in destructing plant species is very low compared to the lower altitudes. The second author also reported an increasing Enset species richness with altitude but not for all species. This increase might be due to Enset species more favors in altitude range between 2000 and 2500 m asl. Whether to get an increasing trend of species richness with altitude or decreasing trend, it is greatly affected by the scale of the study (Nogues-Bravo *et al*., 2008). The author articulated, when a survey of the entire altitudinal gradient was conducted the pattern

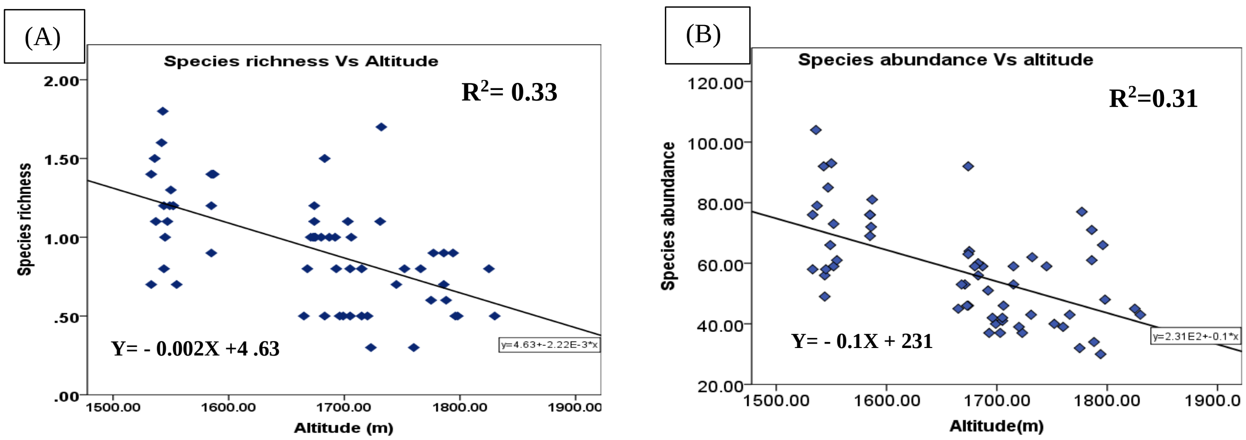


Figure 15. Relation between Altitude and Margalef's species richness index (A), Altitude and species abundance (B) under the three studied AF systems

showed a hump shape, implying that an increasing trend of species richness up to a certain altitude range was observed and then started a decrease. But, if the survey is conducted in a narrow scale of altitudinal gradient the pattern changes progressively to a monotically decreasing trend of species richness withincreasing altitude. Therefore, from the above idea, we could understand that the relationship between species richness and altitude do not necessarily to be negative always but also positive based on the situations.

Species richness and abundance could be also affected by other factors such as education of land owner, land ownership, slope and extension access (Fentahun and Hager, 2009); altitude and farm size (Abebe *et al*., 2006; Fentahun and Hager, 2009). As farmers get awared, become well educated, own bigger size land and got better access to extension service their tendency to grow more number of trees becomes high. In addition, the possibility of incorporating diverse fruit and non fruit trees would be higher. Edaphic factors such as soil conditions could positively or negatively affect species richness and eveness (Luzuriaga and Escudero, 2011). For instance, a study conducted by

Ma (2005) revealed that species richness was negatively correlated with phosphorus and species evenness was negatively correlated with the ratio of organic carbon to total nitrogen in soil.

5.2 Assessing carbon pools of three indigenous agroforestry systems

5.2.1 Biomass and biomass carbon stock in indigenous agroforestry systems

In a real sense, storing carbon in plant biomass is only feasible if the systems are long lived and a type of perennial AF systems such as perennial-crop combinations, agroforests, windbreaks, etc. Such systems allow full tree growth and a major function of the total biomass is mainly represented by the woody component (Albrecht and Kandji, 2003). Another advantage of having these perennial systems is that carbon sequestration does not have to end after harvesting the wood componenet. Because, the boles, stems or branchs can also store carbon if processed in any form of long-lasting products (Roy, 1999).

The above and belowground standing biomass and biomass carbon stock of three AF systems was estimated by adopting allometric equations developed by Kuyah *et al*. (2012a); Kuyah *et al*. (2012b); Negash *et al*. (2013a) and Negash *et al*. (2013b). The mean aboveground woody species biomass, including Coffee and Enset ranged from 81.1 t ha^{-1} (Enset based AF system) to 255.9 t ha^{-1} (C-Ft-E based AF system) and for belowground biomass from 26.9 t ha^{-1} (Enset based AF system) to 72.2 t ha^{-1} (C-Ft-E based AF system) (Table 11). The one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=20) results showed that the mean above-ground, below-ground and total (above plus below-ground) biomass between the three AF systems was significant at ($P<0.05$) (Table 11).

The mean above and belowground biomass values in our study are higher than the biomass values reported from indigenous AF systems of south-eastern rift-valley escarpment of Ethiopia conducted by Negash (2013). The author reported values from 34.9-59.2 t ha^{-1} for aboveground biomass and from 11.6-19.2 t ha^{-1} for belowground biomass. Our results were also relatively higher than the Coffee-Albizia association AF in Southwestern Togo which had an average value of 140 t ha^{-1} in its aboveground and 32 t ha^{-1} in belowground (Dossa *et al*., 2007). This could be due to the difference in density, growth, age and/or site conditions of the AF systems. Similar studies were also conducted on *Coffea arabica-Erythrina* and *C. africana* as shade species on mixed AF systems of Central America and reported that a lower aboveground biomass values than our study (Fassbender *et al*., 1985). The total dry biomass (above- plus belowground) values in the studied

Table 11. Mean±SD; n=20) above and belowground biomass, total (above- plus belowground) biomass (t ha^{-1}) for each of the three studied AF systems) and results of 1-way ANOVAs (at α=0.05, significant differences between AF systems were indicated)

Biomass	C-FT-E AF	Enset AF	C-E AF	F	p
Aboveground biomass[a]	255.9 ±294.0	81.1±69.0	126.7±145.1	4.4	0.017
Belowground biomass[b]	72.2±69.9	26.9 ±21.1	39.4±39.4	4.8	0.012
Agroforestry total biomass	328.1±364	108.0±90.0	166.1±184.4	4.5	0.016

[a] trees, coffee, Enset

[b] stumps, coarse roots (Enset corm + proximal roots) and fine roots

three AF systems ranged from 108.0-328.1 t ha^{-1} were lower than Cacao agroforests of Cameroon with value (304 t ha^{-1}) (Duguma *et al*., 2001). However, the total biomass values in our study are still higher than the global average values reported for forest biomass and some tropical forest types (149 t ha^{-1}) as FAO (2010) has reported. The variation in biomass amount among different AF systems might be stem from several factors. For instance, the environmental conditions, type of soil, the magnitude of land degradation and age of the AF system (Albrecht and Kandji, 2003). Very low land degradation, good environmental conditions and longer aged AF systems probably show high biomass production. Our AF systems as being permanent systems with very less degradation and longer aged they showed better biomass production.

The contribution of biomass from each component (Fruit tree, non-Fruit tree, Enset and Coffee) to the AF was computed for the three AF systems as in table 12 displayed. The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=20) showed that the total biomass of Fruit trees and non-Fruit trees under C-FT-E based AF system were significantly different at ($P<0.05$) from both Enset based and C-E based AF systems but Enset based and C-E based AF were not significantly different (Table 12). This might be due to C-Ft-E based AF had quite higher number of Fruit trees with vigorous growth and thus accumulated more biomass on its above and belowground. the share of non-Fruit trees was found to be higher compared to the other biomass contributors across the three AF systems. In general, the dry biomass t ha^{-1} is in the order of: C-Ft-E based AF > C-E based AF> Enset based AF in both above and belowground biomass.

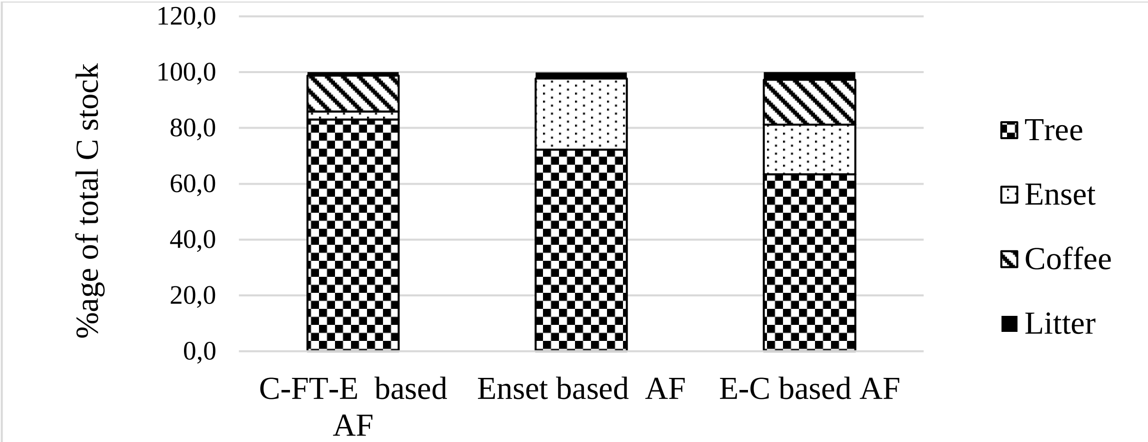
Table 12. Mean (±SD) total biomass (t ha^{-1}) of woody, Enset and Coffee components grown in three AF systems. Within each AF system having the same letter are not significantly different at ($p<0.05$) from each other (Fisher LSD test; n=20 for each AF system).

Agroforestry system	Woody			Enset	Coffee	Agroforestry total biomass
	Fruit	Non-Fruit	Total			
C-Ft-E based AF	154.1±158.8[a]	141.6±283[a]	295.7±372.0[a]	6.8±3.7[a]	25.6±41.5[a]	328.1±364[a]
Enset based AF	29.7±61.2[b]	45.3±67.2[a]	75.0±94.0[b]	29.0±15.6[ab]	-	108.0±90[b]
C-E based AF	31.7±132.4[b]	97.7±128.9[a]	129.4±186.4[b]	19.1±10.2[ac]	17.6±6.5[a]	166.1±184[b]

C-Ft-E based AF= Coffee-Fruit tree-Enset based agroforestry; Enset based AF = Enset based agroforestry

C-E based AF = Coffee-Enset based agroforestry system

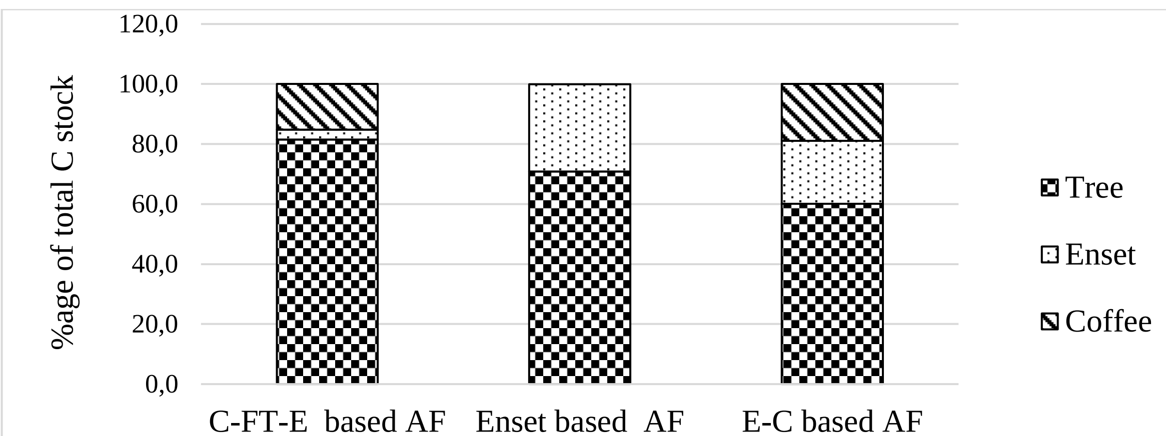
For the determination of biomass C stocks (t C ha^{-1}) only 10 out of the 20 farms from each of the three agroforestry systems were selected and estimated. This is because the numbers of farms where we took soil and litter samples were 10 farms. Therefore, for estimation of ecosystem C stock uniform representation of samples from all components (BM, soil and litter) is very important. Agroforestry system mean aboveground biomass (trees, Coffee, Enset and litter) C stock ranged from 10.2-212.9 t ha^{-1} across the three AF systems. AF system mean below ground biomass (tree and Coffee stumps and course roots, Enset corms and attached proximal roots) carbon stock ranged from 2.9-56.1 t ha^{-1} across the three AF systems. The ratio of mean above ground-biomass C stock to below-ground biomass was 3.4, 3.1 and 3.0 for C-Ft-E based, Enset based and C-E based AF systems respectively. In general, the proportion of total mean aboveground biomass C stock to the total mean biomass C stock was averaged 76% which is almost three times greater than below ground mean biomass C stock across AF systems. The share of trees (fruit trees and non-fruit trees) in the total aboveground biomass C stock was estimated 83%, 72% and 63% for C-Ft-E based, Enset based and E-C based AF systems respectively (Figure 16). The share of trees (Fruit trees and non-Fruit trees) in the total belowground biomass C stock was estimated 82%, 71% and 60% in C-Ft-E, Enset based and E-C based AF systems respectively (Figure 17). In average trees accounted 73% in aboveground biomass C stock and 71% in belowground biomass across all smallholdings. The contribution of Enset, Coffee and litter to the mean above and below-ground biomass C stock



C-Ft-E AF= Coffee-Fruit tree-Enset based agroforestry; C-E based AF = Coffee-Enset based agroforestry

Figure 16. Proportion of carbon stock of each component in the above-ground biomass

of AF system was by far lower than the contribution from trees across all AF systems. Similar studies were conducted on the contribution of woody tree species to the total mean aboveground and belowground C stock and reported that trees had greater share (Seta and Demissew, 2014; Negash and Starr, 2015). The results of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=10) showed that the total mean biomass C stock of C-FT-E based AF was significantly



C-Ft-E AF= Coffee-Fruit tree-Enset based agroforestry; C-E AF = Coffee-Enset based agroforestry

Figure 17. Proportion of carbon stock of each component in the below-ground biomass

different at ($P<0.05$) from both Enset based and C-E based but Enset based and C-E based AF were not significantly different. In general, the total biomass C stock of the AF systems is in the order of: C-Ft-E based AF > Enset based AF > C-E based AF (Table 12).

When is comes to individual AF farms, the highest total biomass C stock was recorded in C-Ft-E based AF system (269 t ha^{-1}) and the least was in an Enset based AF system (13 t ha^{-1}). Our results were substantially high as compared with shaded Coffee AF systems in South-western Togo reported by Dossa *et al*. (2007) with a value of 82 t ha^{-1}, tree-Enset based homgarden AF systems of Hawassa Zuria district (20-50 t ha^{-1}; Birhane *et al*., 2020) and AF systems in south-eastern rift-valley escarpment of Ethiopia (22-122 t ha^{-1}; Negash and Starr, 2015). In addition, Luedeling and Neufeldt (2012) did extensive reviews on the biomass C stocks for West African Sahel countries. In their study, areas which are extremely arid and also humid region of Guinea were included and reported a biomass C stock ranged from 22.2 to 70.8 t ha^{-1}. These C values are lower than values reported in our AF systems. As Dixon (1995); Albrecht and Kandji (2003) reported the biomass C stock of AF systems globally ranges from 12-228 t ha^{-1}. Therefore, our biomass C stock values were within the globally reported range value for AF systems and tropical forest and savannas in Brazil (Silva *et al*., 2013). However, our results were lower than other tropical Cocoa-based AF systems (304 t ha^{-1}) reported in Cameroon (Duguma *et al*., 2001). The high biomass C stock reported in our study specifically in C-Ft-E based AF system might be due to the density of trees, number of fruit trees and non fruit trees growing vigorously and their considerable age. Charles *et al*. (2013) and Bajigo *et al*. (2015) pointed out the biomass C stock could vary depending on the age of the trees, types of species, management and biophysical conditions. Likewise, the type of allometric equation used to estimate biomass C stock by different researchers might also bring difference in the reported values (Kumar, 2006).

5.2.2 Soil organic carbon stock in indigenous agroforestry systems

Agroforestry systems as one of the tree-based land-use systems have a potential to store more carbon in their soil system and thus they come next to forest systems (Nair *et al*., 2009). Soil in general is considered a compartment of terrestrial ecosystems where the higher amount of organic carbon is stored (Batjes, 1996) and it is estimated about 2300 billion tonnes globally within one-meter soil depth (Srivastava *et al*., 2012). This value is nearly 4.5 times the C stored in vegetation (610 billion tonnes). The measured soil organic carbon (SOC) stock of individual AF farms in our study ranged between 103.2 t ha^{-1} (C-E based AF) and 190 t ha^{-1} (C-E based AF) within the 0-40 cm soil layer. From the total SOC stock (0-40 cm), the upper soil layer (0-20 cm) contributed an average of 60.3%, 56% and 55.1 for C-FT-E based AF, Enset based AF and C-E based AF respectively. Higher stocks of SOC are regularly observed in the upper mass soil horizons because they get the first organic matter input from leaves falling litter either by leaching or by biogenic activity. In this study the greater share of SOC in the first layer (0-20 cm) might be due to the abundant addition of litter and/or pruning biomass to the soil thus contributes for accumulation of more soil organic mater.

The highest total mean SOC stock for the AF systems was found in Enset based (146.1 t ha^{-1}) and the least was in C-Ft-E based AF (125.5 t ha^{-1}). As Negash and Starr (2015) mentioned, the higher C stock values in Enset based AF could be attributed by the practice of cutting-off of old Enset leaves left to mulch on site and slower mineralization rates resulting from higher altitude (lower temperature). From our results AF which had highest biomass C stock showed lower SOC stock and vice-versa. The results of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=10) showed that the mean SOC stock was not significantly different between the AF systems at ($P<0.05$) (Table 13). In general, the total mean soil organic C stock of the AF systems is in the order of: Enset based > C-E based > C-FT-E based AF system.

The average SOC stock value (137.1 t ha^{-1}) of our all AF systems (0-40 cm) was comparable with the global average 121-123 t C ha^{-1} and 110-117 t C ha^{-1} (0-60 cm soil depth) for tropical forest and tropical savannah respectively (Lal, 2004). However, the values were considerably higher than reported for low land homegardens of Southern Tigrai of Ethiopia (109.75 t C ha^{-1}, 0-60 cm soil depth; Siyum and Tassew, 2019), *Faidherbia albida* based parkland AF in the central rift-valley of Ethiopia (118 t ha^{-1}, 0-80 cm soil depth; Dilla *et al*., 2019) and semi-arid *Acacia etabica* woodland in southern Ethiopia (43 t C ha^{-1}; Lemenih and Fisseha, 2004). AF systems in other tropical regions such as homegarden AF systems of humid lowlands with a tree density of >750 stems ha^{-1} (70-120 t C ha^{-1}), Silvopastures (grazing and fodder) of humid lowlands with a tree density of >25 stems ha^{-1} (80-120 t C ha^{-1}), humid lowland and tropical highland wood lots >10 years old (80-100 t C ha^{-1}), humid lowland tree intercropping with a tree density of >100 stems ha^{-1} (50-120 t C ha^{-1}) (Nair *et al*., 2009) and for AF systems in Central India (27 t C ha^{-1}) (Swamy and Puri, 2005) were reported. The above reports showed that a lower SOC stock compared to our AF systems. The mean SOC stock value for C-Ft-E based AF systems in our study was however, lower than for Coffee-Fruit tree based AF as was reported by Negash and Starr (2015) although these values were for 0-60 cm soil depth.

5.2.3 Ecosystem carbon stocks

Proper management of AF systems could help to capture and and store a significant fraction of the atmospheric C in plant biomass and in soils (Albrecht and Kandji, 2003). The ecosystem carbon stock is the sum of the below and aboveground biomass carbon stock and SOC stock of the AF. The quantity of AF total C stock greatly varies from AF practice to another AF practice and from region to region depending on the type of ecosystem.

The mean AF total C stock for C-Ft-E based was relatively high as compared to the remaining two AF systems and the least was recorded in C-E based AF (Table 13). The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=10), at ($p<0.05$) showed that the total AF C stock and soil organic carbon (SOC) stock were not statistically significant between the three AF systems although they showed significant difference in their biomass carbon (BMC) stock. This is

Table 13. Mean (±SD; n=10) BMC, SOC and AF system total (total biomass plus SOC 0-40 cm) C stocks (t ha^{-1}) for each of the three AF systems) and results of 1-way ANOVAs (at $\alpha=0.05$)

C stock	C-FT-E AF	Enset AF	C-E AF	F	p
Aboveground biomass[a]	83.8 ±63.0	39.1±32.0	37.8±17.3	3.9	0.033
Belowground biomass[b]	24.4±16.2	12.6 ±9.7	12.7±5.8	3.6	0.042
Total biomass	**108.2 ±79.2 [a]**	**51.7 ±41.7 [b]**	**50.5 ±23.1 [b]**	3.8	0.034
SOC 0-20	75.7±14.2	81.7 ±14.4	76.9 ±18.3	0.4	0.665
SOC 20-40	49.8±7.5	64.4 ±16.3	62.7 ±21.2	8.9	0.103
SOC 0-40	**125.5±17.3 [a]**	**146.1 ±26.5 [a]**	**139.6 ±25.4 [a]**	14.7	0.152
Agroforestry total	233.3±81.0 [a]	197.8 ±58.7 [a]	190.1 ±29.8 [a]	0.1	0.243

[a] trees, Coffee, Enset and litter

[b] stumps, coarse roots (enset corm + proximal roots) and fine roots

because of the weak correlation between the total biomass C and SOC stocks especially under C-Ft-E based and C-E based AF systems. The correlation values for these systems were -0.005 and -0.3 respectively. From the values it could be realized that AF systems which have high biomass C stock does not mean they exhibit high C stock in their soil. There are other factors that affect SOC either to increase or decrease including silvicultural and soil management and land-use history (Nair *et al.*, 2009). The amount and type of AF products which are extracted every year for consumption by humans and livestock also plays an important role.

Total agroforestry C stock (total biomass plus soil organic carbon) of individual AF smallholdings in our study ranged between 132.0 t ha^{-1} (Enset based AF) and 356.4 t ha^{-1} (C-Ft-E based AF). The contribution of the mean biomass C stock to the total AF C stock was 46%, 26% and 27% for C-Ft-E based AF, Enset based AF and C-E based AF respectively. Except for C-Ft-E based AF system the remaining two AF systems had greater contribution from the SOC (about 2.8 times the biomass carbon) to their respective total AF carbon stock. The soil organic carbon stock exceeds the biomass carbon across all AF systems and there was a difference in SOC to total biomass C stock ratio among the AF systems. The highest ratio of SOC (0-40 cm) to total biomass C stock was found in Enset based AF with a value of 2.82 and the least was in C-Ft-E based AF with a value 0.88. The contribution of SOC to the total AF C stock was 54% for C-Ft-E based AF, 74% for Enset based AF and 73 % for C-E based AF. Our results are in consistent with the study conducted on three agroforestry systems by Negash and Starr (2015). The type of ecosystem and latitude affects the distribution of C stocks between biomass and soil. The biomass carbon and SOC stocks (for 1 m

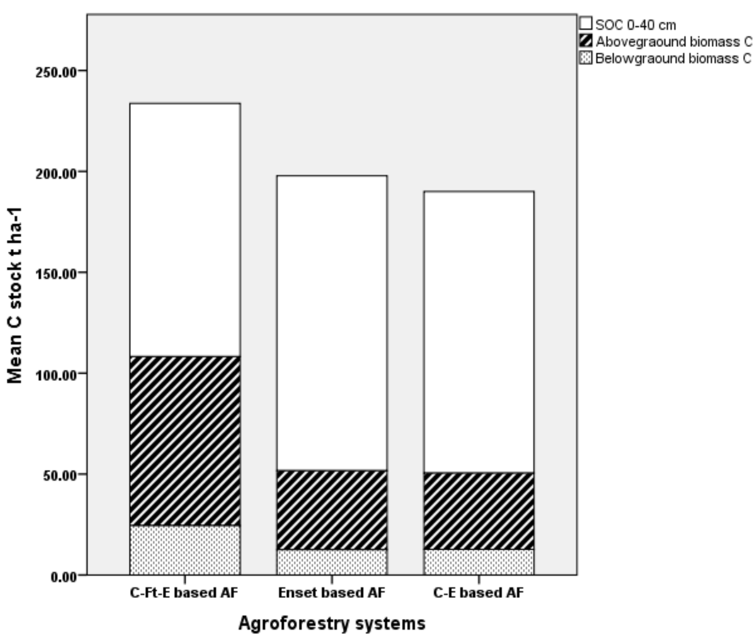


Figure 18. Agroforestry total carbon stocks (including trees, shrubs, Coffee, Enset, stumps and large roots, SOC 0-40 cm) (t ha^{-1}) by AF system.

soil depth) showed variation among different forest ecosystems of the globe (Dixon *et al*., 1994). For instance, the highest SOC stocks were at high latitudes (343 t ha^{-1}) and the lowest were at low latitudes (121 t ha^{-1}). The highest biomass C stocks were in low latitudes whereas the lowest were in high latitudes (Dixon *et al*., 1994). The author added, the proportion of forest ecosystem C stock in biomass increased towards the tropics, from 16 % at high latitudes to 50 % at low latitudes. In general, most of the the organic matter storage in tropical forests resides in the biomass followed by soil and litter with values of 58%, 41% and 1% respectively (Brown and Lugo, 1982). The average ecosystem carbon stock values (biomass plus soil) of our AF systems (207.1 t ha^{-1}) were higher than reported for lowland homegardens of Southern Tigrai in Ethiopia which have 148.3 t ha^{-1} for 60 cm soil depth (Siyum and Tassew, 2019), and they were 2.5 times higher than shaded Coffee plantations of Southwestern Togo 82 t ha^{-1} for 40 cm soil depth (*Dossa et al*., 2007). In a similar range was also in shade-grown Coffee system of Indonesia 82 t ha^{-1} for 40 cm soil depth (van Noordwijk *et al*., 2002). From the above reported carbon stock values we could say that our AF systems sequester considerably more carbon than other tree-based ecosystems generally do in the tropics. However, it was lower than the managed moist tropical forests of Panama (335.1 t ha^{-1} for 40 cm soil depth; Kirby and Potvin, 2007) and tropical forest ecosystems (mean 244 t ha^{-1}; Dixon *et al*., 1994).

5.2.4 Correlation between BM carbon and SOC of agroforestry systems

The correlation between biomass (BM) carbon stock and soil organic carbon (SOC) stocks of AF systems could be either positive or negative depending on different factors. Considering vegetation as one of the many factors influencing SOC stocks (Oueslati *et al*., 2015; Sun *et al*., 2015) studies conducted in wide areas of the tropics showed that a consistent addition of tree/shrub prunings and their root turnover over the years have contributed to accumulation of SOC (Lehmann *et al*., 1998; Rao *et al*., 1997; Kumar, 2001). For the 10 selected farms in all study the result of Spearman rank correlation (2-tailed significance difference) showed that biomass C stock and SOC stock had r= -0.005 for C-Ft-E based AF, r =0.5 for Enset based AF and r= -0.3 for C-E based AF (Table 14). The correlation under Enset based AF showed a positive and higher but was not statistically significant. Results that support the contribution of biomass carbon to the SOC were reported from different countries. For example a trial of hedgerow intercropping that incorporated *Giliricidia sepium* and *Leucaena leucocephala* was done for 12 years in Nigerian Alfisol. As a result of incorporating the trees the surface SOC was increased by 15% (2.38 t ha^{-1}) (Kang *et al*., 1999). Likewise, after five-year trial of hedgerow intercropping that incorporated *Inga edulis* in the Typic Paleudult soils of Peru also observed an increase of 12% (0.23 t ha^{-1}) in SOC stock (Alegre and Rao, 1996). On the contrary, having more tree cover in a given land-use may not necessarily produce additional SOC stocks to the system since it is also affected by the existing extent of soil

Table 14. Correlation between BC stock and SOC stock in the three AF systems

		BC stock of C-Ft-E based AF	SOC stock of C-Ft-E based AF	BC stock of Enset based AF	SOC stock of Enset based AF	BC stock of C-E based AF	SOC stock of C-E based AF
BC stock of C-Ft-E based AF	Pearson Correlation	1					
	Sig. (2-tailed)						
	N	10					
SOC stock of C-Ft-E based AF	Pearson Correlation	-.005	1				
	Sig. (2-tailed)	.989					
	N	10	10				
BC stock of Enset based AF	Pearson Correlation	.184	-.186	1			
	Sig. (2-tailed)	.612	.606				
	N	10	10	10			
SOC stock of Enset based AF	Pearson Correlation	.080	.055	.458	1		
	Sig. (2-tailed)	.825	.881	.183			
	N	10	10	10	10		
BC stock of C-E based AF	Pearson Correlation	-.088	-.069	.029	-.527	1	
	Sig. (2-tailed)	.810	.850	.937	.117		
	N	10	10	10	10	10	
SOC stock of C-E based AF	Pearson Correlation	-.552	.008	-.412	.415	-.246	1
	Sig. (2-tailed)	.098	.983	.237	.233	.493	
	N	10	10	10	10	10	10

**BC:biomass carbon*

disturbances and other human interfrences (Kirsten *et al*. 2016). That is the reason why we found very weak correlation between BM and SOC under C-Ft-E based AF and C-E based AF. Other authors also explained why the correlation between biomass C stock and SOC was weak and the consideration of other factors that affect SOC stock. Kinoshita *et al*. (2016) revealed that SOC stock was influenced mainly by soil properties but topography and vegetation had quite insignificant impact. In addition, Albrecht and Kandji (2003) revealed that the contribution of biomass C stock to SOC stocks at farm and landscape level was attributed by factors such as soil types, precipitation and land-use and land management.

In general, the relationship between the two variables is mainly affected by silvicultural management (such as prunning, lopping, pollarding etc) and land-use history (Nair *et al*., 2009), the age of the agroforestry system, type and number of tree species included and their rotation age (Montagnini and Nair, 2004), elevation and climate (Albrecht and Kandji, 2003; Soto-Pinto *et al*.

2010), soil type and soil properties (Kinoshita *et al*. 2016; Lal, 2004). Our results are in consistent with several other studies where biomass carbon and soil organic carbon stocks showed a very weak relationship even sometimes negative correlation (Noponen *et al*., 2012; Mathew *et al*., 2016; Negash and Starr, 2015).

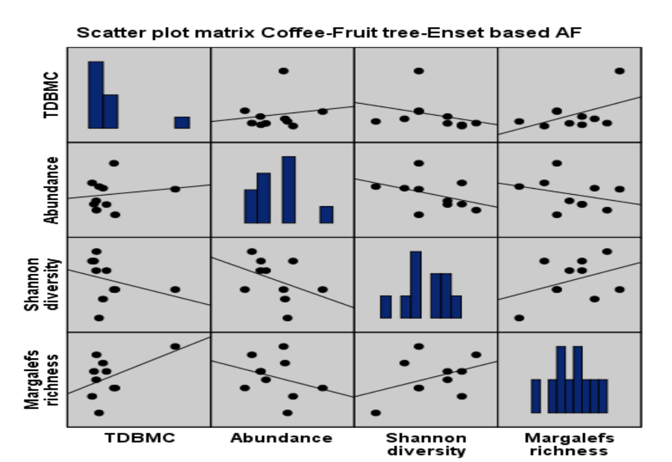
A correlation of SOC stock with slope percent and age of the AF farm were conducted for each of the three AF systems. According to our results, SOC stock was positively correlated with the age of the AF farm with r-values 0.7, 0.64 and 0.44 for Enset based, C-E based and C-Ft-E based AF systems respectively. The r-values under Enset based and C-E based AF systems were statistically significant. Most AF farms which have longer age showed a higher amount of SOC stock. This might be due to the accumulation of more organic matter over the long years. However, SOC stock was negatively correlated with slope percent and thus showed r-values -0.61, -0.55 and -0.21 for Enset based, C-E based and C-Ft-E based AF systems respectively. From the r-values it was understood that most AF farms with less slope percent showed a higher SOC stock. This might be due to the biomass acquisition is more pronounced in gentle slope AF farms as a result of accumulation of biomass by gravity. The r-value under C-Ft-E based AF system was very low. This might be related to the AF farms were in lower elevation and more gentle slope compared to the other two AF systems.

A correlation of SOC stock with wealth status (rich, medium and poor) of the households and number of livestock owned were also conducted for each of the three AF systems. According to our results, SOC stock of the AF farms was a bit higher in rich farm owners compared to the poor ones. It was observed a positive correlation with r-values 0.37, 0.47 and 0.34 for Enset based, C-E based and C-Ft-E based AF systems respectively. From the results it could be undertood that the rich people have less tendency of using bimass from the trees and shrubs for the purpose of house construction, cooking and other uses. However, the poor people are more or less dependent on biomass for different uses and thus lessen the biomass input to the soil. SOC was negatively correlated with number of livestock owned by the practioners. It was assumed that households who have more livestock number could utilize more biomass as a forage than those who have less number of livestocks. This implies, if significant biomass is consumed by the livestocks the biomass input that is returned as a litter to the soil could be dramatically decreased. As a result, the practitioners who have more livestock number showed comparatively less SOC stock under their AF farms than those with less number of livestock. The correlation results showed that the relationship between SOC stock and number of livestock under Enset based AF was statistically significant with r-value -0.66. However, the r-values for C-E based and C-Ft-E based AF systems were -0.49 and -0.31 respectively, and were not significant.

5.2.5 Relationship between TBMC and Abundance, Shannon diversity, Marglefs richness

The level of biomass carbon stock of AF systems could be affected by different variables. Some authors revealed that the age of the tree stand, type of the tree stand (Montagnini and Nair, 2004) and silvicultural management (e.g. planting density, pruning, thinning) (Nair *et al*., 2009) and other factors could determine the biomass carbon stock significantly in different AF systems. The other factors are the most important: humans and their utilization of the AF system. The results of bivariate correlation analysis showed that the amount of total biomass carbon (TBMC) stock was positively correlated with mean species richness, mean abundance and mean diversity in all AF systems except in C-Ft-E based AF. Under C-Ft-E based AF system the relationship between TBMC and diversity was negative. From all AF systems the strongest correlation between TBMC and plant species richness was observed in C-E based AF with r value of 0.52 (Figure 21). Whereas, the weak correlation was observed in TBMC stock with plant diversity (r=-0.32) under C-Ft-E based AF (Figure 19). This result is in consistent with the study conducted in homegarden AF of southern Ethiopia in which they found weak relationship between woody species diversity and biomass carbon stock (Birhane *et al*., 2020). This implies that high plant diversity might not bring greater biomass carbon stock due to AF systems have human interference and greater disturbance level and thus resulted in lower number of plants and lower biomass production (Richards and Mendez, 2014). Socio economic factors may play an important role.

Across the three AF systems TBM C stock was more positively correlated with species richness (r =0.49, r =0.44, r =0.52) for C-Ft-E based, Enset based and C-E based AF respectively than the other variables. Similar results were reported by Seta and Demissew (2014) and Negash and Starr (2015) who found a strong positive correlation between TBMC and species richness under Enset-Coffee-tree agroforests. However, a contradicting result was reported by Kirby and Potvin (2007) who found almost no correlation between total TBMC of trees (including palms and lianas) ≥10

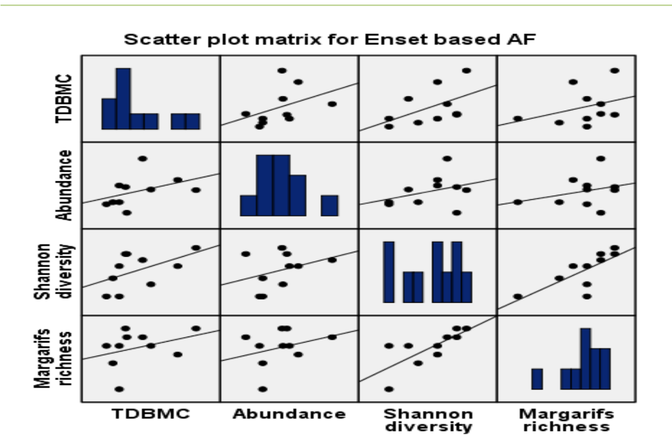


Correlations	
Variables	r
TBMC with abundance	0.15
TBMC with Shannon diversity	-0.32
TBMC with Margalef richness	0.49

TBMC stands for total biomass carbon

Figure 19. Relationship between TBMC and abundance, Shannon diversity, Margalef richness under C-Ft-E based AF

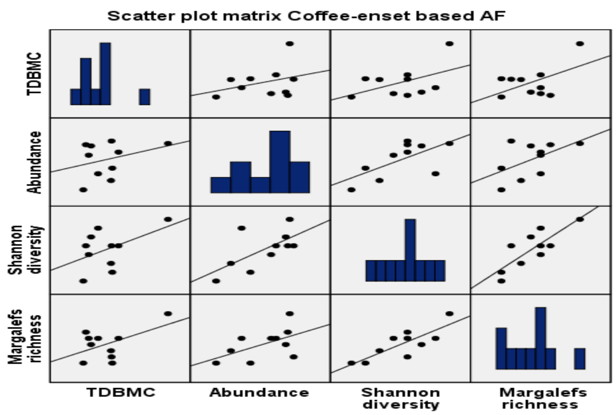
cm DBH and species richness in forest and agroforest plots. The author noticed that showing no correlation is due to biomass carbon is affected by morphospecies richness rather than any species richness. Morphospecies are a group of biological organisms that differs in some morphological respect from all other groups whereas species is a group of living organisms consisting of similar individuals capable of exchanging genes or interbreeding among themselves. Therefore, morphospecies richness is the richness of the species based on morphological differences. We had hypothesized in our study that plant abundance would have a strong correlation with TBMC stock than with plant richness. However, it was found a weak correlation of plant abundance with TBMC



Correlations	
Variables	r
TBMC with abundance	0.41
TBMC with Shannon diversity	0.42
TBMC with Margalef richness	0.44

TBMC stands for total biomass carbon

Figure 20. Relationship between TBMC and Abundance, Shannon diversity, Margalef richness under Enset based AF



Correlations	
Variables	r
TBMC with abundance	0.32
TBMC with Shannon diversity	0.49
TBMC with Margalef richness	0.52

TBMC stands for total biomass carbon

Figure 21. Relationship between TDBMC and Abundance, Shannon diversity, Margalef richness C-E based AF

stock compared to the correlation of TBMC stock with plant richness does. Thompson *et al*. (2012) emphasized that C stock of AF systems depends more on their functional diversity than on woody and non woody plant species diversity. Henry *et al*. (2009) and Mandal *et al*. (2013) also pointed out the increasing plant species biomass contributed much more to the carbon stock of the AF systems than having high plant species diversity.

The benefit acquired from carbon sequestration is one of the promising incentives to introduce AF practices. This inturn contributes for sustainable land-use in tropical regions (Takimoto *et al*., 2008). Considerably high C stocks in our studied AF systems might indicate that they make a significant contribution in C sequestration and climate change mitigation as compared to other land-uses. Thangataa and Hildebrand (2012) emphasized that the future success in C trading and payments through the implementation of payment for ecosystem services and REDD$^+$ programs could help local communities to maintain AF systems utilizing these incentives. In addition, the financial cost needed to sequester C through AF is expected to be much lower (approximately $1–69/t C, median $13/t C) than through other CO_2 mitigating options. This is because some costs could be easily offset by the monetary benefits from the multiple AF products and C trading incentives.

5.3 Soil nutrient availability of indigenous agroforestry systems versus monocropping

5.3.1 Soil physico-chemical properties in AF systems and comparison with adjacent monocropping fields

Consistent addition of litterfall biomass prunings and root turnover in AF systems are contributing to the development of soil organic matter and nutrient stocks in the AF soils (Lehmann *et al.*, 1998; Rao *et al.*, 1997). Beyond that, AF systems improve the infiltration potential of the soil, reducing problems related with acidification and salinization and certaintoxicities in the soil by ameliorating the physio-chemical characteristics of the soil (Young, 1989; Nair, 1998; Sarvade *et al.*, 2014).

5.3.1.1 Comparison of soil physico-chemical properties among the three AF systems

Physical properties such as soil texture, structure and soil bulk density could help to evaluate soil quality in terms of water holding capacity, water infiltration and so on. For example, soil texture is one of the physical soil variables that affect soil sustainability by affecting the absorption of nutrients, microbial activities, the infiltration and retention of water, soil aeration, tillage and irrigation practices (Gupta, 2004). The result displayed in table 15 showed that, percent clay content was found to be higher in the soil layer 20-40 cm than the soil depth 0-20 cm across all the three AF systems. According to the U.S. Department of Agriculture (USDA, 1987) soil texture classification, the total soil texture evaluation of the three AF systems showed that clay was the dominant soil texture except for Enset based AF system in which we found silty clay texture, but only for 0-20 cm soil depth. Since soil texture depends predominantly on mineral composition of the soil parent material and weathering processes and management may only play a minor role (Agena *et al.*, 2014), the similarity of soil texture is a good indicator that the AF systems are stocking on comparative sites. Similar result was found by Komicha *et al.* (2018) in which he compared of *Faidherbia albida* (Delile) A. Chev and *Acacia tortilis* (Forssk.) Hayen in park land AF system in Central Rift-valley, Ethiopia. As some literatures pointed out the clay component in soils may play an important role in stabilizing the SOC through sorptive protection or microaggregate formation (Yu *et al.*, 2019). It has been reported that the soil clay is able to bind and stabilize the soil organic matter up to an extent of 90% of its organo-mineral part through the formation of SOM–clay complex (Sparks, 2002). The studied AF systems seem also to have good soil fertility due to the formation of clay-humus complexes and they have more percent of organic matter (averagely 5.7%) compared to other AF systems as for example one in central mid-hills of Nepal (2.2%)(Schwab *et al*., 2015).

It is observed regularly under most normal soil consitions; the mean value of bulk density was found to be higher in the deeper soil depth of 20-40 cm than in the soil depth 0-20 cm across all the three AF systems. Similar results were obtained by Singh *et al.* (2018). C-E based AF system showed higher bulk density with average of 1.12 g cm^{-3} and the least was found under the C-Ft-E based AF system with average of 0.95 g cm^{-3}. The one-way ANOVA followed by post-hoc testing (Fisher's LSD test) at ($P<0.05$) results showed that C-Ft-E based AF system was significantly different from both Enset based AF and C-E based AF systems for the soil depths (0-20 and 20-40 cm). However, C-E based and Enset based AF system were not significantly different in both soil layers (0-20 and 20-40 cm) (Table 15). The lower bulk density under C-Ft-E based AF could be related with high production of litterfall (indicated in litterfall part of this study) as a result of high tree density which could produce more fine roots widely spread within the soil vertically as well as horizontally. In addition, it might be due to the existance of more soil fauna (decomposers) and their activitiy which is loosening the soil, enhancing porosity and modify aggregate structure. As Singh *et al.* (2018) and Komicha *et al.* (2018) revealed that high litterfall input coupled with greater fine root turnover, twigs etc attributed for lower bulk density. As previously known, incorporation of organic matter in soil improves physical variables such as aggregate stability, bulk density and water retention (Komicha *et al.,* 2018). In consequence of the above arguments that enhanced litterfall and fine root turnover may lead to lower bulk density. It may be expected that SOC stocks in the C-Ft-E based AF systems should be the highest among the AF systems. But, this is not the case, in contrary the SOC stocks of C-Ft-E based AF systems were lower (see Table 13). This may point towards a former degradation of these systems due to heavy biomas extraction or litter utilization for fire use.

Chemical properties of soil such as soil pH, cation exchange capacity (CEC) and base saturation percentage (BS%) could help to evaluate the soil quality in the study area. As the result in table 14 displayed, the mean soil pH (H_2O) and pH ($Cacl_2$) was found to be higher in the soil depth 20-40 cm than the soil depth 0-20 cm across all the three AF systems. This shows soil pH increased withincreasing soil depth across all AF systems. The lower pH and the highest SOC values under all studied AF systems within 0-20 cm soil layer could be due to nutrient uptake (K^{1+}, Ca^{2+}) by plants for this layer, the addition of litter to the surface layer, recycling of fine root biomass and root exudates lead to a building of humus (SOC). But, further mineralization and oxidation is affected by the tree shades (Bertin *et al*., 2003; Gill and Burman, 2002). The pH values in the soil depth 20-40 cm was a bit higher compared to soil layer 0-20 cm across all AF systems (Table 15). Similar findings were observed by (Singh *et al.*,2018; Prasadini and Sreemannarayana, 2007; Kumar *et al.,* 2008 and Newaj *et al.,* 2007). In general, the soils of these AF systems could be categorized from slightly acidic to neutral and according to the criterion for tropical soils pH (H_2O) values >5.3 correspond to good soil fertility (Cochrane *et al.*,1985). Mean values of CEC and BS% were found to be higher in the soil depth 0-20 cm than the soil depth 20-40 cm across all AF systems (Table 15). From all, Enset based AF system showed higher values in terms of CEC and BS% in the 0-40 soil depth. The least value for CEC was observed in C-Ft-E based AF system while for BS% it was in Enset-Coffee based AF system. The low CEC value in the C-Ft-E based AF system fits also well to the observed fact that this system was also the lower in humus (SOC) stocks in its mineral soil. The average CEC values of our AF systems were within the range reported by Carson *et al*. (1986); Schreier *et al*. (2006). But, it was considerably higher than reported for AF in central mid-hills of Nepal (Schwab *et al*., 2015; Shrestha, 2009). The average BS% values in the present study were in comparable with the results reported by Tchienkoua and Zech (2004) and Schwab *et al*. (2015) in AF and fertilized Tea plantations respectively.

The percentage contribution of calcium (Ca^{2+}) towards base saturation was by far higher as compared to potassium (K^{1+}) and magnesium (Mg^{2+}) across all AF systems and both soil layers. In general, the contribution to the BS% of the cations was found to be in the order of calcium (Ca^{2+})> potassium (K^{1+})> magnesium (Mg^{2+}) across all the three AF systems. From our results in general the status of the soil could be considered as fertile as far as the mean total CEC and BS% were high. Mulyono *et al*. (2019) reported CEC value > 16-25 meq/100 grams classified as moderate soil fertility and BS% value >80 classified as high. The one-way ANOVA followed by post-hoc testing (Fisher's LSD test) at (P<0.05 result for mean CEC showed that Enset based AF system was statistically significant different from Enset-Coffee based AF (0-20 cm layer). However, we did not find significant difference between Enset based and C-Ft-E based AF system (0-20 cm layer). In the soil layer 20-40 cm Enset based AF showed significant difference from C-Ft-E based AF system. But, C-E based did not show significant difference from C-Ft-E based AF system.

Table 15. Comparison of soil physico-chemical properties among the three AF systems (Mean±SD). Within each agroforestry systems having the same letter are not significantly different at ($p<0.05$) from each other (Fisher LSD test; n=10 for each AF system).

Parameters		Agroforestry system					
		Enset based AF		C-E based AF		C-Ft-E based AF	
		Soil depth		Soil depth		Soil depth	
		0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
pH	H_2O	6.1	6.3	6.4	6.7	6.4	6.6
	$CaCl_2$	5.0	5.2	5.1	5.3	5.3	5.4
	%sand	12.0	9.0	13.2	12.4	25.4	22.5
	%silt	44.0	37.7	35.9	31.4	32.5	26.7
	%clay	44.0	53.3	50.9	56.2	42.1	50.8
	evaluation	Silty clay	Clay	clay	Clay	Clay	Clay
Bulk density g/cm³		1.04 ±0.07 ^{a}	1.2 ±0.1 ^{a}	1.04 ±0.03 ^{a}	1.2 ±0.06 ^{a}	0.9 ±0.08 ^{b}	1.0 ±0.09 ^{b}
CEC meq/100 grams		24.2 ±4.9 ^{a}	18.5 ±5.5 ^{a}	18.1 ±7.4 ^{b}	15.6 ±6.8 ^{ab}	19.1 ±6.6 ^{a}	12.3 ±4.5 ^{bc}
BS%		99.4 ± 0.6 ^{a}	98.3 ±3.7 ^{a}	97.3 ±2.1 ^{b}	97.1 ±2.6 ^{a}	98.7 ±1.3 ^{a}	96.3 ±4.3 ^{a}

*The comparison was conducted for similar soil layers of the three AF systems.

In the case of BS%, Enset based AF system showed significant difference over the two systems (0-20 cm). Whereas C-E based and C-Ft-E based AF system did not show significant difference in this soil layer. There was not significant difference in BS% among the three AF systems for the soil layer 20-40 cm (Table 15). The high values of CEC and BS% under Enset based and C-Ft-E based AF systems might be due to the higher soil organic matter percentage. Because, high CEC and BS% for soils is explained by high adsorptive capacity of soil OM particularly at pH above 5 (Duraes *et al*., 2018). When the litter material from the canopies of the woody and non-woody tree/shrub species incorporated into the soil the organic matter undergoes microbial decomposition. After decomposition of organic matter humus is released and followed by mineralization, implying that better nutrient cycling (Komicha *et al.*, 2018). However, due to the shading effect minirelizaion might be delayed in AF systems.

From the results we could understand that as it goes deeper into the soil the level of soil pH in both H_2O and $CaCl_2$ showed an increase whereas the values of CEC and BS% getting decreased. The high value of CEC and BS% in 0-20 cm than 20-40 cm soil layer across all the three AF systems might be due to the fact that high accumulation of organic matter in upper soil layer than the lower layer. Addition of organic matter to the soil fosters better opportunity for increasing the status CEC and BS% in the soil be undergoing microbial decomposition followed by mineralization (Komicha *et al.* 2018). This result is in consistent with (Abdallah *et al.*, 2012) who reported a higher CEC values under immediate tree canopies than far distance from the tree trunk due to added organic matter.

Studies reported that there is a difference in soil physico-chemical properties between AF systems and monocropping farms. For instance, Belsky *et al.* (1993) revealed that soil physical conditions can be improved by trees in the AF systems but this situation does not happen in agricultural fields. Showing increased porosity (Campbell *et al*., 1994; Dalland *et al*., 1993), lower bulk density (Campbell *et al*., 1994; Dalland *et al*., 1993; Hulugalle and Kang, 1990), greater aggregate stability and lower surface resistance to penetration (Campbell *et al*., 1994; Lal, 1989d) could be some of the improvements reflected in tree-based systems. As Rao *et al*. (1997) explained the primarily enhancement of soil physical conditions under AF is highly associated withincreased SOM.

Based on the average soil texture values displayed in table 16 the soils in our AF systems and their adjacent monocropping farms were evaluated as clay. This clay texture of the soils was observed in both soil layers (0-20, 20-40 cm). The classification of texture in our study was based on the U.S. Department of Agriculture (USDA, 1987). The average pH (H_2O) and pH (Cacl$_2$) and bulk density of AF systems was found to be lower than its adjacent monocropping farms in both soil depths (Table 16). Higher pH level and bulk density was also noticed in the soil layer 20-40 cm for both land use types. Similar results were reported by Kahi *et al*. (2009); Schwab *et al*. (2015) and Singh *et al*. (2018). The lower bulk density and pH under AF systems compared to adjacent monocropping farms is attributed to the addition of organic matter as litter fall, fine root recycling, twigs and others (Singh *et al*., 2018). The findings of the present study are in agreement with Liao *et al*. (2011) who reported soil bulk density and soil organic carbon content are inverse relation. Higher pH level under the soil layer from 20-40 cm of our finding in both land uses might be due to the leaching of soluble salts from the surface to the deeper layers of soil (Singh *et al*., 2018). Prasadini and Sreemannarayana (2007) and Kumar *et al*. (2008) who conducted a research under white Siris (*Alluaudia procera*) based AF system reported similar results and trends of variation in soil pH under AF systems in comparison to monocropping farms.

Table 16. Comparison of soil physico-chemical properties of AF systems and adjacent monocropping. two-tailed t-test, n=30 (Mean ±SD)

		Land use type					
		0-20 cm Soil depth			20-40 cm Soil depth		
Parameters		Average value of AF farms	Average value of Adjacent Monocrop farm	Sig. (2-tailed)	Average value of AF farms	Average value of Adjacent Monocrop farm	Sig. (2-tailed)
pH	H_2O	5.6	6.5		6.0	6.7	
	$CaCl_2$	4.8	5.8		4.9	5.4	
	%sand	16.9	17.4		14.6	15.6	
	%silt	37.5	27.2		31.9	26.0	
	%clay	45.7	55.5		53.4	58.4	
	evaluation	clay	clay		Clay	Clay	
Bulk density g/cm^3		1.0±0.00	1.1±0.03	0.000**	1.1±0.03	1.2±0.05	0.037*
CEC meq/100 grams		20.5 ±4.0	13.5±2.0	.000**	15.5 ±2.7	12.5±1.8	0.013*
BS%		98.5 ±0.8	91.9 ±7.8	.024*	97.2 ±1.8	90.5±7.7	0.010*

** Significant at the 0.01 level
* Significant at the 0.05 level
NS-Not significant

The pairwise 2-tailed t-test result showed that bulk density and CEC under AF systems was highly significantly different at ($P<0.01$) compared to adjacent monocropping farms within the 0-20 cm soil layer. Whereas, BS% was significantly different at ($P<0.05$) compared to its adjacent monocropping farms in the same soil layer. In the case of 20-40 cm soil layer, all (BD, CEC and BS%) of AF systems showed significant different at ($P<0.05$) compared with their adjacent monocropping farms (Table 16). Similar results were investigated by different researchers as fully developed AF systems have higher CEC and BS% (Schwab *et al*., 2015) than monocropping fields. Other scholars such as (Pandey and Singh, 2009; Abdallah *et al.*, 2012 and Singh *et al*., 2018) also found similar results by comparing CEC of home-garden AF with control monocrop field thus noticed greater CEC level under AF systems than the control.

5.3.1.2 Comparison of soil fertility of AF systems and adjacent monocropping (OM, N, P, K, Ca, Mg, C:N ratio)

Concentrations of the nutrients such as exchangeable calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), extractable phosphorus (P), OM%, total nitrogen (TN) and C:N ratio are some of the soil fertility indicators. From the result displayed in table 16, the exchangeable Ca^{2+}, K^{+}, and Mg^{2+} were higher under Enset based AF system as compared to C-Ft-E based and C-E based AF systems for both soil layers (0-20, 20-40 cm). The high value of exchangeable Ca^{2+}, K^{+} and Mg^{2+} in both soil layers (0-20, 20-40 cm) in Enset based AF system compared with the two remaining systems might be also due to the fact that presence of more quality litter as a result of having native nitrogen fixing trees. These trees could fix more nitrogen and facilitate nutrient cycling by rapid circulation of N through the litterfall (Haggar *et al*., 1993). Therefore, when the litter of these materials from the canopies of the woody perennial incorporated into the soil it undergoes microbial decomposition followed by mineralization, implying that good exchange of elements in the soil solution (Komicha *et al.*, 2018). Looking the status of soil fertility across all the studied AF systems we found that high soil fertility by considering the criterion set by Cochrane *et al*. (1985) in which > 4 meq/100 grams for Ca^{2+}, >0.3 meq/100 grams for K^{+}, > 0.8 meq/100 grams for Mg^{2+}.

The one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=10) result showed that only Enset based AF was significantly different at ($P<0.05$) from the two remaining systems in terms of exchangeable potassium (K^{+}) and magnesium (Mg^{2+}) within the soil layer 0-20cm.

However, in the case of 20-40 cm soil layer, exchangeable K^+ of Enset based AF showed significant different only from C-Ft-E based AF. Exchangeable Mg^{2+} of Enset based AF was significantly different from both C-Ft-E based and C-E based AF within the soil layer 20-40 cm. Unfortunately, the exchangeable Ca^{2+} did not show significant difference between all AF systems in both soil layers (0-20, 20-40 cm) (Table 17). The exchangeable Ca^{2+} and K^+ average values of the present study are comparable with the result reported by Komicha *et al.* (2018) and Mulyono *et al*. (2019) for park land agroforestry and *C. arabica*, *Artocarpus heterophyllus* Lam, *Mangifera indica L, Musa paradisiaca* L AF respectively. However, exchangeable Mg^{2+} was reported higher than our study in these systems.

From the results we could understand that as it goes deeper into the soil the exchangeable Ca^{2+}, K^+ and Mg^{2+} decreases across all AF systems. However, the BS% of these elements showed a decreasing trend except for calcium. The reason why BS% of (K^+) and (Mg^{2+}) showed an increasing trend from 0-20 cm to 20-40 cm could be due to leaching especially during the wet season (Tapia-Coral *et al*., 2005; Jobb´agy and Jackson, 2001). The decreasing BS% of (Ca^{2+}) in the 20-40 cm soil depth however may be related with the faster nutrient cycling as result of high decomposition rate that release nutrient quickly and taken by roots of short cycle plants in the 0-20 cm soil layer. As a result, the amount of (Ca^{2+}) going to the lower layers reduced (Salim *et al*., 2018).

Available phosphorus (avail. P) and TN were higher in Enset based AF compared to C-E based and Coffee-Ft-Enset based AF in both soil layers (0-20, 20-40 cm). Whereas C:N ratio was higher in Coffee-Ft-Enset based AF in both soil layers (Table 16). The highest OM% was found in Enset based and C-Ft-E based AF systems with average value of 5.8. From the results we could understand that as it goes deeper into the soil TN, OM% and available phosphorus (avail. P.) showed a decreasing trend across all AF systems. Whereas the C:N ratio showed an increasing trend. The highest values of TN found in soil layer 0-20 cm than 20-40 cm may be attributed mainly to the contribution made by more turn-over of the organic residues on the surface layer of soil (Chaudhry *et al*., 2007) and release of nutrient into the soil through the process of mineralization

Table 17. Comparison of soil fertility among the three AF systems (Mean±SD). Within each AF systems having the same letter are not significantly different at ($p<0.05$) from each other (Fisher LSD test; n=10 for each AF system).

Parameters	Agroforestry system					
	Enset based AF		C-E based AF		C-Ft-E based AF	
	Soil depth		Soil depth		Soil depth	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Ca exch meq/100grams	18.5 ±3.8 [a]	13.2 ±4.6 [a]	14.4 ±6.1 [a]	11.9 ±5.4 [a]	15.6 ±6.2 [a]	9.43 ±4.7 [a]
K exch meq/100grams	2.9 ±1.9 [a]	2.4 ±0.8 [a]	1.4 ±1.1 [b]	1.3 ±1.7 [ab]	1.4 ±0.8 [b]	1.2±1.2 [bc]
Mg exch meq/100grams	2.4 ±0.6 [a]	2.5 ±0.8 [a]	1.8 ±0.5 [b]	1.9 ±0.6 [b]	1.8 ±0.5 [b]	1.2 ±0.4 [c]
Ca BS%	76.8 ±6.6 [a]	69.7 ±6.9 [a]	78.9 ±4.1 [a]	75.9 ±6.7 [a]	80.1 ±8.5 [a]	73.0 ±19.0 [a]
K BS%	11.6 ±6.2 [a]	13.8 ±4.9 [a]	7.0 ±3.3 [a]	7.2 ±7.0 [a]	7.8 ±6.4 [a]	11.8 ±17.8 [a]
Mg BS%	10.1 ±2.2 [a]	13.4 ±2.4 [a]	10.6 ±1.9 [a]	12.6 ±2.1 [a]	9.8 ±1.7 [a]	9.5 ±2.8 [b]
OM%	6.8 ±1.5 [a]	4.8 ±1.3 [a]	6.3 ±1.3 [a]	4.5 ±1.6 [a]	7.2 ±1.7 [a]	4.4 ±0.6 [a]
TN g/kg	3.5±0.9 [a]	2.2±0.6 [a]	3.5±0.7 [a]	2.5±1.0 [a]	3.4±0.8 [a]	1.9±0.4 [a]
CN Ratio	11.9±1.8 [a]	13.0±2.5 [a]	11.2±1.3 [a]	11.1±1.8 [b]	12.5±0.8 [ab]	13.9±1.5 [c]
Avail. P mg/kg	31.2±3.0 [a]	18.0±1.9 [a]	18.9±1.4 [a]	17.1±2.6 [a]	14.4±0.9 [a]	8.3±0.3 [a]

*The comparison was conducted for similar soil layers of the three agroforestry systems.

of organic matter (Osman *et al*., 2001). Singh *et al.* (2018) and Chaudhry *et al*. (2007) who conducted a research on Poplar based AF systems and Kaur *et al.* (2000) on Acacia based AF systems investigated a deceasing trend of TN as it goes deeper into the soil. Higher concentration of available phosphorus under 0-20 cm soil layer could be due to the release of avail. P by the time of organic matter decomposition (Komicha *et al.,* 2018). Higher microbial population stimulated by organic matter input which supported phosphorus solubilisation from fixation could also another reason (Komicha *et al.,* 2018). Similar study results were reported by (Swamy *et al.,* 2006 and Singh *et al.*, 2018).

The average values of OM% across the three AF systems that ranged from 5.5-5.8% were considerably higher than reported by Neupane and Thapa (2001) with 1.5–2.3%, Desbiez *et al*. (2004) with 2–3%, and Carson (1992) with 0.5–3%. The highest amount of TN found in soil layer 0-20 cm compared to 20-40 cm soil layer may be attributed mainly to the contribution made by more turn-over of the organic residues on the surface layer of soil (Bhardwaj *et al*., 2001) and release of nutrient into the soil through the process of mineralization of organic matter (Osman *et al*., 2001). The average TN values of our AF systems were comparable with other reports else where (Desbiez *et al*., 2004; Shrestha, 2009 and Mulyono *et al*., 2019).

The relatively high C:N ratio of C-Ft-E based AF system compared with the other two systems might be due to less mobilization of nutrients, especially nitrogen (Cadisch and Giller 1997). The lower C:N ratio observed in Enset based AF system might be related with better nitrogen contents of the tree's litter material and thus faster decomposition rate that facilitates nutrient cycling. As we reported in plant diversity part of our study Enset based AF system had comparatively better incorporation of indigenous nitrogen fixing trees/shrubs such as such as *M. ferruginea and Erythrina brucei*. Whereas in C-Ft-E based AF most of the tree/shrub species were exotic Fruit trees such as *Mangifera indica, Persea Americana*. As Negash and Starr (2013) woody species like *M. ferruginea*, *Erythrina brucei* have greater nitrogen content in their litter material than fruit trees such as *Mangifera indica and Persea Americana*. Except for C:N ratio the other parameters such as OM%, TN and avail. P showed a decreasing trend as we go from upper soil layer to the lower in all AF systems. The decreasing trend of avail. P and TN with an increase in soil depth in the present investigation is in conformity with the findings of (Swami *et al*., 2006 and Ghimire, 2010) who studied the soil properties under poplar-based AF system. Similar results were also reported by Singh *et al.* (2018), Chaudhry *et al*. (2007) and Kaur *et al.* (2000) who conducted a research on different AF systems.

The C:N ratio in C-Ft-E based AF system showed a significant difference at ($P<0.05$) compared from C-E based AF. Whereas C-E based and Enset based did not show significant difference in their soil layer 0-20 cm. In the case of 20-40 cm soil layer, there was significant difference between all AF systems. Unfortunately, there was not significant difference between all AF systems in terms of OM%, TN and avail. P in both soil layers (0-20, 20-40 cm) (Table 17). The AF systems with their adjacent monocropping farms were also compared. The average values of exchangeable Ca, K and Mg, OM%, TN, C:N ratio and avail. P in our AF systems were higher than the average values of their adjacent monocropping farm in all soil depths (0-20, 20-40 cm) (Table 18). The higher values of soil fertility indicators in the AF systems compared to monocropping farms in general is attributed by the process of mineralization of organic matter, root decay and other important substitutes in tree-based land use systems releases nutrient into the soil and thus brings

Table 18. Comparison of soil fertility of AF systems and adjacent monocropping. two-tailed t-test, n=30 (Mean±SD)

Parameters	*Land use type*					
	0-20 cm Soil depth			20-40 cm Soil depth		
	Average value of AF farms	Average value of Adjacent Monocrop farm	Sig. (2-tailed)	Average value of AF farms	Average value of Adjacent Monocrop farm	Sig. (2-tailed)
Ca exch meq/100gram	16.2±3.5	10.2±1.7	0.000**	11.5±2.1	9.2 ±1.7	0.033*
K exch meq/100gram	1.9 ±1.0	1.0±0.6	0.022*	1.6±0.8	1.0±0.7	0.027*
Mg exch meq/100gram	2.0±0.3	1.5±0.2	0.000*	1.8±0.3	1.4±0.2	0.006**
OM%	6.8±1.0	4.8±0.6	0.000**	4.6 ±0.9	3.7±0.7	0.042*
TN g/kg	3.5±0.5	2.4±0.3	0.000**	2.2±0.4	1.8±0.3	0.031*
CN Ratio	11.9±0.9	11.7±0.5	0.733NS	12.7±0.9	12.3±1.0	0.172NS
Avail. P mg/kg	21.4±10.4	15.2±3.7	0.051NS	1.4±1.01	1.2±0.5	0.50NS

** Significant at the 0.01 level (2-tailed)
* Significant at the 0.05 level (2-tailed)
NS-Not significant

enhancement in the nutrient status of soil (Osman *et al*., 2001; Chaudhry *et al*., 2007; Pandey and Singh, 2009). Our results were in consistent with other reports else where high TN (Haggar *et al*., 1993; Kaur *et al*., 2000; Gill and Burman, 2002; Singh *et al*., 2018), increased soil organic matter content (Beer *et al*., 1990; Beer *et al*., 1997; Kang, 1997; Singh *et al*., 2018) better available phosphorus, exchangeable calcium and magnesium (Komicha *et al*.,2018; Singh *et al*., 2018; Schwab *et al*.,2015). Similarly, a study conducted in four *Faidherbia Albida* parklands of Burkina Faso by Depommier *et al*. (1992) confirmed that the soils of the AF had greater nutrient level than soils in monocrop fields with 13% to 117% more organic N, 18% to 36% more extractable P, 2% to 67% more exchangeable Ca, and 60% to 100% more exchangeable K. In addition, the author reported most of the soil fertility improvement was observed in the first soil layer (0-20 cm) like we noticed in our study. Other authors like (Pandey and Singh, 2009; Singh *et al*., 2018) also found similar results by comparing TN, avail. P, and exchangeable K, Ca, and Mg, and OM% of home-garden agroforestry with control monocrop field thus noticed greater nutrient level under AF systems than the control.

The pairwise 2-tailed t-test result showed that exchangeable Ca, OM% and under AF systems were highly significantly different at ($P<0.01$) and K and Mg were significantly different at ($P<0.05$) compared to adjacent monocropping farms within the 0-20 cm soil layer. Whereas, in the case of 20-40 cm soil layer only exchangeable Mg was highly significantly different at ($P<0.01$) and Ca, K, OM% and TN were significantly different at ($P<0.05$) (Table 16). Generally, our AF systems showed considerable difference in nutrient availability compared to some other tree-based land-use systems and their adjacent monocropping farms. As it is already known having good soil fertility like in our AF systems contributes a lot for production enhancement since greater soil fertility improves productivity of the land. As a result of better production, the livelihood of the community could be improved and will have significant role in alleviating the issues of food security.

5.3.2 Soil organic carbon stocks of AF systems versus their adjacent monocropping farms

The amount of soil organic carbon under AF is higher than monoculture systems. Because, trees/shrubs in AF system play a great role in recycling of nutrients and soil organic carbon improvement (Lehmann *et al*., 1998; Sarvade *et al*., 2014, Kaur *et al*., 2000). A pairwise comparison was conducted to see the SOC stocks of three AF systems and their adjacent monocrop farming systems. The mean total soil organic carbon stock of the three studied AF systems was higher than their adjacent monocrop smallholdings. According to the results of paired 2-tailed t-test C-Ft-E based AF and C-E based AF showed a statistically highly significant difference compared to their respective monocrop smallholding. However, the SOC stock of Enset based AF system did not show significant difference with its adjacent monocrop plots (Table 19). This less variation in SOC stock between Enset based AF systems and their adjacent monocropping farms might be due to soil management employed to these monocropping farms. This could be related with addition of livestock manure, ashes and compost to the monocropping farms by farm owners.

Table 19. Mean±SD; n=10) soil organic carbon (SOC) stock 0-40 cm (t ha^{-1}) for each of the three studied AF systems and their adjacent mono crop plot and results of paired samples two tailed T-test

	Land use type	N	Mean ±SD	t	df	Sig. (2-tailed)
Pair 1	SOC Coffee-Ft-Enset AF	10	125.5±17.3	5.0	9	0.001**
	SOC monocrop plot	10	90.5±15.3			
Pair 2	SOC Enset based AF	10	146.1±26.5	0.4	9	0.688 NS
	SOC monocrop plot	10	141.8±28.1			
Pair 3	SOC Coffee-Enset AF	10	139.6±25.4	5.4	9	0.000**
	SOC monocrop plot	10	95.3±14.6			

** Significant at the 0.01 level (2-tailed).
* Significant at the 0.05 level (2-tailed).
NS-Not significant

High amount of SOC stock in the three AF systems might be due to the lignified cells found in trees' litter, branches, bark, roots etc which could lead to carbon stabilization in the soil (Six *et al*., 2002), slower oxidation rate of organic matter under the tree shades (Gill and Burman, 2002), addition of root exudates from the trees in the rhizosphere (Bertin *et al*., 2003) and accumulation of more organic matter as a result of litterfall from the trees/shrubs or/and fine root degradation in the underground (Komicha *et al*., 2018). Similar results were reported by Henry *et al.* (2009) who found higher SOC stock in home-garden AF than food crops monoculture land, Saha *et al*. (2010) home-garden AF systems showed 114% greater in SOC stock than rice paddies and Kaur *et al*. (2000) observed increased soil organic carbon by 11-52% in AF systems compared to monocropping fields. In addition, a study was conducted by Alfaia *et al*. (2004) in central Amazonia of Brazil and he observed similar levels of SOC under AF and the forest. As the author mentioned, the observed high level of SOC might be as the result of incorporation of nitrogen fixing cover crops into the system. Therefore, we could understand that AF systems have higher SOC levels than monocrop fields even some times similar level with forest areas depending on the plant mixture and management of the AF system.

5.3.3 Relationship of basic soil fertility indictor nutrients in the three agroforestry systems

According to our results the nutrient stock of (calcium and carbon) under Enset based AF system showed a very strong positive correlation at ($P<0.01$) within the 0-20 soil depth. In addition, calcium also showed a strong positive correlation with available phosphorus at ($P<0.05$) within the 0-20 soil depth (Appendix 2). Whereas, in soil layer 20-40 cm of the same AF system we found that a very strong positive correlation at ($P<0.01$) between (calcium and soil organic carbon), (calcium and available phosphorus) and (calcium and total nitrogen) (Appendix 3). In addition, (potassium and magnesium) showed a strong positive correlation at ($P<0.05$) within the 20-40 soil depth (Appendix 3).

Under C-E based AF system the relationship between (calcium and potassium), (calcium and magnesium), (calcium and soil organic carbon), (calcium and available phosphorus), (potassium and magnesium), (magnesium and available phosphorus) and (magnesium and SOC) showed statistically very strong positive correlation at ($P<0.01$) within the 0-20 soil depth) (Appendix 4). The correlation between (potassium and available phosphorus), (potassium and SOC), (TN and available phosphorus) and (available phosphorus and SOC) also showed a strong positive correlation at ($P<0.05$) within the 0-20 soil depth (Appendix 4). Whereas, in soil layer 20-40 cm of the same agroforestry system we found that a very strong positive correlation at ($P<0.01$) among (calcium and SOC), (calcium and available phosphorus), (calcium and total phosphorus), (calcium and TN), (TN and available phosphorus), (total nitrogen and soil organic carbon) and (available phosphorus and SOC) (Appendix 5). In addition, (potassium and magnesium), showed a strong positive correlation at ($P<0.05$) within the 20-40 cm soil depth (Appendix 5). From the above results, we understood that the positive correlation among the nutrient stocks of different elements was stronger in the soil depth 0-20 cm than the soil depth 20-40 cm in this type of AF.

The third AF system that we did the correlation between the nutrients was C-Ft-E based AF system. The relationship between (calcium and magnesium) and (TN and SOC) showed statistically very strong positive correlation at ($P<0.01$) within the 0-20 soil depth (Appendix 6). Whereas, in soil layer 20-40 cm of the same AF system we found that a very strong positive correlation at ($P<0.01$) between (TNand available phosphorus) and (TN and SOC (Appendix 7). In addition, only (available phosphorus and SOC) showed a strong positive correlation at ($P<0.05$) within the 20-40 soil depth (Appendix 7).

The correlation between soil organic carbon and total nitrogen was found to be positively very strong at ($P<0.01$) across all the three AF systems and both soil depths except in Enset based AF system that showed significant different at ($P<0.01$) in its 0-20 cm soil depth. The highest correlation ($r = 0.95$) between SOC and TN was observed under C-Ft-E based AF system (0-20 cm depth). Almost all soil nutrient stocks showed a positive correlation between them across all the AF systems and both soil layers. Some of them showed strong and some with very strong positive correlation. Overall, we noticed that the strength of relationship between the nutrient stocks differs from AF system to AF system and soil layer. Similar results were reported by Mulyono *et al*. (2019) who found positive and very strong correlation between (TN and SOC), (available phosphorus and TN), (potassium and available phosphorus) and (calcium and magnesium) of soil sample taken from sixteen different AF practices in Upper Citarum Watershed, Indonesia. Other scholars like Adhikari and Bhattacharyya (2015) reported that, there was positive strong correlation between SOC and TN for soil samples collected from seven sites of tropical rainforest in the state of state of Assam, India. The relationship between SOC and TN stocks in our study sites was very strong positive correlation. This might be related with accumulation of organic matter through litterfall and fine root traits that mainly affect the SOC and TN stocks. Therefore, as the amount of organic matter that derived mainly from quality plant material increases the SOC and TN level that is going to be released also increases proportionally.

5.4 Quantifying litterfall and nutrient influx in indigenous agroforestry systems

There are various ecological processes that have influence on the transfer of organic matter and energy, as well as carbon and other nutrients from vegetation to the soil in forest ecosystems. Litterfall is considered one of the most important ecological processes in AF systems and is a dominant link in the biogeochemical cycling of matter within the system (Liu *et al*., 2004). The litterfall that comes from the trees and/or shrubs and herbs constitutes leaf litterfall and prunings. These are the main components of litterfall production in which nutrients could be returned back to the soil (Sharma *et al*., 2005; Andivia *et al*., 2012). The extent of rebuilding soil nutrients and improving crop production depends on the amount of litter biomass generated after pruning and through natural litterfall (Rivest *et al*., 2009).

5.4.1 Quantity and distribution of litterfall production

The amount of litterfall that was produced in each month under the three studied AF systems was calculated. The values from the 5 AF farms having three replications of each AF system were pooled since quantity of litterfall is highly variable in time and space (Sharma and Ambashi, 1987). A pattern for monthly litterfall per unit area of the three AF systems was constructed. As the results displayed in figure 22, the months February and August had the highest peak mean monthly litterfall amount across all the three AF systems with 124.0 g m^{-2} mo^{-1} and 133.7 g m^{-2} mo^{-1} respectively for C-Ft-E based; 42.2 g m^{-2} mo^{-1} and 46.1 g m^{-2} m^{-1} for Enset based and 55.7 g m^{-2} mo^{-1} and 49 g m^{-2} mo^{-1} for C-E based AF system respectively. The months April and June had the lowest mean monthly litterfall amount across all the three AF systems with 24.0 g m^{-2} mo^{-1} and 37.5 g m^{-2} mo^{-1} for C-Ft-E based; 23.9 g m^{-2} mo^{-1} and 24.6 g m^{-2} mo^{-1} for Enset based; and 17.0 g m^{-2} mo^{-1} and 27.8 g m^{-2} mo^{-1} for C-E based AF system respectively.

A fluctuation of litterfall by season and month was observed in all the studied three AF systems. Similar to our results Wang *et al*. (2008) and Triadiati *et al*. (2011) found that litterfall fluctuated by season and month respectively. This was mainly influenced by the interaction of monthly climatic factors i.e in natural forest and Cocao AF systems of Central Sulawesi, Indonesia high litterfall coincides with low humidity and high temperature (Triadiati *et al*.,2011). The monthly litterfall pattern was similar in all the three AF systems, but the amount of the actual litterfall varied among the stands. From all, C-Ft-E based AF system showed higher mean monthly litterfall (81.8±37.7 g m^{-2} mo^{-1}) while the lowest mean monthly litterfall was found in Enset based AF system (30.7±8.6 g m^{-2} mo^{-1}) (Table 19). In C-Ft-E based AF, the mean monthly litterfall was more than twice compared to the Enset based. This might be due to the fact that the former AF system had more species diversity, abundance and stem density of mainly Fruit trees which have vigorous growth and thus it is expected to produce more biomass. Similar results were found in Maya homegardens of Mexico where the homegarden which had greater number of fruit trees showed higher production of litterfall (Benjamin *et al*., 2001).

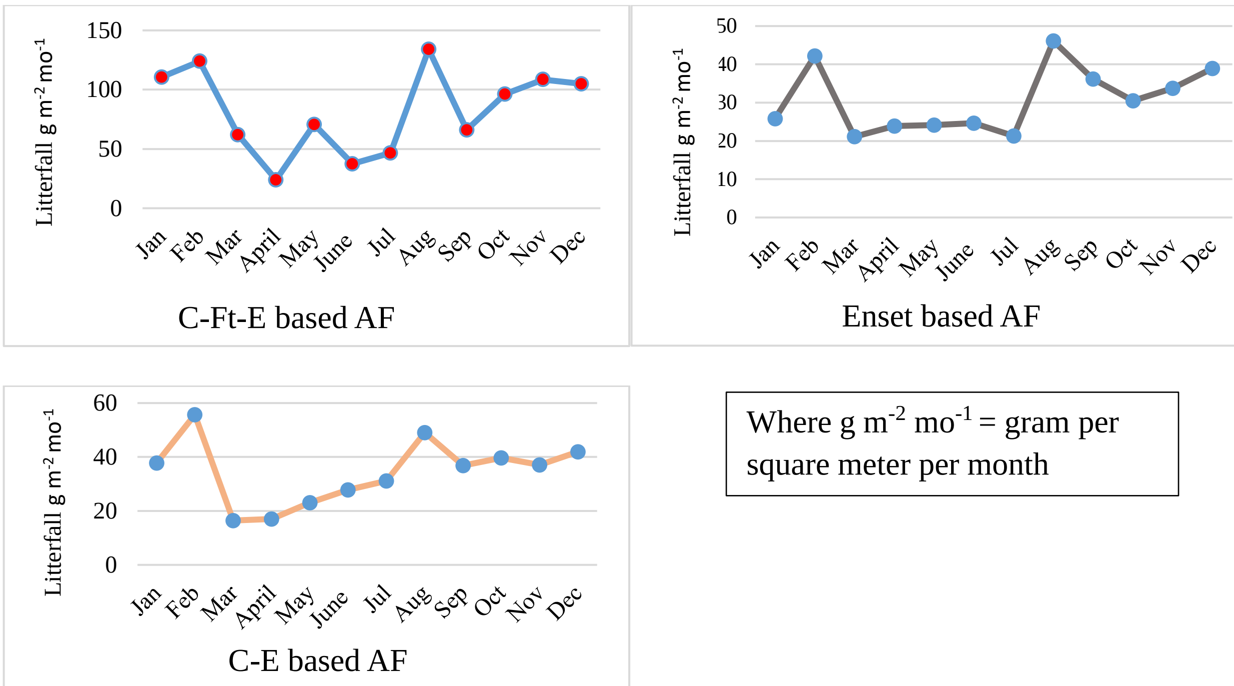


Figure 22. Mean monthly litterfall gram per unit area across the three AF systems

The annual litterfall kilogram per hectare of AF systems in the present study (9.8 t ha^{-1} yr^{-1}, C-Ft-E based AF) was considerably higher than reported for homegardens, Cacao AF systems and Caatinga alta forests (Jensen, 1993a, b; Medina and Cuevas, 1996; Benjamin *et al*., 2001; Triadiati *et al*., 2011). Our litterfall values were higher than reported for Cacao agroforestry of Central Sulawesi, Indonesia (5.0-8.23 t ha^{-1} yr^{-1}; Triadiati *et al*., 2011), Terra firme rainforest of Lampung province, Indonesia (7 t ha^{-1} yr^{-1}; Medina and Cuevas, 1996) and Homegardens of Java, Indonesia (4.4 t ha^{-1} yr^{-1}; Jensen, 1993a, b). In addition, these values were also higher than reported for Asian tropical and sub-tropical coniferous and broadleaved forests (5 t ha^{-1} yr^{-1}; Liu *et al*., 2004), traditional home gardens of India (6.2 t ha^{-1} yr^{-1}; Das and Das, 2010) and in multistrata AF systems of Ghana, West Africa (average of 6.8 t ha^{-1} yr^{-1}, Isaac *et al*., 2005). However, our results were relatively lower than these reported for natural forest in Central Sulawesi, Indonesia (13.67 t ha^{-1} yr^{-1}; Triadiati *et al*., 2011), for moist deciduous forests of the Western Ghats in Peninsular India (12-14 t ha^{-1} yr^{-1}; Kumar and Deepu, 1992), forest plantations of Costa Rica (8.2-12.6 t ha^{-1} yr^{-1}; ;

Montagnini *et al*., 1993) and pure stand of *Acioa barteri* (9.8 t ha^{-1} yr^{-1}) and *teak* (9.0 t ha^{-1} yr^{-1}) in tropical humid regions of Nigeria (Okeke and Omaliko, 1991).

The difference in annual litterfall values recorded in our AF systems compared with other systems might be related with differences in type of plant species, trees/shrubs density, climatic factors, age of the stands, management practice (pruning, lopping etc), site and soil factors among the studies. This was in line with study conducted by Goma-Tchimakala and Bernhard-Reversat (2006) and Starr *et al*. (2005) that litterfall in natural forest systems were also strongly influenced by age structure, stand volume/tree density and season. In addition, climatic variables (especially rainfall and temperature) and tree phenology and metabolism are also major factors controlling litterfall (Murovhi *et al*., 2012).

The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=12) showed that C-Ft-E based AF system was significantly different at ($P<0.05$) from both Enset based and C-E based AF systems. But, Enset based and C-E based AF systems were not significantly different (Table 20). The inter-monthly variation percentage was also calculated. According to our results inter-monthly variation for C-Ft-E based AF system was higher (82%), implying that a wider variation in monthly litterfall per unit area (Table 20). Such variation in litterfall may not be beneficial for the system. For instance, high litterfall in certain months (during August in our case) may have a negative effect on the growth of crops under the canopies due to extrem ground mulching. But, it could be beneficial in protecting raindrop splash erosion within the system.

Table 20. Monthly mean±SD; n=12, inter-monthly variation and mean annual litterfall (g m^{-2} yr^{-1}) across AF systems

Agroforestry system	N	Monthly mean	Inter-monthly variation (%)	Annual mean g m^{-2} yr^{-1}
C-Ft-E based AF	12	81.8±37.7 $^{(a)}$	82.0	981.30
Enset based AF	12	30.7±8.6 $^{(b)}$	54.3	368.50
C-E based AF	12	34.5±12.0 $^{(b)}$	70.9	413.40
P-value		<0.05		

Note: similar letter shows not significant difference and different letters indicate significance differences between groups according to LSD multiple test (Fisher LSD test) at $P<0.05$;

The lowest inter-monthly variation was observed in Enset based AF system (54.3%), implying that a narrow variation in monthly litterfall per unit area (Table 20). This situation shows the litterfall was almost evenly distributed across the months of the year, which means that dropping from the canopy trees is not synchronized and not all canopy trees may drop leaves at certain times during the year. Thus continuous shading for shade loving crops, ensuring protection of the herbaceous food crops and supply of organic matter and a steady flow important nutrients to the soil (Negash and Starr, 2013) is quantified.

To show the dispersion of the monthly litterfall values over the year we constructed a box plot graph (Figure 23) and the result of Kruskal–Wallis test $P<0.05$ showed that, under Enset based and C-E based AF systems the monthly litterfall values were closer to the mean. However, under C-Ft-E based AF system the monthly values showed greater variation, implying that the plant species defoliate their leaves, drop their catkins, twigs and barks in certain months indicating a pronounced seasonal pattern of litterfall. This might be due to most species under C-Ft-E based AF system have similar season for the senescence of their leaves and other plant parts. The annual litterfall in the present study in general was in the order of C-Ft-E based AF > C-E based AF > Enset based AF with 981.3, 413 and 368.5 g m^{-2} yr^{-1} respectively.

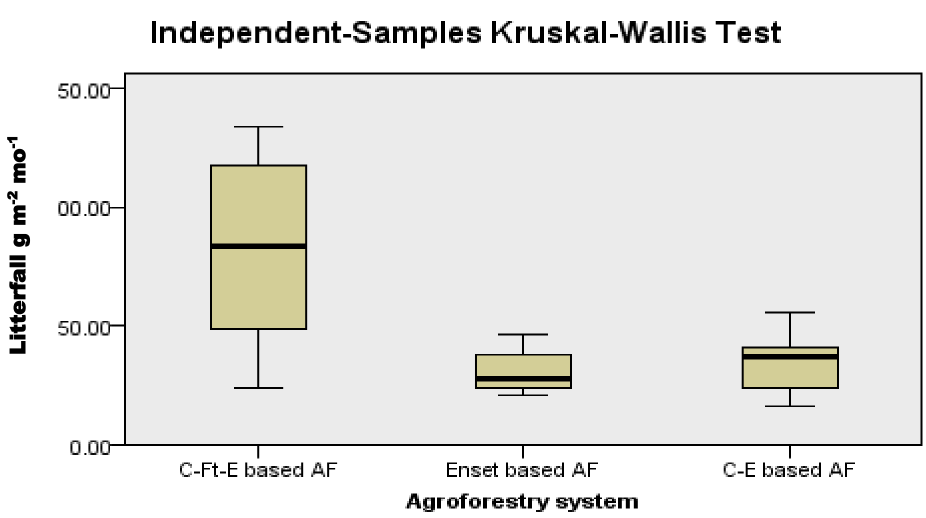


Figure 23. Boxplot of variation and mean monthly litterfall in the three AF systems

The distribution of litterfall under the three AF systems over the 12 months is displayed in figure 24. C-Ft-E based AF system showed higher quantity of litterfall over the other remaining AF

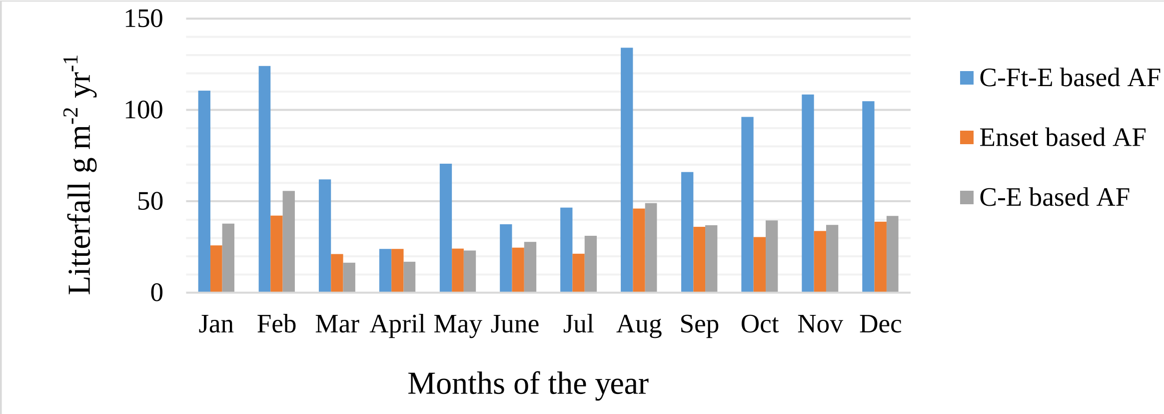


Figure 24. Comparison of mean monthly litterfall (g m^{-2} yr^{-1}) across the months and among the three AF systems

Table 21. Summary of litterfall status in different forest and agroforest land use systems of some tropical and sub tropical regions

Location	Plant community	Total litterfall (t ha^{-1} yr^{-1})	Reference
Central Sulawesi, Indonesia	Natural Forest	13.67	Triadiati *et al*., 2011
Central Sulawesi, Indonesia	Cacao agroforestry	5.0 - 8.23	Triadiati *et al*., 2011
Western Ghats in Peninsular India	moist deciduous forests	12-14	Kumar and Deepu 1992
Lampung province, Indonesia	Terra firme rainforest	7	Medina and Cuevas, 1996
Amazon Forest, Venezuela	Caatinga alta	4	Medina and Cuevas, 1996
Costa Rica	Forestry plantations	8.2-12.6	Montagnini *et al*., 1993
Los Tuxtlas, Veracruz, Mexico	Perennial high forest	16.3	Alvarez and Guevara, 1993
Henequen zone, Yucatan, Mexico	Maya Homegardens	2	Benjamin *et al*., 2001
Java, Indonesia	Homegardens	4.4	Jensen, 1993a, b
South-eastern rift valley landscapes of Ethiopia	Indigenous agroforestry	9.8	The present study

systems across the 12 months of the year. The greater litterfall of this system over the others might be related with the highest species diversity and abundance observed in C-Ft-E based AF system. As Guo *et al*. (2019) reported, tree species diversity and richness have a positive direct effect on annual litterfall of heterogenous tropical rainforests. Therefore, annual litterfall was increased significantly with tree/shrubs species richness and diversity.

Litterfall (leaf, twigs, fruit, flower, and branch litter) production status of some forest and agroforest land use systems located in different tropical regions of the world are summarized under Table 21. The maximum annual litterfall was recorded in Perennial high forest land use systems of Los Tuxtlas, Veracruz, Mexico with a value of 16 t ha^{-1} yr^{-1} **(**Alvarez and Guevara, 1993) and least litterfall value in Maya Homegardens of Yucatan, Mexico with 2 t ha^{-1} yr^{-1} (Benjamin *et al*., 2001).

5.4.2 Litterfall nutrient flux (Ca, K, Mg, Mn, P, N, C) of indigenous agroforestry systems

Smallholder farmers induce various mechanisms in which they counter the challenges related with soil fertility issues. Integration of trees/shrubs into farming systems is one of the plausible option. These trees/shrubs are believed to have positive effects on soil improvement and enhance productivity of the agroforestry system (Muzoora *et al*., 2011; Ludwig *et al*., 2004). The litterfall that comes from upper storey of trees/shrubs in AF systems have a profound effect on soil nutrient status and also is an important component in nutrient cycling (Murovhi *et al*., 2012; Ssebulime *et al*., 2019). Trees and shrubs bring nutrients from deeper layers in the soil with the help of their roots and return it to the floor through dead organic matter. This litter material not only supplies nutrients but also contributes to the improvement of soil structure, intercepts and stores more moisture, thereby reducing run-off, erosion and bulk density once it has been incorporated (Liu *et al*., 2017, Blanco-Sepúlveda and Aguilar-Carrillo, 2015; Misra, 2011). As Aponte *et al*. (2012) revealed, the knowledge regarding the quality of the litter material from various tree species and how this varies seasonally is also very important. Because, it helps for a proper judgement of the effect of these changes in ecosystem function.

The pattern in monthly nutrient flux of each element under the three AF systems was constructed. As the results displayed in figure 25, calcium and potassium showed greater nutrient flux compared with the other elements and the highest values were recorded during the months February and August across all AF systems. Sodium showed the least nutrient flux across the 12 months and in all the three AF systems. However, the mean monthly flux for aluminium, iron, manganese, sodium, phosphorus and sulphur showed a variation from month to month across the three AF systems. The highest mean nutrient flux for Calcium (Ca) was 28 kg ha^{-1} mo^{-1} (August), 10 kg ha^{-1} mo^{-1} (February) and 10 kg ha^{-1} mo^{-1} (February) for C-Ft-E based AF; Enset based and C-E based AF systems respectively. The highest mean nutrient flux for potassium (K) was 17 kg ha^{-1} mo^{-1} (February), 7 kg ha^{-1} mo^{-1} (February) and 9 kg ha^{-1} mo^{-1} (February) for C-Ft-E based; Enset based and C-E based AF system respectively.

The results of annual nutrient flux (kg ha^{-1} yr^{-1}) of calcium, potassium, magnesium, manganese, sodium, phosphorus and sulphur showed that, there was a higher flux under C-Ft-E based AF system compared to the two systems (Table 22). However, Enset based and C-E based had almost equivalent values in most of the elements. Nutrient values mainly calcium and potassium showed superior under C-Ft-E based AF system over the other AF systems.

The annual nutrient flux of Ca (186 kg ha^{-1} yr^{-1}) and K (99 kg ha^{-1} yr^{-1}) for C-Ft-E based AF in our study were considerably higher than reported for Hawaiian montane rainforests with values of Ca (68-136 kg ha^{-1} yr^{-1}) and K (5-12 kg ha^{-1} yr^{-1}) (Vitousek *et al*., 1995), and for montane rain forests in Jamaica with values of Ca (50 kg ha^{-1} yr^{-1}) and K (39 kg ha^{-1} yr^{-1}) (Tanner, 1977). Similarly, there are studies on different forest based systems conducted by other authors such as Edwards (1982) and Liu *et al*. (2002) who reported lower annual Ca and K nutrient flux than in our C-Ft-E based AF systems. The reason for the difference in nutrient flux of our AF systems from others is most likely related with difference in species composition, climate and soil fertility (Vitousek and Sanford, 1986; Herbohn and Congdon, 1998). For instance, forest/agroforest stands which have grown in fertile soil produced high litterfall rates and this biomass input returned via litterfall to the ground contributed again high nutrient stocks (Dawoe *et al*., 2010). From results of the present study, we observed that the mean monthly nutrient flux (Ca and K) and mean monthly litterfall clearly showed a direct relationship between them across the three AF systems. This means, months with higher litterfall showed higher nutrient flux. This proportionality of amount of litterfall to the nutrient fluxes confirms also that the quality of the litter. E.g. the nutrient concentration in the litter stays fairly constant over the months. Therefore, the higher annual nutrient flux observed in our AF systems was due to greater annual litterfall than the others. But, higher quantity of litterfall in general does not necessarily release higher amounts of nutrient and thus the potential of litterfall for soil fertility management also depends on the quality of the litter

Table 22. Annual total nutrient flux of elements across the three AF systems kg ha^{-1} yr^{-1}

AF systems	Al	Fe	Ca	K	Mg	Mn	Na	P	S
C-Ft-E based AF	24.0	19.0	186.0	99.0	23.0	6.0	1.0	8.0	10.0
Enset based AF	11.0	13.0	75.0	44.0	11.0	1.0	1.0	4.0	5.0
C-E based AF	6.0	5.0	74.0	67.0	11.0	1.0	1.0	5.0	6.0

material (Aponte *et al*., 2012). It is evident that nutrient concentrations in the plant tissues in turn vary in accordance with availability of nutrients in the soil and the specific seasonal requirements of each species (Benjamin *et al*., 2001). As a result of fluctuation of climatic factors such as temperature, rainfall, wind speed and relative humidity, the quantity of litterfall produced in each month was affected and thus nutrient flux across the months also showed variations.

The annual nutrient flux from litterfall for magnesium (Mg) (11-23 kg ha^{-1} yr^{-1}) and phosphorus (P) (4-8 kg ha^{-1} yr^{-1}) of our AF systems were within the range of values reported for montane rain forest in New Guinea (Edwards, 1982), forest ecosystem of the Western Andes of Venezuela (Fassbender and Grimm, 1981) and montane moist evergreen broad-leaved forest in Ailao Mountains, South-west China (Liu *et al*., 2002). Our Mg and P values are relatively higher than reported for Hawaii-Puu Makaala montane rainforests (Vitousek *et al*., 1995) but lower Mg values than reported for Hawaii-Olaa montane rainforests (Vitousek *et al*., 1995).

We had hypothesized that nutrient flux of some elements (Mg, K and Ca) from litterfall would be reduced in the months with high rainfall as a result of leaching derived from rain washing. However, we did not find any clear and significant effect that could really change the pattern of the graph, implying that the litterfall and its respective nutrient flux showed similar pattern across the months of the year in all agroforestry systems. Overall, C-Ft-E based AF systems showed higher nutrient flux almost in all elements and the least nutrient flux was observed in Enset based AF systems.

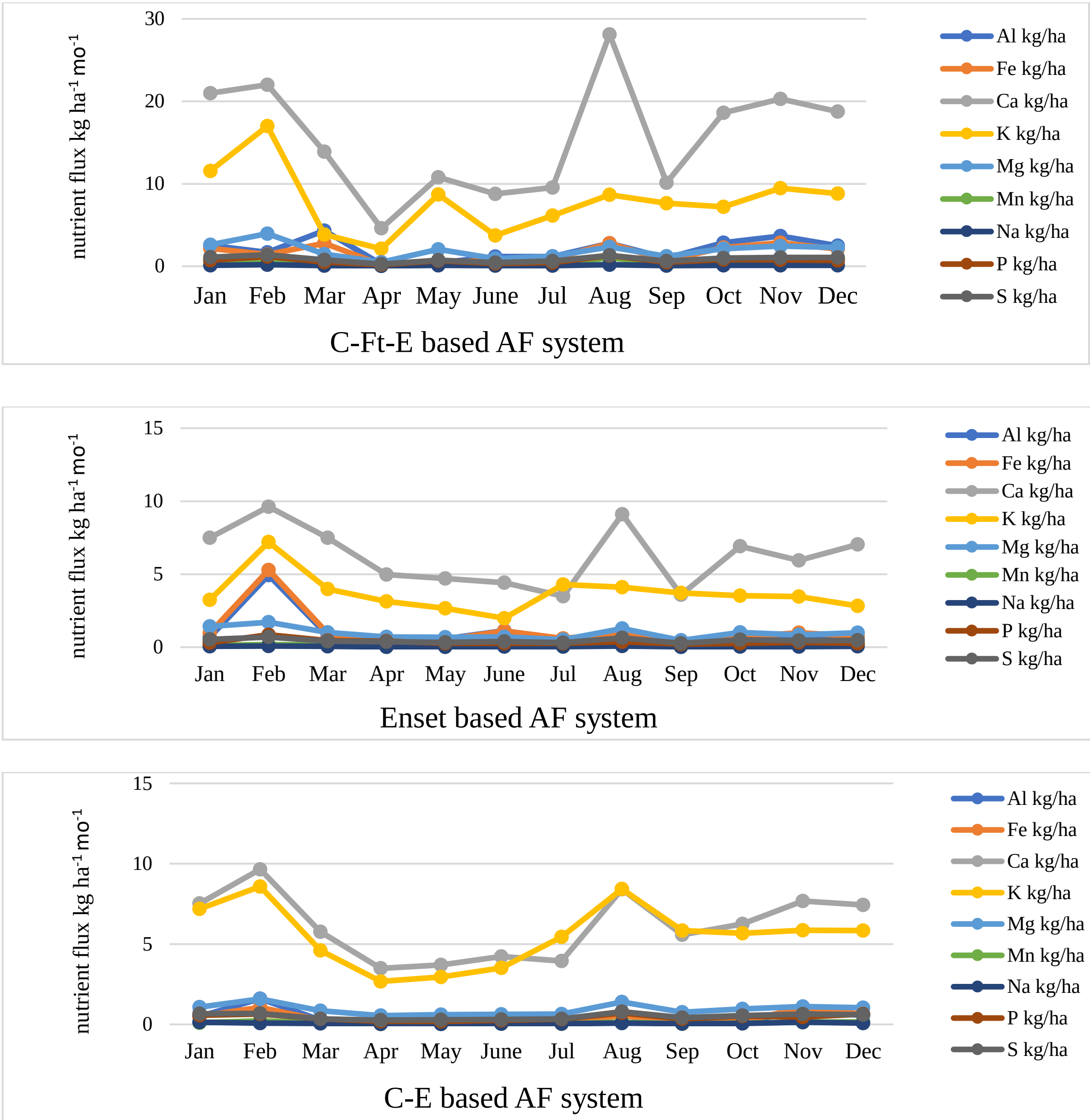


Figure 25. Mean monthly nutrient flux of each nutrient across AF systems

The result of one-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=12) showed that C-Ft-E based AF system was significantly different at ($P<0.05$) from both Enset based and C-E based AF systems for all nutrients (Ca, K, Mg, Mn, Na and P) (Table 23). However, Enset based and C-E based AF were not significantly different at ($P<0.05$) for all nutrients. The mean monthly flux for Ca (15.5 kg ha^{-1}), K (8.2 kg ha^{-1} mo^{-1}) and Mg (1.9 kg ha^{-1} mo^{-1}) was higher in C-Ft-E based AF system as compared to the remaining two AF systems (Table 23). Our results revealed that the nutrient flux from litterfall that was contributed from Ca, K and Mg shows similar stoichiometric as it is found in other ecosystems. This could also help to materialize with minor nutrients.

Table 23. Mean±SD; n=12) monthly nutrient flux (kg ha^{-1} mo^{-1}) for each of the three studied AF systems) and results of 1-way ANOVAs followed by post-hoc testing (Fisher's LSD test) (at α=0.05, significant differences between AF systems were indicated)

Agroforestry system	Number of Months	Elements	Nutrient flux
C-Ft-E based AF	12	Ca kg ha^{-1} mo^{-1}	15.5± 6.9 ^{a}
Enset based AF	12		6.1± 2.0 ^{b}
C-E based AF	12		6.2± 2.0 ^{b}
C-Ft-E based AF	12	K kg ha^{-1} mo^{-1}	8.2± 4.8 ^{a}
Enset based AF	12		3.7± 1.3 ^{b}
C-E based AF	12		5.6± 1.9 ^{b}
C-Ft-E based AF	12	Mg kg ha^{-1} mo^{-1}	1.9± 0.9 ^{a}
Enset based AF	12		0.9± 0.4 ^{b}
C-E based AF	12		0.9± 0.3 ^{b}
C-Ft-E based AF	12	Mn kg ha^{-1} mo^{-1}	0.5± 0.3 ^{a}
Enset based AF	12		0.1± 0.1 ^{b}
C-E based AF	12		0.1± 0.1 ^{b}
C-Ft-E based AF	12	Na kg ha^{-1} mo^{-1}	0.1± .1 ^{a}
Enset based AF	12		0.05± 0.01^{b}
C-E based AF	12		0.1± .04 ^{b}
C-Ft-E based AF	12	P kg ha^{-1} mo^{-1}	0.7± 0.3 ^{a}
Enset based AF	12		0.4± 0.2 ^{b}
C-E based AF	12		0.4± 0.2 ^{b}
C-Ft-E based AF	12	S kg ha^{-1} mo^{-1}	0.9± 0.4 ^{a}
Enset based AF	12		0.5± 0.1^{b}
C-E based AF	12		0.5± 0.2 ^{b}

Assessment on the carbon and nitrogen contents and especially the C:N ratio of litter are among other internal (litter quality) and external (climate and soil) factors important for the estimation of the decomposition rate and thus the status of nutrient cycling within the system. (Dhanya *et al*., 2013; Zeng *et al*. 2010). For instance, litter material with high content of nitrogen, low carbon to nitrogen ratios and/or low lignin to nitrogen ratios decompose faster compared with lower concentration of nitrogen but with very high carbon/lignin content. As Sharma and Ambashi (1986) pointed out C:N ratio of litter material played a greater role in ascertaining decomposition rates than temperature or moisture; in spite of the fact that temperature and moisture still have a significant impact on decomposition.

The mean monthly nitrogen and carbon flux was also calculated for our AF systems and the monthly distribution was displayed in figure 26. According to the results, both carbon and nitrogen flux showed higher values in the months February and August across all AF systems. Like calcium and potassium carbon and nitrogen also showed significant fluctuations over months of the year. Overall, the mean monthly nitrogen flux (16 kg ha^{-1} mo^{-1}) and carbon flux (391 kg ha^{-1} mo^{-1}) was higher in C-Ft-E based AF system as compared with the other AF systems. The Enset based and C-E based AF systems had (8 kg ha^{-1} mo^{-1}) nitrogen flux each. But, their carbon flux was 150 kg ha^{-1} $mo^{-1}$and 173 kg ha^{-1} mo^{-1} respectively.

The nitrogen flux from litterfall of our AF systems ranged from 93-187 kg ha^{-1} yr^{-1} were considerably higher than reported for *Alnus*-cardamom AF systems of India's Himalayan region (56.15, kg ha^{-1} yr^{-1}) and the forest-cardamom AF systems of the same region (20 kg ha^{-1} yr^{-1}) (Sharma *et al*., 1997), montane rain forest in New Guinea (90 kg ha^{-1} yr^{-1}) (Edwards, 1982), forest ecosystem of the Western Andes of Venezuela 8 (69 kg ha^{-1} yr^{-1}) (Fassbender and Grimm, 1981) and montane moist evergreen broad-leaved forest in Ailao Mountains, South-west China (80 kg ha^{-1} yr^{-1})(Liu *et al*., 2002). The nitrogen flux in our AF systems was 4.65-9.35 times greater than the nitrogen flux in forest-cardamom AF of India's Himalayan region. The difference for such greater nitrogen flux is most likely related with the presence of sufficient number of nitrogen fixing trees and shrubs (in average 4 in each AF farm plot) in our AF systems. This result is in consistent with a study conducted by Sharma *et al*. (1997) who reported higher nitrogen flux in large cardamom-based agroforestry with N_2-fixing *Alnus nepalensis* as a shade tree than large cardamom-based AF with non-N_2-fixing mixed tree species.

The mean C:N ratio for C-Ft-E based AF system was higher and the least was for Enset based (Table 24). The One-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=12) result showed that C-Ft-E based was significantly different at ($P<0.05$) from both Enset based and C-E based AF systems for their mean N% and C:N ratio (Table 24). However, Enset based and C-E based were not significantly different at ($P<0.05$) in their mean N% and C:N ratio. The mean C% of litterfall in C-Ft-E based AF system was significantly different at ($P<0.05$) from C-E based but

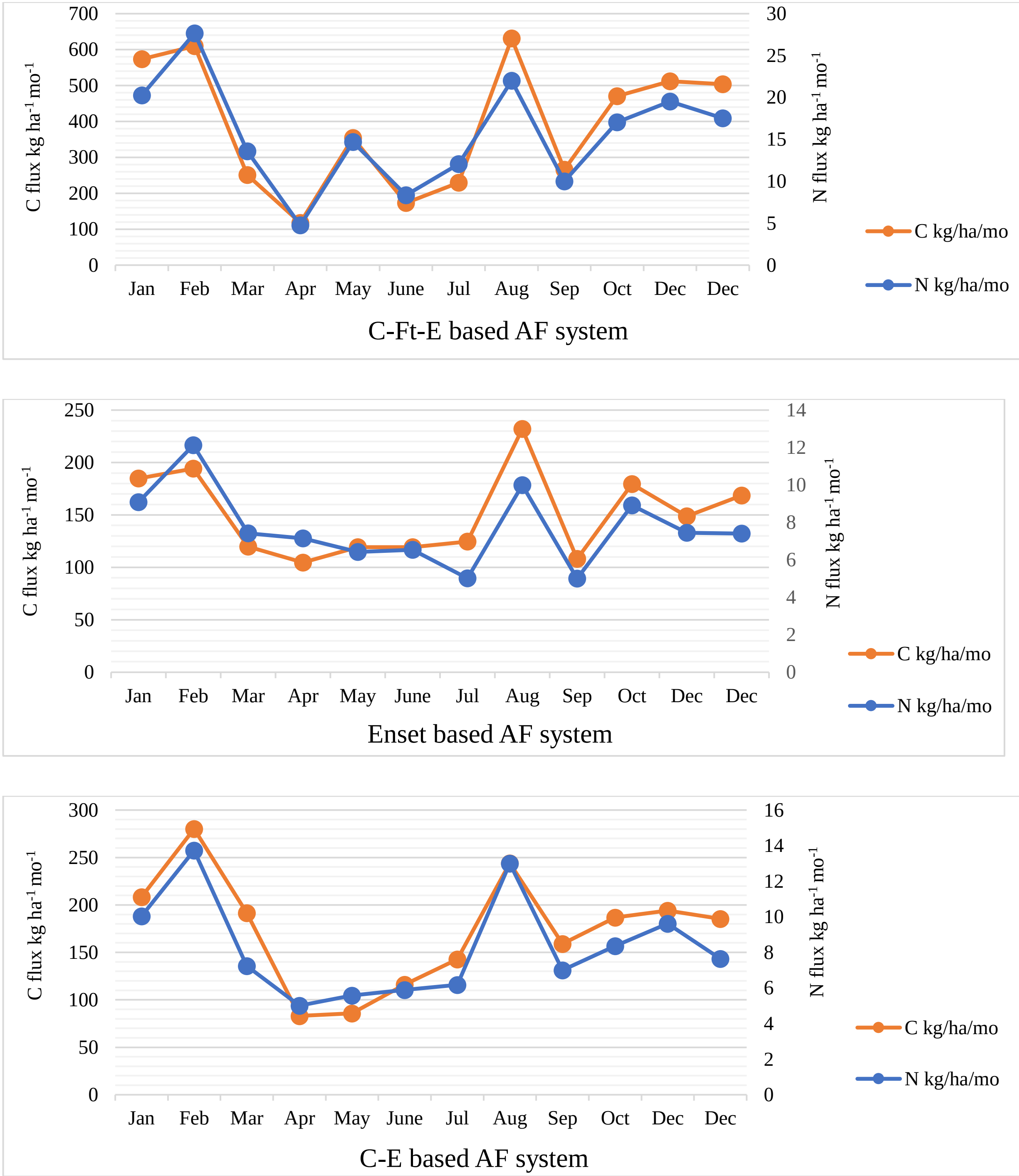


Figure 26. Mean monthly carbon and nitrogen flux (kg ha^{-1} mo^{-1}) across the three AF systems

not from Enset based. The relatively high C:N ratio of C-Ft-E based AF system (24.6:1) implies that there might be less mobilization of nutrients, especially nitrogen (Cadisch and Giller, 1997). The lower C:N ratio implies, tree/shrub species which are found in Enset based and C-E based AF system had a bit higher nitrogen content in their litter material. As a result, relatively faster decomposition may occur and thus helps to facilitate nutrient cycling within the system. Higher nitrogen content observed in Enset based AF system (C:N ratio of 20:1) as compared to C-Ft-E based AF system might be due to the presence of more indigenous nitrogen fixing trees/shrubs (average of 6 in each AF farm plot). The species richness of the nitrogen fixers under Enset based AF is a bit higher. Species such as *M. ferruginea*, *E. brucei*, *A. gumifera*, *C. Africana*, *S. siamea* etc were incorporated in this system. In C-Ft-E based AF as it was mentioned in the plant diversity part of this study, most of the tree/shrub species that dominate the system were exotic fruit trees such as *Mangifera indica*, *Persea Americana*. As Negash and Starr (2013) reported woody species such as *M. ferruginea*, *Erythrina brucei* have greater nitrogen content in their litter material than fruit trees such as *Mangifera indica and Persea Americana*. The implication of this finding is that the nitrogen input from the fruit tree dominated AF homegardens is slightly lower compared to the other two AF systems. However, if fruit trees continued to dominate the system we may need to supplemente by planting more indigenous nitrogen fixing trees (Sharma *et al*., 1997) to enhance the nutrient status of the soil. In general, 2% upto 2.5% N content in the litterfall could be a considered as very good. From content of N and other macro nutrients in the litterfall of these AF systems it may be also connected that the litter consisted mainly of leaves and only little woody component.

Table 24. Carbon (C) and nitrogen (N) contents (mean±SD and C:N ratio of litterfall for each of the studied AF systems

Agroforestry system	Months	C %	N %	C:N ratio
C-Ft-E based AF	12	47.8±2.1 [(a)]	2.0±0.3 [(a)]	24.6±3.8 [(a)]
Enset based AF	12	49.1±2.0 [(a)]	2.5±0.4 [(b)]	20.0±3.5 [(b)]
C-E based AF	12	50.3±0.7 [(b)]	2.5±0.1[(b)]	20.8±3.1 [(b)]
P-Value		<0.05	<0.05	<0.05

Note: same letter shows not significant difference and different letters indicate significance differences between groups according to LSD multiple test (Fisher LSD test) at P<0.05.

C-Ft-E based AF: Coffee-Fruit tree-Enset based agroforestry; Enset based AF: Enset based agroforestry and C-E based AF: Coffee-Enset based agroforestry

The C:N ratio values of the present study (20-24.6) are within the range reported for seven native species in indigenous AF systems of South-eastern rift-valley, Ethiopia (12-29; Negash and Starr, 2013). However, our values were considerably less than reported for leaf litter of three non-native fruit tree species of Nelspruit, South Africa (43.85-46.72; Murovhi *et al*., 2012). The C:N ratios reported from South Africa however did not include total litter (twigs, branches and leaf) but only leaf litter. In general, C:N ratio values from 20-30 is an indicator of the good quality litter. But, if it is above these levels microbial decomposition might be showed down within the system (Sharma and Ambashi, 1987). Low quality of litter from trees and shrubs could be expressed in terms of having low N and P, high C:N ratio, high lignin content. But, besides these factors decomposition of litter may also be hampered by the content of phenol, waxes, some strong resins and other compounds in leaves which protect them against herbivores and some leaves litter recalcitrant for decomposers. If a given AF system is in such situation it might be difficult to meet the nutrient requirements of annual food crops growing within that system, particularly for nitrogen and phosphorus (Murovhi *et al*., 2012).

5.4.3 Relationship between litterfall and climatic factors

The quantity of monthly litterfall and variation in forest related systems is affected by climatic factors such as temperature, rainfall, wind speed and relative air humidity (Triadiati *et al*., 2011). Some of the variables have positive effect and the others might have negative effect on litterfall production. The effect of climate on litterfall in tree-based systems also varies between local scale and continental scale. For instance, the effect at local scale is dependent on the annual course of temperature and precipitation. In addition, the distribution of temperature and precipitation over the year and on a balanced supply of heat and water can affect the litterfall (Liu *et al*., 2004).

The results of cross correlation showed that monthly litterfall under Enset based AF system was negatively correlated with rainfall (r=-0.3) and relative air humidity (r=-0.1) (Table 25). In addition, under C-Ft-E based AF systems the correlation of litterfall with rainfall was negative (r=-0.6), slightly weak negative correlation with relative air humidity and temperature (r=-0.3) and positively correlated with wind speed (r=0.3) (Table 27). The correlation of litterfall with rainfall and temperature under C-E based AF system were also negative with r-value of -0.5, implying a moderate negative correlation (Table 26). However, the correlation of litterfall with wind speed and relative air humidity were very week. As in our results indicated the correlation of litterfall

Table 25. Correlation matrix of litterfall and climatic factors for Enset based AF system

		LF	*RF*	*WS*	*T*	*RH*
LF	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	12				
RF	Pearson Correlation	-.311	1			
	Sig. (2-tailed)	.326				
	N	12	12			
WS	Pearson Correlation	.112	-.304	1		
	Sig. (2-tailed)	.729	.337			
	N	12	12	12		
T	Pearson Correlation	-.346	.267	.526	1	
	Sig. (2-tailed)	.270	.401	.079		
	N	12	12	12	12	
RH	Pearson Correlation	.027	.571	-.416	-.453	1
	Sig. (2-tailed)	.934	.053	.179	.139	
	N	12	12	12	12	12

Where LF :litterfall, RF: rainfall, WS: wind speed, T: temperature and RH:relative air humidity

Table 26. Correlation matrix of litterfall and climatic factors for C-E based AF system

		LF	*RF*	*WS*	*T*	*RH*
LF	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	12				
RF	Pearson Correlation	-.524	1			
	Sig. (2-tailed)	.080				
	N	12	12			
WS	Pearson Correlation	.091	-.304	1		
	Sig. (2-tailed)	.778	.337			
	N	12	12	12		
T	Pearson Correlation	-.499	.267	.526	1	
	Sig. (2-tailed)	.099	.401	.079		
	N	12	12	12		
RH	Pearson Correlation	-.104	.571	-.416	-.453	1
	Sig. (2-tailed)	.748	.053	.179	.139	
	N	12	12	12	12	12

Where LF :litterfall, RF: rainfall, WS: wind speed, T: temperature and RH:relative air humidity

with rainfall and temperature under C-E based AF systems were not statistically significant at ($P<0.05$) eventhough the r-values were a bit higher. Similarly, the correlation of litterfall with rainfall under C-Ft-E based was not statistically significant at ($P<0.05$). The results of the present study are inconsistent with Valenti *et al*. (2008) who reported negative relationship between rainfall and monthly litterfall. This fact could be explained by the decreased plant demand for water, less transpiration and water stress of leaves and twigs during the wet season and thus reduces the quantity of litterfall that comes to the ground. However, in dry season the plant water demand increased and defoliating of leaves and dropping of twigs get augmented as a strategy aiming to reduce water requirements during a period of water deficit.

Table 27. Correlation matrix of litterfall and climatic factors for C-Ft-E based AF system

		LF	*RF*	*WS*	*T*	*RH*
LF	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	12				
RF	Pearson Correlation	-.548	1			
	Sig. (2-tailed)	.065				
	N	12	12			
WS	Pearson Correlation	.288	-.304	1		
	Sig. (2-tailed)	.364	.337			
	N	12	12	12		
T	Pearson Correlation	-.287	.267	.526	1	
	Sig. (2-tailed)	.366	.401	.079		
	N	12	12	12	12	
RH	Pearson Correlation	-.283	.571	-.416	-.453	1
	Sig. (2-tailed)	.372	.053	.179	.139	
	N	12	12	12	12	12

Where LF :litterfall, RF: rainfall, WS: wind speed, T: temperature and RH:relative air humidity

The results displayed in figure 27 shows that mean monthly litterfall and monthly rainfall have an inverse relationship, implying that as rainfall increases the litterfall showed a decreasing trend across all AF systems. Months which received lower rainfall showed greater litterfall amount and vice versa (Figure 27). But, for the month of August the relationship between litterfall and rainfall do not follow this trend. Litterfall and rainfall where high for this month contributes to trend for the other months. Higher litterfall during August might be related with mechanical effect assisted by heavy rain shower and wind. Because, August is one of the months in which the study area receives more rainfall. De-Moraes *et al*. (1999) also mentioned the peak litterfall when rainfall was high in some months could be related with the effect of mechanical factors. Having lower litterfall during the months with high rainfall amount in our study sites is possibly due to less plant stress related with droughts and higher saturation deficit of the air.

The temporal trend of litterfall during the year could also depend upon other factors. For instance, the stress situations (water stress, leaves senescence), annual course of climatic variables and pests and pathogen attacks. Our results are inconsistent with (Dawoe *et al*., 2010) who reported an increase of litter production under primary forest and Cacao agroforestry in Ghana during the dry season than the wet season. Similar results were also reported by Sharma and Ambashi (1986) in *Alnus Nepalensis* stand in the Eastern Himalaya and Sharma *et al*. (1997) in AF systems involving large cardamom (*Amomum subulatum*) and mandarin (*Citrus reticulata*) in the Sikkim Himalaya, India. The above results were based on temporal litterfall recorded at AF farm level. But, taking the AF systems as an ecosystem and at continental scale, increasing rainfall amount would lead to

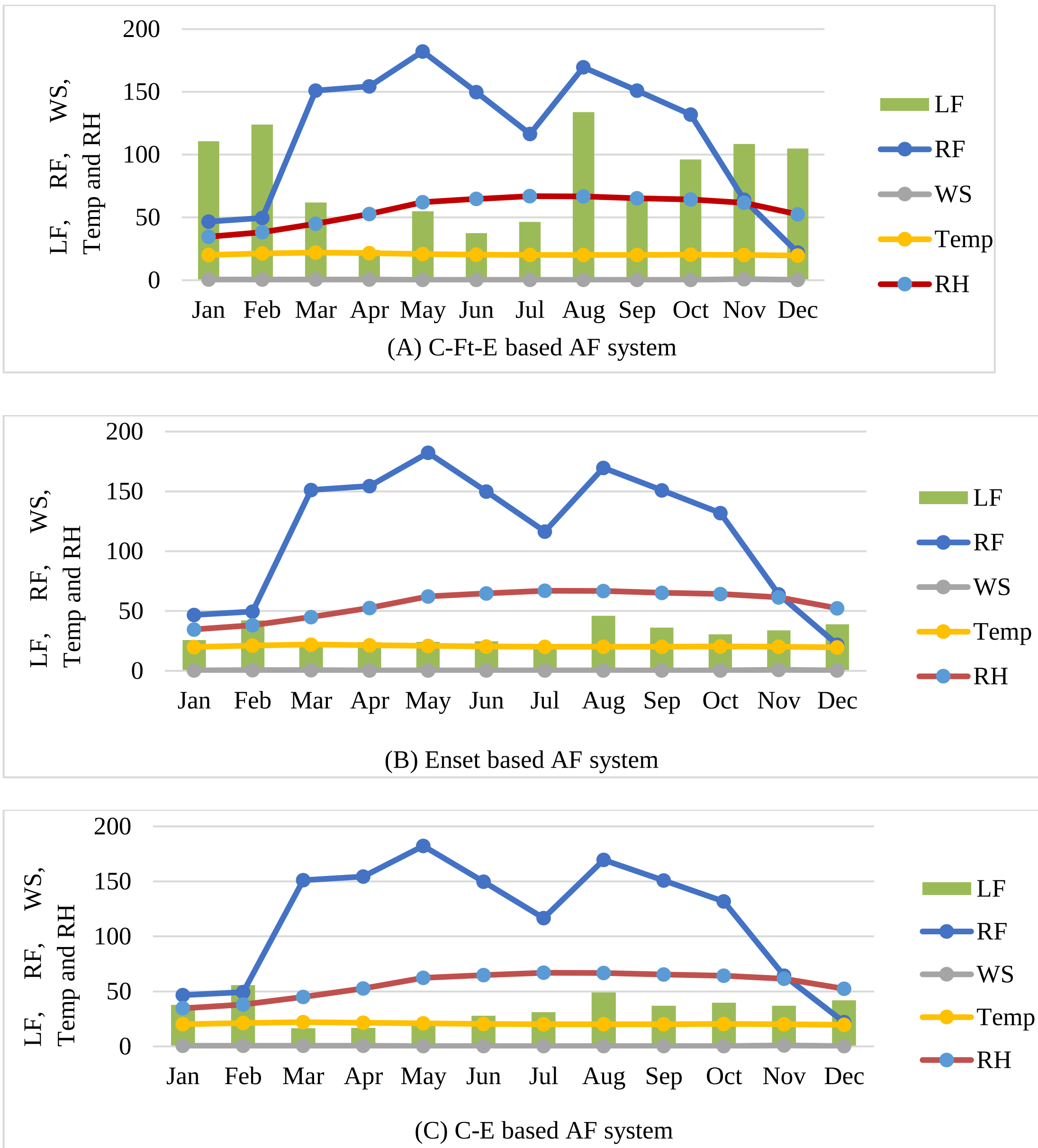


Figure 27. Relationship of the climatic factors (rainfall:RF, mm); temperature:Temp, ^{o}C; wind speed:WS, m/s) and relative air humidity:RH, %) with litterfall (kg ha^{-1} mo^{-1}) across AF

higher total annual litterfall as a result of higher productivity of the system (Meentemeyer *et al*.,1982 and Lonsdale, 1988). Ecosystems with rich soils, humid climates are more related with having higher leaf area index which brings higher ecosystem productivity. This situation might lead to higher litterfall amount within the ecosystem.

The relationship of mean monthly litterfall and relative air humidity was also assessed. As the results in the climatic variables and litterfall pattern clearly displayed, months with higher litterfall showed lower relative air humidity except for the month August. Therefore, litterfall has an inverse relationship with relative air humidity as it was found with rainfall across the three AF systems. Our results are in consistent with Dawoe *et al*. (2010) who reported increase in litterfall during times of reduced humidity in primary forest and Cacao agroforestry. The negative effect of relative air humidity on litterfall variation might be due to its direct relationship with rainfall. In times of high relative air humidity leaves, twigs, fruits and flowers do not dry out and fall to the ground easily. This implies the dry period having months with low relative air humidity, dry air and lower rainfall most probably expected to have higher litterfall (Triadiati *et al*., 2011). The relationship between litterfall and other climatic factors (mean monthly wind speed and temperature) in the present study was neither positive nor negative. This is because, the mean monthly values of these two climatic factors did not show significant variation across the months although the litterfall showed variation. Of course, higher temperature and wind speed could have a positive effect on litterfall as Triadiati *et al*. (2011) and Liu *et al*. (2004) pointed out.

In general, the correlation between the monthly litterfall and the climatic factors were not significant. Even some of the climatic factors had very weak correlation, implying that their effect on increasing or decreasing the monthly litterfall was so low. As Breymeyer *et al. (*1996) and Liu *et al.* (2004) revealed, the reason why monthly litterfall was less affected by climatic factors was because it might be also influenced by the existence of disease, pest and pathogen attacks. In addition, the phenology in the AF systems may also affect the monthly litterfall. For instance, time of breaking of buds, young leaves flourishment, flushing of flowers and bearing of fruits might significantly affect the monthly litterfall in our AF systems. As the practitioners said, most of the Fruit and non-Fruit trees/shrubs in the studied AF systems start breaking of buds during onset of rainfall (August month). More leaves development starts in the late of August month and continues until late September. The flushing of flowers starts on October and continues till November. Bearing of fruits starts late of November and continues till December. Besides, shading of leaves mostly happens in these months depending on the type of tree/shrub and climatic factors such as rainfall and temperature.

The results of multiple regression analysis using stepwise backward model fit method are displayed below. The factors that were thought to account for more of the variations in the monthly litterfall are shown in table 28 and table 29 for C-E based AF and C-Ft-E based AF systems respectively. Therefore, the predictors, that are: the rainfall, wind speed, temperature and relative air humidity were regressed against the litterfall. From the regression analysis, it was observed that the mentioned factors somehow explained the litterfall production in C-E based AF because none of their standard coefficients was equal to zero. The regression model explained 50% of the variations in the factors affecting the AF systems's litterfall as indicated by the R^2 (Table 28). Out of the four predictors only the temperature was included in the analysis and it was statistically significant

$\boxed{Y = -15X + 369.9 \qquad r^2 = 0.5}$ Where, 'Y' is Litterfall and 'X' is temperature

.

Table 28. Regression results of the factors influencing the litterfall under C-E based AF system

Coefficients:

Predictor	Estimate	SE	t value	Pr(>|t|)
(Intercept)	369.9	119.9	1.689	0.015 *
Rainfall	0.016	0.130	0.124	0.9 NS
Wind speed	11.0	8.1	1.355	0.213 NS
Temperature	-15.6	5.6	-0.9	0.023*
Relative humudity	-0.3	0.3	-1.123	0.294 NS

Significance level: '*' 0.05 '

Residual standard error: 2.4 on 8 degrees of freedom

Multiple R-squared: 0.5

Adjusted R-squared: 0.3

(P<0.05). Temperature had (β value of -0.9). The remaining predictors were not statistically significant in influencing the litterfall at (P<0.05). Therefore, it could be undertood that temperature affects more for litterfall than the other climatic factors. The monthly litterfall and temperature have showed inverse relationship. The regression model is as follows:

The regression model explained 47% of the variations in the factors affecting the AF system's litterfall in C-Ft-E based AF system as indicated by the R^2 (Table 29). Out of the four predictors only the temperature was included in the analysis and it was statistically significant (P<0.05). Temperature had (β value of -2.328). The remaining predictors were not statistically significant in influencing the litterfall at (P<0.05). Therefore, it could be understood that temperature affects more for litterfall than the other climatic factors. The monthly litterfall and temperature have showed inverse relationship. The regression model is as follows

$\boxed{Y = -40.4\ X + 968.2 \quad r^2 = 0.47}$ Where, 'Y' is Litterfall and 'X' is temperature

Table 29. Regression results of the factors influencing the litterfall under C-Ft-E based AF system

Coefficients:

Predictor	Estimate	SE	t value	Pr(>|t|)
(Intercept)	968.2	371.6	2.605	0.031 *
Rainfall	0.114	0.402	0.283	0.9 NS
Wind speed	41.1	25.1	1.634	0.213 NS
Temperature	-40.4	17.3	-2.328	0.048*
Relative humudity	-1.3	0.9	-1.372	0.207 NS

Significance level: '*' 0.05 '

Residual standard error: 1.58 on 8 degrees of freedom

Multiple R-squared: 0.47

Adjusted R-squared: 0.27

Multiple regression analysis using backward model fit method of the predictors was also conducted for the Enset based AF system. Unfortunately no one predictor was included in the model. This might be due the fact that the system is dominated by Enset species and thus the natural litterfall from this species is extremely very low. The removal and fall of the leaves is mostly done by farm owners in such away that deliberate cutting and putting on the floor as soil multh. Therefore, litterfall in such type of systems is less affected by climatic factors.

Generally, the litterfall and associated nutrient flux of macronutrients in the studied agroforestry systems were relatively good compared with other tropical AF systems and forest lands. The implication of having good nutrient flux is there will be sustainable production of crops, Fruit trees, vegetables and other spices that grow beneath the trees as a result of good nutrient cycling within the system. This could enhance the livelihood of the households and play a great role in addressing food security.

5.5 The role of indigenous agroforestry systems in enhancing local community livelihoods

5.5.1 Socio-demographic characteristics of respondents

Agroforestry systems such as Coffee-Fruit tree-Enset AF systems and other well managed AF practices provide multiple benefits. These benefits contribute to rural livelihoods, improved socio-economic status and ecosystem functioning of the land use systems (Kalaba *et al.*, 2010). The diversified products from Fruit tree based AF systems almost similar to Coffee-Fruit tree-Enset AF systems has great roles to play in the livelihood improvement. This intern provides multiple contributions to household cash income and supplementary food for smallholder farmers who are involved in that practice (Adane *et al*., 2019).

A socio-economic survey was conducted on randomly selected households which are practicing the C-Ft-E based AF system. From the 160 interviewed respondents, most of the household were male-headed (87.5%) (Table 30). As the results indicated both males and females were involved in farming activities. Overall, the involvement of mens in the farming activities was by far higher than their women. Focus group discussion was conducted to check why men participation was higher. The practitioners pointed out it is due to the fact that farming in general is usually labor-intensive and requires a lot of energy. Due to this, the work is assumed to be performed by mens and usually regarded as a men’s job. As the results of (Adekunle, 2009) showed women can only participate in activities that require less effort while men are working on the farm the hardest jobs. In addition, females mainly participate in activities such as planting of crops, cooking for the family, collection of firewood and non-timber forest products such as Fruits and vegetables for family use.

The mean age of the respondents was between 49 and 50 years and almost all of them were married (92.5%) (Table 30). The average family size in each household was between 6 and 7 persons. This family size is high and it could be understood that the households in the study area may not be constrained by labor. As far as working in the AF systems is one of the labor-intensive activities, the family members can engage themselves in different farming activities and can increase the income from AF products such as fruit, crop, livestock, vegetables and trees. The involvement of the family members in the AF activities could also have a role in minimizing labor costs related to management of the farm. The regression model result also confirms family size is one of the factors that influence household income. This result is in line with the finding of (Adane *et al*., 2019; Adekunle *et al*., 2010; Croppenstedt *et al*., 2003) who found that farming is very labor-intensive and tedious. Because, in developing countries it is done manually and the family's needs to have more members in order to provide sufficient labor to work on their farm land. This in turn enable households to accomplish various agricultural tasks particularly during peak seasons.

The mean landholding of each household was 0.7 hectare. During the focused group discussion the respondents complained that their farms were too small with regard to the family size they have. As a result, this 0.7 hectare of land may suffice enough to meet all requirements of most of the reported household size of 6-7 persons in times of frequent drought. This was despite of the fact that C-Ft-E based AF system is highly productive system. Most of the households got land from their family by inheriting (84.4%) while getting a new land from the government was very limited (1.3%). In comparison, 12.5 % of the households area farming a land which was in one part rented and other parts inherited from their family (Table 30). The results from the regression model showed, household income was positively influenced by land holding. The larger farm size they possessed the more income they obtained from the different components of the AF system within the farm. Either decreasing or increasing the land size could bring a significant change in household income in the study area. This might be due to the fact that the practitionners grow variety of consumable plants with highly diversified and vertically stratified planting system in the smaller land size they have. This result is in agreement with (Adane *et al*., 2019) who revealed that households which have bigger farm size got higher income than those who own smaller farm size in Dale district of Southern Ethiopia. Abebe (2005) and Desta (2012) additally mentioned that when there is a large size of land there is more diversification of components, which increases the income from the system. Because diversification of components within the AF system is directly affected by size of the farm, and thus increase in diversification may also contribute to household income security.

Table 30. Socio-demographic characteristics of respondents in the study area

Variable	Frequency (f)	percentage (%)
Gender		
- Male	140	87.5
- Female	20	12.5
Marital Status		
- Married	148	92.5
- Divorced	1	0.6
- Spouse Died	11	6.9
Land ownership of household		
- Got from Government	2	1.3
- Shared	3	1.9
- Inherited	135	84.4
- Inherited and Rented	20	12.5
Educational status		
- Informal education	18	11.25
- Elementary completed	122	76.25
- High school and above	20	12.5

Variable	N	Minimum	Maximum	Mean	SD
Age of respondents (years)	160	25	84	49.90	11.48
Family size of household	160	3	13	6.78	2.25
Tot land holding HHs (ha)	160	0.2	1.5	0.7	0.38
Experience of farming (years)	160	2	60	25.33	10.59

The average experience of the respondents in farming was between 25 and 26 years (Table 30) implying that the households have better experience in practicing the agroforestry system. This study is in agreement with Adane *et al*. (2019) who conducted a research in Dale district of Southern Ethiopia and found an average farming experience of 21.64 years in practicing fruit tree based AF. The authors also categorized this experience as good and helpful for better production. Most of the respondents (88.75%) had undergone formal education, with the majority (76.25%) having completed elementary education and few (12.5%) had some high school and above education (Table 30). This implies that, introduction of various AF innovations in the study area are likely to be successfully adopted because the majority might not only be trained by the extension experts but also read from books and newsletters listen to media and other sources of information.

5.5.2 Revenues from Coffee-Fruit tree-Enset based agroforestry system

Under the C-Ft-E based AF system there are different components which contribute to the accumulation of revenue and the tangible benefits obtained by households are diverse. The revenues which are obtained from the system are mainly from the sale of crop, vegetables, fruit and non-fruit tree components, livestock and livestock products sale and other off-farm activities. Similar studies conducted in North America showed that AF focuses strongly on the increase in income through involving a diversity of components and conservation of natural resources (Williams *et al*., 1997).

The main cash and non-cash crop species produced include Coffee (*C. arabica)*, Enset *(E. ventricosum)*, Maize (*Zea mays L.)* and Haricot bean (*Phaseolus vulgaris*); vegetables such as Yam (*Dioscorea alata L.),* Taro (*Collcasia esculenta(L.) Schoot*), Ginger (*Zingiberaceae*), Sweet potato (*Ipomoea batatas L. lam.*) and Kale (*Brassica oleracea L.)*; fruits such as Mango (*M. indica L.),* Avocado (*P. americana Mill*), Annona (*Annona squamosa L.),* Papaya *(C. papaya)*, Banana (*M. acuminata*) and Guava (*Psidium guajava L.)*, Kazmir (*Casimiroa edulis* Lal lave and Lex) and Orange (*Citrus sinensis* Osb.); non-fruit tree species such as *Spathodea campanulata*, *M. ferruginea (Hochst.) Baker, P. Africana, C. africana, Ficus vasta Forsk. Rhamnus prinoides L. Herit., Senna siamea (Cassia siamea), A. gummifera (J.F. Gmel.) C.A.Sm, Solanum betaceum, Leucaena leucocephala, E. brucei Schweinf., Jacaranda mimosifolia, Vernonia amygdalina Delile*, *C. macrostachyus, Ficus sur Forssk, Maytenus senegalensis, Trichilia dregeana, E. brucei, S. sesban, F. albida, G. robusta, Eucalyptus camaldulensis, Eucalyptus grandis and Cupressus lusitanica*. The above mentioned non fruit trees and shrubs contribute to the total revenue by selling the timber, firewood, medicinal, brewery products, fodder for their livestock and seedling.

The AF products obtained from a given farm might be market oriented, for onfarmconsumption or for both. As the respondents mentioned, for example: Coffee was primarily used as source of cash income (cash crop). Kocho, which is extracted from Enset, was mainly used for household consumption (main staple food). Root crops (taro and yam) are commonly used for household consumption (food). Haricot bean is also used for home consumption but surplus may be sold. The

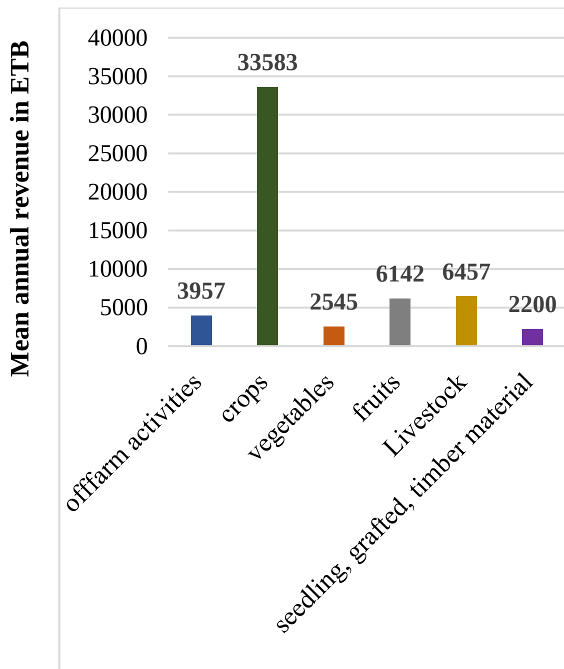


Figure 28. Total mean annaul revenue in ETB of housholds from different components yr $^{-1}$

Figure 29. A man carrying Banana fruit product from the agroforestry system

shade trees (pruned branches) are used for home consumption (fodder, fuelwood and building materials) and income generation (pole, timber). Trees like *E. camaldulensis* are mostly used as a source of fuelwood, house construction and income generation and trees like *C. africana* are mostly used as a source of income generation. Similar results were found by Ayele *et al*. (2014) in Yirgachefe district of Gedeo zone, Southern Ethiopia which was focused on economic evaluation of C-E based AF. From the survey conducted on economic benefits from the different AF products We calculated the mean annual revenue of each individual household. Comparing the different revenue sources, we found that the majority was obtained from the crop component with an annual mean of 33,583 ETB per household and the least was obtained from seedling and timber sale with an annual mean of 2,200 ETB per household (Figure 28). It was tried to compare also the contribution of different crop types to the mean total annual farm incom. Accordingly, the highest share came from Coffee (70.8%) and the least contribution was from Maize (4%) (Figure 30). The reason why Coffee contributed so much to the total revenue was because the Coffee grown in these traditional AF systems is internationally recognized (known by the name Yiregachefe Coffee), considered organic and prized for its high quality. Therefore, the households sell the Coffee with

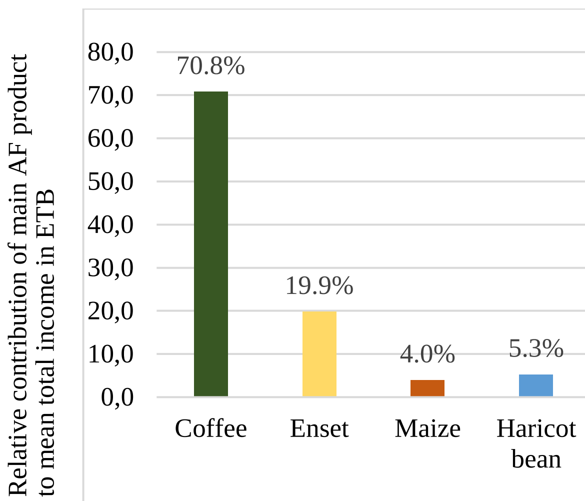


Figure 30. Share of total mean annual revenue in ETB from different crop types per household

Figure 31 People selling Fruits in local market

ETB stands for Ethiopian Birr and one ETB is equivalent to 0.022 Euro. Source: Commerial bank of Ethiopia, Oct, 2020

high price and produce more in volume. A study conducted by Kufa *et al*. (2011) revealed that more than 95% of the total volume of Coffee beans produced in Ethiopia comes from smallholders in agroforestry systems such as those in the Gedeo zone which is in agreement with our results. Similar studies in the Burkitu Peasant Association in the Oromia region of Ethiopia by Asfaw (2006),) in the Gedeo zone of Southern Ethiopia (Kanshie, 2002) and in Indonesia by Retnowati (2003) indicated that agroforestry systems provided the households with diversified types of benefits such as source of cash income (from high value crop sale, Fruit and timber), household consumption, traditional medicine for both human and livestock diseases and employment opportunity. Asfaw (2006), further explained that AF practices are means of survival and safety net against the effects of natural disaster that may cause food insecurity (a decreased vulnerability may result from the practice of diversified types of farming).

5.5.3 Expenses for Coffee-Fruit tree-Enset based agroforestry system implementation

For the implementation and better productivity of a given AF system some costs are to be expected. These costs could be fixed or variable costs. As far as C-Ft-E based AF system is concerned some cost for its implementation were calculated. They are total mean annual expense of different cost categories. As the result is displayed in fgure 32, the highest mean expense of the household was for food, cloth and daily consumables (16,077 ETB) and the least was for land rent (41 ETB) used for the C-Ft-E based AF farm.

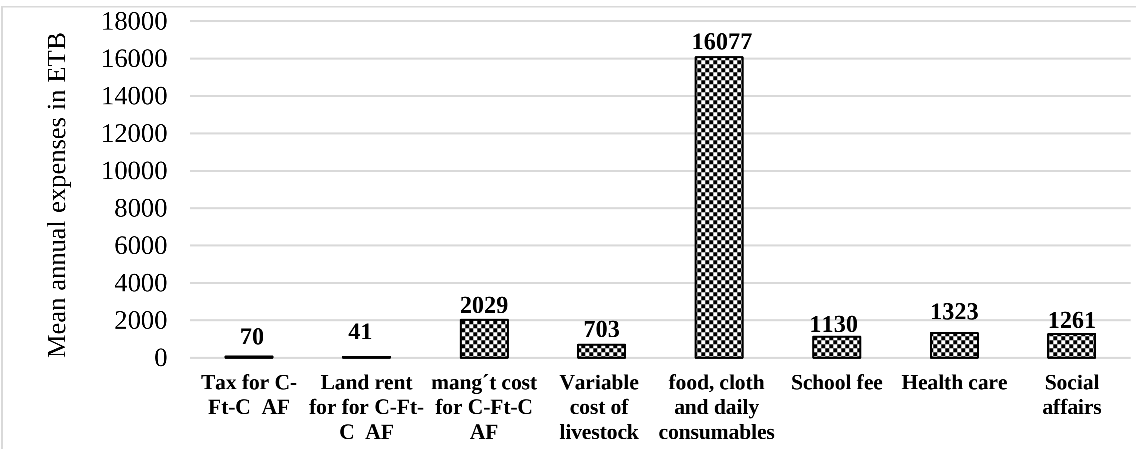


Figure 32. Total mean annual expenses in ETB for different components yr $^{-1}$

5.5.4 Profitability of Coffee-Fruit tree-Enset based indigenous agroforestry system

The total annual revenues for each household from all income sources such as crop, fruit, non-fruit, vegetable, livestock products sale and other off-farm activities income was calculated and at the same time the total annual expenses for the management of C-Ft-E based AF and household expenditures was calculated. To see how this practice is profitable and contribute to the improvement of the livelihood of the community it is good to conduct economic analysis. One of the best cost-benefit analysis indicators is Benefit-Cost Ratio and helps in a decision making scenario for the profitability of the agroforestry system. Therefore, by using our data, we calculated the mean net return for the rotation and found a positive value of 51,393.6 ETB (Table 31). Looking the benefit cost ratio (BCR), we found a positive value of 3.22 although the data was collected for only one year production. The present result of BCR of 3.22 is relatively higher than reported by Neupane and Thapa (2001) for improved agroforestry-based farming system (BCR value of 2.5) in the Middle hills of Nepal. Moreover, our BCR values are considerably higher than park land AF

Table 31. Summary of total mean annual revenue versus total mean annual expenditure in ETB of households.

Variable	N	Minimum	Maximum	Mean	SD
Total revenue ETB year	160	37200	123100	74577.6	17177
Total expenditure ETB year	160	12033	39817	23184.3	5878.8
Return ETB per year				51393.6	
Benefit-cost ratio (BCR)		-	-	3.22	-

*The labor contribution of the family members within the household was not considered in the calculation.

systems of the Yirgachefe district of Southern Ethiopia with a value of 1.28 (Ayele *et al*., 2014). However, the BCR values for C-Ft-E based AF in this study are considerably lower than the Coffee-Enset based AF systems of Yirgachefe district of Southern Ethiopia with a value of 8.23 (Ayele *et al*., 2014).

Many studies reported that agroforestry practices showed by far higher BCR values than monocropping agriculture. For instance, a comparative study between multistrata AF system and conventional monoculture in Northern Bangladish revealed that, the BCR value was almost two times in the former (7.7) than the later (3.77) system (Rahaman *et al*., 2007). Similar study was conducted in Konso District of Southern Ethiopia and Moringa tree based AF practice was compared against monocropping agriculture system. The result revealed that the former system showed a higher BCR with a value of 8.54 and the later system with a value of 2.87 (Shode and WoldeAmanuel, 2016). As it was shown from the values, the Moringa tree based AF practice had a BCR value almost three times than the monocropping agriculture system. It could be understood that AF systems are more economically attractive and benefiting farmers than monocropping if they are properly managed ad utilized.

5.5.5 Comparison of revenue from Coffee-Fruit tree-Enset based agroforestry system among villages

The site where our study was carried out is administratively divided into four villages namely Chito, Gamata, Sharo and Tuba. The result of difference intotal annual revenue of the households among the villages showed that the highest mean annual revenue in ETB per household was for the village Tuba and the least was for Gumata. One-way ANOVA followed by post-hoc testing (Fisher's LSD test) (n=160) result showed that Tuba was significantly different from Gumata and Sharo but not from Chito at ($P<0.05$). Chito was also significantly different from Gumata but not from Sharo.

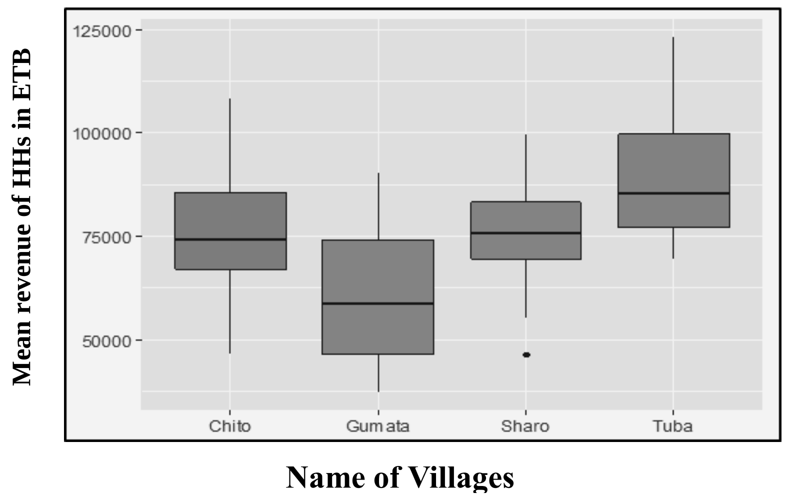


Figure 33. Comparison of mean annual revenue in ETB per household among villages

The significant difference in total annual mean revenue among the villages can be mainly seen as a result of having different size of land holding. As land holding of the household increases the revenue that is obtained from the different income sources increases. The results of multiple regression showed that villages with larger land holding size comparatively obtained better total mean annual revenues. For example the households in the village Tuba have an average land holding of almost 1 hectare whereas the households in the village Gumata have 0.43 hectare.

5.5.6 Factors influencing household's income in Coffee-Fruit tree-Enset based agroforestry system

The cross correlation matrix for the variables which were thought to be good predictors for the variation in the household's annual revenue are displayed in table 32. The independent variables which are: age of practitioner, land holding, family size, farming experience, off-farm income and household expense were regressed against dependent variable the household's annual revenue. From the regression analysis, it was observed that the mentioned variables explained the household's level of revenue from the AF systems because none of their standard coefficients was equal to zero. The regression model explained 94% of the variations in the factors affecting the household's revenue as indicated by the R^2 (Table 33). As the result showed, out of the six predictors the four were included in the analysis, which are, the land holding and off-farm income which were statistically highly significant ($P<0.001$), household expense which is statistically significant ($P<0.01$) and family size statistically significant at (<0.05). Land holding was the best predictor of the household's revenue (β value of 12.270) while off-farm income (β = 4.950), Household expense (β=3.343) and Family size (β =2.154). With lower levels of significance the remaining predictors were not statistically significant in influencing the household's revenue.

Table 32. Correlation results between the seven predictors for C-Ft-E based AF systems of South-eastern rift-valley landscapes, Ethiopia.

Correlation matrix

	Revenue of HH	Cost of HH	Off-farm income	Land-holding	Farming Experience	Family size	Age
Revenue of HH	1.00						
Cost of HH	0.861	1.00					
Off-farm income	0.924	0.789	1.00				
Land Holding	0.934	0.822	0.942	1.00			
Farming experience	0.020	0.014	0.065	0.011	1.00		
Family size	0.478	0.584	0.448	0.393	0.012	1.00	
Age	0.090	-0.064	-0.047	-0.069	0.738	-0.031	1.00

A study conducted in Lushoto District of Tanzania by Namwata *et al*. (2012) is partly inconsistent with our results. It revealed that, household's income in agroforestry was significantly affected by production cost and farm size. In addition, a study conducted by Adane *et al*. (2019) on the contribution of a fruit tree-based AF system in Dale district of Southern Ethiopia revealed that not only farm size but also extension service and family size were significantly affecting household's income. Our result also confirmed that family size significantly affect the household's income implying that as family size of the household increase the total annual household income increases by some amount.

Table 33. Multiple linear regression model results of the factors influencing the household's total revenue

Coefficients:

Predictor	Estimate	SE	t value	Pr(>|t|)
(Intercept)	-55034.9	26402.8	-2.084	0.03877 *
Log (HH expense)	8391.1	2509.8	3.343	0.00104 **
Log (Off-farm income)	6013.0	1214.9	4.950	1.93e-06 ***
Log (Land holding)	18868.9	1537.7	12.270	< 2e-16 ***
Log (Family size)	2698.4	1252.8	2.154	0.03281 *
Log (Farming experience)	537.7	664.9	0.809	0.41993
Log (age)	-72.8327	51.5977	-1.412	0.160

Significance levels: '***' 0.001 '**' 0.01 '*' 0.05 '

Residual standard error: 4175 on 154 degrees of freedom

Multiple R-squared: 0.9428,

Adjusted R-squared: 0.9409

F-statistic: 507.5 on 5 and 154 DF,

P-value: < 2.2e-16

95% Confidence interval for the significance explanatory variables

(Intercept)	-107276.6426	-3083.853
Log (household expense)	3554.6775	13445.180
Log (Income off-Farm)	3720.0015	8492.620
Log (Land.Holding	15712.2015	21740.806
Log (Family size)	197.4788	5139.479

Model Diagnostic Plot

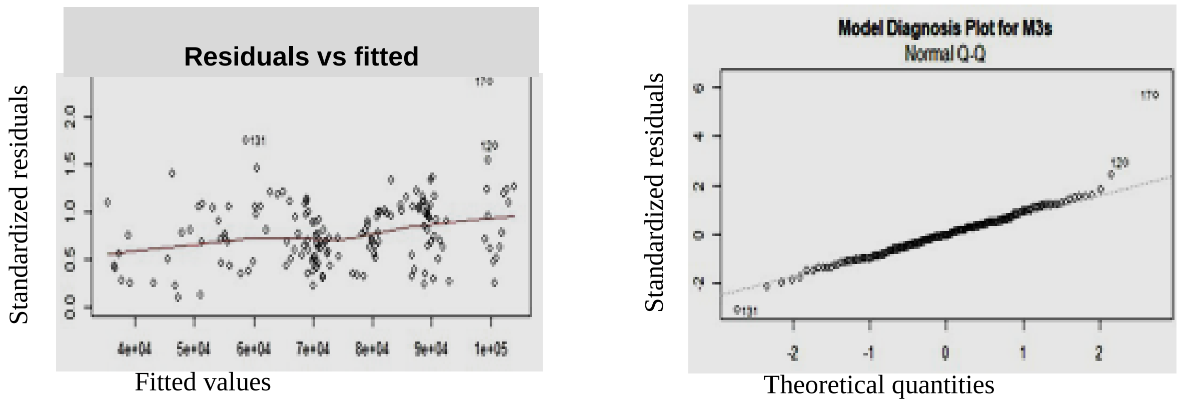


Figure 34. Model diagnostic plot for the predictor variables

During the regression model selection using the stepwise backward model fit method, different steps were employed to get the final fitted model. For example, it was tried to look the value of akaike information criterion (AIC). This was used as one of the mechanisms to know for a given model whether it is fit and/or best since it is an estimator of the relative quality of statistical models for a given set of data. Therefore, from our result, we found that the AIC value was 3128.4 which is a medium value. This is an indicator of a good model. Because, the smaller the value of the AIC the higher is the quality of the model. Checking the value of the residual standard error is another indicator to see whether our model is fit. Accordingly, the result showed a medium value of residual standard error 4175 which is an indicator of a good model. Generally, the following summarized result was found and the regression formula is given as follows.

Coefficients:

(Intercept)	Off-farm income	Land Holding	HH expense	Family size
55034.9	6013.0	18868.9	8391.1	2698.4

The general formula of the multiple linear regression model is:

$$\boxed{Y = \log(6.01\times10^{3})X_1 + \log(1.89\times10^{4})X_2 + \log(8.4\times10^{3})X_3 + \log(2.7\times10^{3})X_4 + 55034.9}$$

Where "Y" is the total revenue per household per annum, "X_1" is off-farm income in Ethiopian birr (ETB) per household per year,"X_2" is land holding in hectare, "X_3" is the total expense in ETB per household per year and "X_4" is family size in number.

In this model we have already the dependent variable in its original metric and the independent variable log-transformed. Therefore, the interpretation will be a one percent increase in the independent variable increases (or decreases) the dependent variable by (coefficient/100) units. In this particular model we would say that other factors held constant a one percent increase in the average annual income in ETB from off-farm activities would result in a (6013.0/100) = 60.13 ETB increase intotal annual household revenue. In the case of land holding, other factors held constant a one percent increase in the average farm size in hectare would result in a (18868.9/100) = 188.69 ETB increase intotal annual house-hold revenue, other factors held constant a one percent increase in the average household expense related with management costs would result in a (8391.1/100) = 83.91 ETB increase intotal annual household revenue and other factors held constant a one percent increase in the average family size would result in a (2698.4/100) = 26.98 ETB increase intotal annual household revenue. Generally, the selected explanatory variables were statistically significant and positively associated with the income generated from the C-Ft-E based AF.

5.5.7 Impact of Coffee-Fruit tree-Enset based agroforestry on household fixed asset building

Practicing agroforestry could contribute a lot to the increment of total revenue within one's household. This increment intotal revenue has an impact on enhancement of the livelihood of the community in terms of building and owning fixed assets at household level. For example: practitioners could improve their house, kitchen, store, and own motor cycle or bicycle, cart, television etc. As the result in Table 34 indicated, most of the households improve their house (97.5%) as a result of practicing C-Ft-E based AF system. In addition to this, 83.8% and 44.4% of the households built kitchen and own radio and television respectively. The possibility of building and owning more assets was high in farmers who were practicing C-Ft-E based AF system than mono-cropping. A study conducted in Meta and Kombolicha districts of northern Ethiopia revealed that the farmers who were engaged in conventional agriculture had less number of fixed assets than those who were practicing C-Ft-E based AF system (InnovAfrica, 2018). For instance, ownership of cart, motor-cycle, bicycle, refregirator and beehive was missed in the above mentioned districts but they were owned by the households in our study site. This might be because of the households in these districts have lower income from the agricultural activities and thus could not afford to buy those properties. Besides, 44.4% of the households in our study owned television and radio whereas in the two districts average of 27.9% households owned these properties. In general, there was significant difference in fixed asset ownership both interms of distribution as well as availability.

Table 34. Impact as result of implementing C-Ft-E based AF system on household fixed asset building

Variables	Frequency	Percentage (%)
Construction of better house	156	97.5
Construction of kitchen	134	83.8
Construction of store	9	5.6
Owning motor-cycle	9	5.6
Owning bicycle	6	3.8
Owning cart	5	3.1
Owning refrigerator	2	1.3
Owning radio and television	71	44.4
Buying mobile phone	3	1.9
Owning beehive	18	11.3
Owning livestock	46	28.8

Table 35. Total price of all the fixed assets accumulated over the last 10 and 15 years and estimated in current price in ETB per household

Category	**N**	**Minimum**	**Maximum**	**Mean**	**SD**
Total estimated current asset values of household in ETB	155	50500.00	360100.00	105843.93	66395.81

5.5.8 Profound challenges and threats in Coffee-Fruit tree-Enset based agroforestry

Under C-Ft-E based AF, there are three main components namely (the tree, crop and livestock) that have contribution to household total revenues. However, during the implementation of the system, these components face different challengesand threats which may impede or decrease production and thus affect the total revenue gained by the households. As the result from farmers interview on the threats and challenges of C-Ft-e based AF system showed, the greatest challenge mentioned under crop production component (A) was coffee disease which accounts (67%), under the tree component (B), avocado and mango disease (54 %) and for the livestock component (C), luck of feed (68%) (Figure 35). Although the above mentioned challenges were the most profound there were also additional threats that negetaively affect the impelementation and sustainable production under the C-Ft-E based AF system.

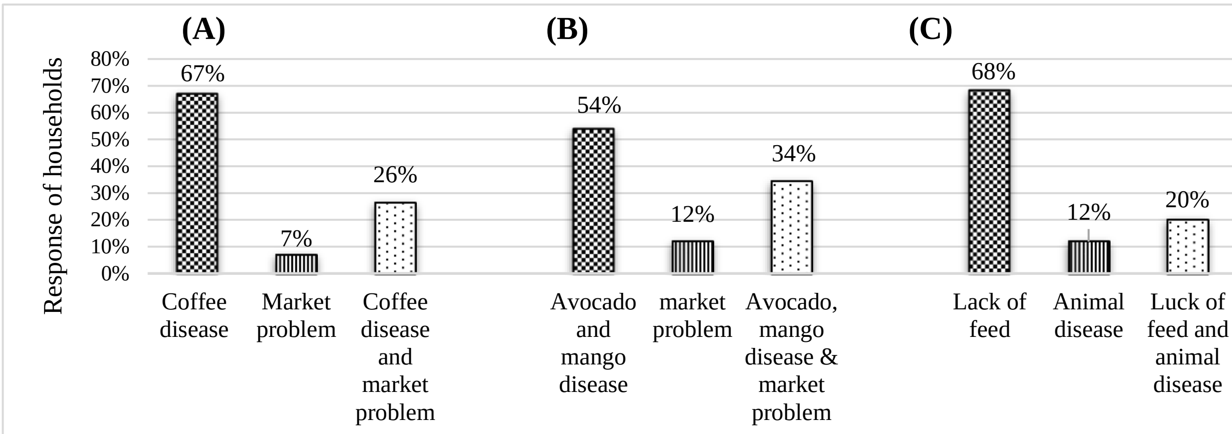


Figure 35. Common challenges in C-Ft-E based agroforestry

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In a densily human populated landscapes of Gedeo zone, intensively used tree-based land-use systems could conserve and maintain a large proportion of biodiversity. Agricultural landscapes which integrate agroforestry (AF) systems showed a great potential for maintaining woody and non-woody species diversity to an equal extent as the forest lands do. The cumulative species richness in our study sites was for woody and non-woody species in a comparable range as the one reported for other AF systems of Southern and Central Ethiopia. Our study sites also recorded a relatively higher number of species compared to parkland AF and homegardens in Northern parts of Ethiopia. The percentage of native plant species in the present study was relatively higher than a study reported for homegardens of six regions in South-western Bangladesh. C-Ft-E based AF was dominated by exotic fruit tree species. This could be a threat for the maintenance of native species, but it may be also seen as the result of global preference and marketing of these fruit species.

The inventory from the three agroforestry systems showed that a total of 13 species were listed as species of conservation concern according to the IUCN Red Lists and local criteria. Out of the total, two species were registered as endemic. The finding of such a number of species which are of conservation concern in our study sites, could be linked with how strong agroforestry systems are able to serve as a refuge for species and also for maintaining the native ones. Our results showed that the highest number of species diversity was recorded in C-Ft-E based AF system whereas the least was in Enset based AF system. The average Shannon diversity index in the present study was in a range comparable to that from other studies in agroforestry systems of Southern Ethiopia and other tropical countries. Species richness and abundance was affected by altitude of the study area. AF systems located in higher altitude showed a lower species richness and abundance.

Higher carbon stores either in the above or belowground are achieved if the land use systems are covered by perennial plant species and effective management is employed. The indigenous agroforestry systems of our study not only conserve biodiversity, protect soils and conserve watersheds, but are also very important sinks for carbon. The results of our study revealed that soil carbon stocks were greater than biomass carbon stock in all AF systems. The advantage of high SOC stocks in these systems is that soils are maintaining and storing most C fractions for longer period than biomass. Although the C stock of our AF systems varies, we did not find any significant difference between them. The C stock values of the present study are substantially higher than those of tropical forests and other agroforestry systems. High C stocks in C-Ft-E based AF was attributed by high diversity and proportion of woody and non-woody species and thus we found positive correlation between biomass and soil C stock. However, in the remaining two systems the correlation was negative. In addition, total biomass C stock was positively correlated with plant species richness and abundance across all AF systems. In general, indigenous AF systems of the south-eastern rift-valley landscapes in Ethiopia could serve as large sinks for C and thus play a vital role in mitigating climate change. Quantifying and understanding the C stock, storing potential of the studied AF systems may also help to design and develop climate change mitigation strategies. Because, if we able to identify which AF systems could store more carbon, our strategy will be towards scalling up these systems in order to mitigate climate change.

The results of soil analysis in the studied agroforestry systems showed a difference in both physical as well as chemical properties among them. They also showed a difference to the adjacent monocropping farms. Bulk density one of the physical properties of soil, showed a moderate increase down the sampling depth of 40 cm across all the three agroforestry systems and in the adjacent mono crop farms. The increasing trend of bulk density from top soil down is related to the decreasing content of organic matter that comes from the tree/shrub or herbaceous as litterfall. However, the soil texture which is clay was similar in all AF systems and their adjacent monocrop farms. Enset-Coffee based AF system showed higher average bulk density and the least was observed under the C-Ft-E based AF system. The lower bulk density under C-Ft-E based AF could be related with high amounts of litterfall (as indicated in litterfall data in this thesis) as a result of high tree density which could also produce more fine roots widely spread within the soil vertically as well as horizontally. Soil chemical properties such as pH showed an increasing trend withincreasing soil depth, while CEC and BS% showed a decreasing trend across all AF systems. The bulk density, BS% and CEC under AF systems were significantly different compared to adjacent monocropping farms in both soil depths. Soil fertility indicators such as exchangeable calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), available phosphorus (P) showed higher concentrations under Enset based AF system compared to C-Ft-E based and C-E based AF system for both soil layers (0-20, 20-40 cm). The concentration of extractable Ca^{2+}, K^{+}, Mg^{2+} as well as OM%, SOC and TN under agroforestry systems was significantly higher than the adjacent monocrop farms. Soil nutrient improvement under trees and AF systems is in great part related to increases in organic matter. This is because soils which have high organic matter content most probabily have greater CEC, soil aeration and microbial activitiy. The values of soil fertility indicators in our AF systems were relatively higher than reported for other tropical AF systems. As a result of good soil fertility in the study sites, the practioners are getting more production and thus are less prone to drought and food insecurity.

The observed fluctuations of litterfall production by season and month in all the studied three AF systems can be related to the course of different climatic factors and vegetation composition in the systems. The annual litterfall production in kilogram per hectare in AF systems of the present study was considerably higher than ones reported for some forests and agroforestry systems of tropical regions. The difference in annual litterfall values compared with other AF systems might be related to differences in type of plant species, trees/shrubs density, climatic factors, age of the stands, management practice, site and soil factors. There has been fluctuation in nutrient flux with the litterfall among the months of the year and calcium and potassium showed greater fluxs compared to the other elements across all the AF systems. The annual nutrient flux of elements such as Ca, Mg, P, TN and K in our AF systems were considerably higher than those reported for some AF and some rainforests. The reason for the difference in nutrient flux of our agroforestry systems from others is most likely related with difference in species composition, climate and soil fertility of the sites. Monthly litterfall was highly affected by climatic factors such as rainfall, temperature and relative humidity. Almost in all months rainfall showed an inverse relation with litterfall production whereas temperature showed a positive correlation. The developed multiple regression model showed that monthly litterfall was significantly affected by temperature compared with the other climatic variables. The model was developed only developed for C-E based and C-Ft-E based AF systems. Rainfall might have an effect on nutrient flux from leaching. However, we did not find clear effect of rainfall on nutrient flux in our study sites.

Implementing AF in a given farming system could potentially improve the livelihoods of households by increasing the agricultural productivity of the landscape. C-Ft-E based AF system in the study provided the households with diversified benefits such as source of cash income (from high value crop sale, fruit and timber), household consumption, and traditional medicine for both human and livestock diseases and employment opportunity. The AF system is also helping the practitioners to make them more resilient against food insecurity and hunger in the face occurring natural disasters. Because, having diversified types of farming and products means to be less vulnerable. In the study area, even though the agrarian system is still subsistence oriented and despite of the fact that they own very small land holdings the farmers are getting multiple benefits out of the AF system. A multiple regression model for the prediction of household income showed, out of the six predictors the four (land holding, off-farm income, family size and household expense) were included in the analysis and showed statistically significant. These selected predictors have more influence on household income from C-Ft-E based AF system and were positively associated. The result of the financial analysis showed that, Coffee-Fruit tree-Enset based AF system was a profitable land use system with Benefit-Cost Ratio value of 3.22 although the calculation was done only for one-year production. The result of BCR in the studied AF system was relatively higher than improved agroforestry-based farming system in the Middle hills of Nepal, park land AF systems of the Yirgachefe district of Southern Ethiopia. Many studies reported that agroforestry practices showed by far higher BCR values than monocropping agriculture. In our multiple linear regression model land holding and expense of the household were the most significant factors that affected household income C-Ft-E based AF system.

6.2 Recommendation

Based on our results the following recommendations may be drafted to maintain the AF system and contribute more towards mitigation of climate change and livelihood improvement for smallholder farmers in the study area.

- Some native tree species were found to be rare in our study sites although they are dominant in other areas. For instance, species such as *Trichilia dregeana*, *Ficus sur Forssk.*, *Prunes africana* and *Combretum species* were some of them. Therefore, a special conservation priority coupled with wise utilization of native plant species should be done by the community to maintain their presence in the study areas.

- Species that were reported as conservation concern according to the IUCN Red Lists and local criteria should get also conservation priority by the government as well as by the local community.
- The governmental, nongovernmental organizations and other concerned stakeholders should promote different AF practices to conserve native woody and non-woody plant species through circa situm conservation. Since our study was in limited and selected AF sites, conducting further research on broader scale is needed to see the potential of the systems to accommodate further native and endangerd native taxa.
- Utilizing the great potential of AF systems to sequester carbon, the government should think of ways to scale up theses practices to different parts of the country which have similar agro-ecological settings.
- For sustainable and long-term carbon storing in our AF systems appropriate silvicultural and soil management activities should be done by the practitioners.
- A strategy that benefits AF practitioners from the carbon trading should be designed and planned. Because, this would encourage farmers to conserve perennial plants for long-term and thus fostering more carbon to be stored in the biomass and soil permanently. This could be done by linking with governmental or non governmental projects who are working on carbon trading.
- Further study is needed on other additional soil fertility indicators such as soil moisture content and porosity.
- The Coffee-Fruit tree-Enset based agroforestry system should be promoted by solving the profound challenges related with fruit and crop disease and market problem. Challenges related to livestock disease and shortage of animal feed should be solved since the income from the livestock could also enhance the livelihood of households.
- In this study, only the marketable benefits were surveyed and evaluated. However, still further study should be conducted by including and quantifying the non-marketable benefits such as ecosystem services in order to estimate the total economic value of the agroforestry system.
- For better profitability of the agroforestry system creating market linkage between the producers and agro-industry enterprises, studying the value chain analysis and value addition should be get due attention.

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List of appendixes

Appendix 1. List of perennial woody and non-woody plant species recorded across the three studied AF systems of our study sites

Number	vernacular name	Scientific name	Family	Origin
1	Ensete	*Ensete ventricosum* (*Welw. Cheesman*)	Musaceae	Native
2	Buno	*Coffee arabica* L.	Rubiaceae	Native
3	Mango	*Mangifera indica* L.	Anacardiaceae	Exotic
4		*Spathodea campanulata*	Bignoniaceae	Native
5	Tatato	*Millettia ferruginea (Hochst.) Baker*	Leguminosae	Native
6	Avocato	*Persea americana* Mill.	Lauraceae	Exotic
7	Muse	*Musa acuminata*	Musaceae	Exotic
8	Sholla	*Psidium guajava L.*	Myrtaceae	Exotic
9	Wedesa	*Cordia africana* Lam.	Boraginaceae	Native
10	Kilto	*Ficus vasta Forsk.*	Moraceae	Native
11	Gesho	*Rhamnus prinoides L. Herit.*	Rhamnaceae	Native
12	Gorbe	*Albizia gummifera (J.F. Gmel.) C.A.Sm*	Fabaceae	Native
13	Lusina	*Leucaena leucocephala*	Mimosoideae	Exotic
14	Welale/Gedogna	*Erythrina brucei* Schweinf.	Leguminosae	Native
15	NI	*Jacaranda mimosifolia*	Bignoniaceae	Exotic
16	Hebicha	*Vernonia amygdalina Delile*	Asteraceae	Native
17	Cho'e	*Dracaena steudneri* Schweinf. Ex Engl.	Dracaenaceae	Native
18	Mokonisa	*Crot macrostachyus*	Euphorbiaceae	Native
19	wagela	*Ficus sur Forssk.*	Moraceae	Native
20	NI	*Dovyalis abyssinica*	Salicaceae	Native
21	Godere	*Clausena anisata (Willd.)* Benth.	Rutaceae	Native
22	Kulkal	*Euphorbia abyssinica*	Euphorbiaceae	Native
23	Gorbe	*Prunus africana*	Rosaceae	Native
24	Papaya	*Carica papaya*	Caricaceae	Exotic
25	Geshita	*Annona chrysophylla* Bojer	Annonaceae	Exotic
26	Abukere	*Casimiroa edulis* Lal lave and Lex	Rutaceae	Exotic
27	timatim zaf	*Solanum betaceum*	Solanaceae	Exotic

Continued

Number	vernacular name	Scientific name	Family	Origin
28	NI	*Senna siamea (Cassia siamea)*	Fabaceae	Native
29	NI	*Combretum sp.*	Combretaceae	Native
30	NI	*Trichilia dregeana*	Meliaceae	Native
31	Kobo/gulo	*Maytenus senegalensis*	Celastraceae	Native
	List of perennial woody and non-woody plant species **recorded out of the study plots**			
32	Motokomo	*Celtis sp.*	Ulmaceae	Native
33	Birtukan	*Citrus sinensis (L.)* Osbeck	Rutaceae	Exotic
34	NI	*Sesbania sesban*	Fabaceae	Exotic
35	NI	*Faidherbia albida*	Fabaceae	Native
36	NI	*Grevillea robusta*	Proteaceae	Exotic
37	Bahirzaf	*Eucalyptus camaldulensis*	Myrtaceae	Exotic
38	Bahirzaf	*Eucalyptus grandis*	Myrtaceae	Exotic
39	Bahirzaf	*Eucalyptus globules Labill.*	Myrtaceae	Exotic
40	NI	*Cupressus lusitanica*	Cupressaceae	Exotic
41	Lomie	*Citrus limon (L.) Osbeck*	Rutaceae	Exotic
42	Motokomo	*Celtis africana N.L.* Burm	Ulmaceae	Native
43	NI	*Ricinus communis*	Euphorbiaceae	Native
44	Chate	*Catha edulis (Vahl) Forssk. ex Endl*.	Celastraceae	Native
45	NI	*Melia azedarach L.*	Meliaceae	Exotic
46	NI	*Azadirachta indica var.*	Meliaceae	Exotic
47	Tilo	*Cassipourea malosana (Baker) Alst*	Rhizophoraceae	Native
48	NI	*Albizia grandibracteata Taub.*	Fabaceae	Native
49	Yebelo	*Bridelia micrantha (Hochst.) Baill.*	Phyllanthaceae	Native
50	Kilto	*Ficus elastica Roxb.*	Moraceae	Native
51	Tibero/Sessa	*Bersama abyssinica Fresen*	Francoaceae	Native
52	NI	*Hagenia abyssinica*	Rosaceae	Native

Appendix 2 Correlation among soil macro nutrients and carbon stocks in Enset based Agroforestry system 0-20 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*TN AF tot stock kg/m2*	*Avail. P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	0.467	1				
	Sig. (2-tailed)	0.174					
Mg AF tot stock kg/m2	Pearson Correlation	-0.029	0.504	1			
	Sig. (2-tailed)	0.936	0.138				
TN AF tot stock kg/m2	Pearson Correlation	0.523	0.239	0.326	1		
	Sig. (2-tailed)	0.121	0.506	0.357			
Avail.P AF tot stock kg/ha	Pearson Correlation	0.647*	0.484	-0.010	0.691*	1	
	Sig. (2-tailed)	0.043	0.157	0.979	0.027		
SOC AF total stock kg/m2	Pearson Correlation	0.769**	0.239	0.170	0.751*	0.527	1
	Sig. (2-tailed)	0.009	0.506	0.639	0.012	0.117	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Appendix 3 Correlation among soil macro nutrients and carbon stocks in Enset based Agroforestry 20-40 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*TN AF tot stock kg/m2*	*Avail. P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	0.491	1				
	Sig. (2-tailed)	0.149					
Mg AF tot stock kg/m2	Pearson Correlation	0.610	0.648*	1			
	Sig. (2-tailed)	0.061	0.043				
TN AF tot stock kg/m2	Pearson Correlation	0.828**	0.282	0.259	1		
	Sig. (2-tailed)	0.003	0.430	0.469			
Avail. P AF tot stock kg/ha	Pearson Correlation	0.873**	0.341	0.203	0.911**	1	
	Sig. (2-tailed)	0.001	0.335	0.575	0.000		
SOC AF total stock kg/m2	Pearson Correlation	0.848**	0.543	0.347	0.925**	0.882**	1
	Sig. (2-tailed)	0.002	0.105	0.326	0.000	0.001	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Appendix 4 Correlation among soil macro nutrients and carbon stocks in C-E based AF system 0-20 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*TN AF tot stock kg/m2*	*Avail.P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	0.850**	1				
	Sig. (2-tailed)	0.002					
Mg AF tot stock kg/m2	Pearson Correlation	0.954**	0.897**	1			
	Sig. (2-tailed)	0.000	0.000				
TN AF tot stock kg/m2	Pearson Correlation	0.534	0.580	0.631	1		
	Sig. (2-tailed)	0.112	0.079	0.051			
Avail.P AF tot stock kg/ha	Pearson Correlation	0.855**	0.761*	0.790**	0.666*	1	
	Sig. (2-tailed)	0.002	0.011	0.007	0.035		
SOC AF total stock kg/m2	Pearson Correlation	0.801**	0.760*	0.877**	0.894**	0.758*	1
	Sig. (2-tailed)	0.005	0.011	0.001	0.000	0.011	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Appendix 5 Correlation among soil macro nutrients and carbon stocks in C-E based AF system 20-40 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*TN AF tot stock kg/m2*	*Avail.P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	0.491	1				
	Sig. (2-tailed)	0.149					
Mg AF tot stock kg/m2	Pearson Correlation	0.610	0.648*	1			
	Sig. (2-tailed)	0.061	0.043				
TN AF tot stock kg/m2	Pearson Correlation	0.828**	0.282	0.259	1		
	Sig. (2-tailed)	0.003	0.430	0.469			
Avail. P AF tot stock kg/ha	Pearson Correlation	0.873**	0.341	0.203	0.911**	1	
	Sig. (2-tailed)	0.001	0.335	0.575	0.000		
SOC AF total stock kg/m2	Pearson Correlation	0.848**	0.543	0.347	0.925**	0.882**	1
	Sig. (2-tailed)	0.002	0.105	0.326	0.000	0.001	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Appendix 6 Correlation among soil macro nutrients and carbon stocks in C-Ft-E based AF system 0-20 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*TN AF tot stock kg/m2*	*Avail. P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	0.474	1				
	Sig. (2-tailed)	0.166					
Mg AF tot stock kg/m2	Pearson Correlation	0.852**	0.368	1			
	Sig. (2-tailed)	0.002	0.295				
TN AF tot stock kg/m2	Pearson Correlation	0.488	0.382	0.564	1		
	Sig. (2-tailed)	0.152	0.276	0.090			
Avail. P AF tot stock kg/ha	Pearson Correlation	0.173	-0.039	0.183	-0.167	1	
	Sig. (2-tailed)	0.633	0.914	0.612	0.645		
SOC AF total stock kg/m2	Pearson Correlation	0.593	0.450	0.587	0.946**	0.108	1
	Sig. (2-tailed)	0.071	0.192	0.075	0.000	0.767	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Appendix 7 Correlation among soil macro nutrients and carbon stocks in C-Ft-E based AF 20-40 cm depth

		Ca AF tot stock kg/m2	*K AF tot stock kg/m2*	*Mg AF tot stock kg/m2*	*N avail AF tot stock kg/m2*	*Avail. P AF tot stock kg/ha*	*SOC AF total stock kg/m2*
Ca AF tot stock kg/m2	Pearson Correlation	1					
	Sig. (2-tailed)						
K AF tot stock kg/m2	Pearson Correlation	-0.064	1				
	Sig. (2-tailed)	0.861					
Mg AF tot stock kg/m2	Pearson Correlation	0.550	0.228	1			
	Sig. (2-tailed)	0.099	0.526				
N avail AF tot stock kg/m2	Pearson Correlation	0.565	-0.468	0.385	1		
	Sig. (2-tailed)	0.089	0.172	0.272			
Avail. P AF tot stock kg/ha	Pearson Correlation	0.433	-0.508	-0.008	0.817**	1	
	Sig. (2-tailed)	0.211	0.134	0.983	0.004		
SOC AF total stock kg/m2	Pearson Correlation	0.469	-0.547	0.164	0.886**	0.756*	1
	Sig. (2-tailed)	0.171	0.102	0.650	0.001	0.011	

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

HOUSEHOLD QUESTIONNAIRE TO ASSESS THE CONTRIBUTION OF COFFEE-FRUIT TREE-ENSET BASED AGROFORESTRY IN ENHANCING THE LIVELIHOOD OF THE COMMUNITY: THE CASE OF DILLA ZURIA DISTRICT, ETHIOPIA

Name of enumerator__________________________

Date of interview__________________

District ____________ site (kebele) ________________ Village_______________________

A. **GENERAL DEMOGRAPHIC INFORMATION OF THE RESPONDENT**

1. a) Respondents' name _________________________ b) Respondents' code _________

2. Sex: 1) Male 2) Female

3. Age in years ___________

4. Marital status: 1) Single 2) Married 3) Divorced 4) widowed

5. Family size within the household ____________

6. Family characteristics

	Family age category in year	number	Labor participation
1	More than 60		
2	35-60		
3	15-34		
4	Less than 15		
5			

Put (1) if the participation is Full day, (2) half day and (3) if it is quarter day

7. Educational level 1) illiterate 2) read and write only 3) elementary completed 4) High school Completed 5) University completed

8. Total land holding

1) >2 ha 2) 1 – 2 ha 3) <1 ha

9. Type of land ownership

1) Got from government 2) Rented 3) Shared 4) Inherited

10. Experience since you start practicing Agroforestry? _____ (Year)

11. Farm characteristics

	Farm characteristics	Area in hectare	remark
1	Cultivated land		
2	Land covered with seasonal crops(Maize, Barley etc)		It could be at both farm and homestead
	Land covered with fruit trees(Mango, Avocado, Banana etc)		It could be at both farm and homestead
	Land covered with enset		It could be at both farm and homestead
	Land covered with coffee		It could be at both farm and homestead
	Grazing land		It could be at both farm and homestead
3	Woodlot		It could be at both farm and homestead
4	others		
5	Total farm land		

12. Do you have land certificate? 1) yes 2) No

13. If your answer for Q12 is yes, do you think the registration is useful? 1)Yes 2) No

14. Productivity situation and distribution along the seasons

a) Crops

	Type Crops	Area in Ha	Production along Seasons of the year				Production kg/year	Production kg/Ha	For sale		Reason for selling
			Sep- Nov	Dec- Feb	Mar- May	Jun-Aug			%	Yearly revenue in ETB	
1											
2											
3											
4											
5											
6											
7											
8											

b) Vegetables and spices

	Type of vegetables and Spices	Area in Ha	Production along seasons of the year				Production kg/year	Production kg/Ha	For sale		Reason for selling
			Sep- Nov	Dec- Feb	Mar- May	Jun-Aug			%	Yearly revenue in ETB	
1											
2											
3											
4											
5											
6											
7											

C) Fruit trees

	Type of Fruits	Area in Ha	Production along seasons of the year				Total production kg/year	Production kg/Ha	For sale		Reason for selling
			Sep- Nov	Dec- Feb	Mar - May	Jun-Aug			%	Yearly revenue in ETB	
1											
2											
3											
4											
5											
6											
7											

D) Forest trees/shrubs as source of fuelwood and their distribution

	Type of tree/shrub	Season of the year			
		Sep - Nov	Dec -Feb	Mar - May	June - July
1					
2					
3					
4					
5					
6					
7					

15) Livestock situation

A) Types, distribution and income

	Type of livestock	number	Yearly revenue in ETB	What do they do with this money?
1				
2				
3				
4				
5				
6				

B) Livestock feed source and availability

	Type of feed	Seasons of the year			
		Sep - Nov	Dec –Feb	Mar - May	June - August
1					
2					
3					
4					
5					

16) Additional revenues from Coffee-Fruit tree-enset based agroforestry practice

Source of revenue	Banana	Avocado	Mango	Coffee	Enset	Other non-fruit trees and shrubs
	Revenue in ETB/year	Revenue in ETB/year	Revenue in ETB/year	Revenue in ETB/year	Revenue in ETB/year	Revenue in ETB/year
Seedling sale						
Grafted seedling sale						
Scion cuttings sale						
Fuel/fire wood sale						
Timber tree sale						
Pole/posts sale						

17) Fixed costs for Coffee-fruit tree-enset based agroforestry practice

	Type of fixed cost	Costs per year in ETB
1	Land tax	
2	Interest	
3	Land rent	
4		

18) Variable costs for Coffee-Fruit tree-Enset based agroforestry practice

	Activities	Labor-man days	Payment per person per day	Total cost per year In ETB
1	Establishment			
	1) Site preparation			
	2) Manuring/composting			
	3) Planting			
2	Management and treatment			
	1) Weeding			
	2) Hoeing			
	3) Pest, insect protection			
	4) Manuring/composting			
	5) Pruning			
3	Other Inputs			
	Fertilizer cost			
	6) Plant material			

19) Summary of revenues and cost estimations for Livestock enterprises

Type of livestock	Costs in ETB					Revenue in ETB			
	feeding	keeping	health	Selling tax	Total annual cost	Price per individual	Total price	Other revenues	Total annual revenues
Oxen									
Cows									
Heifers									
Calves									
Sheep									
Goats									
Donkeys									
Mules									
Chicken									
Others									

20) Do you involve in off-farm activities

1) Yes 2) No

If your answer for Q 20 is yes fill the following table

	Type of activities	Income gained in ETB
1	Daily labor	
2	Petty trade	
3	Handcraft	
4	Remittance	
5	Gift/inheritance	
6	Flattery	
7	Others	
	Total	

21) Cost estimation of household expenditures

	Type of item	Cost in ETB
1	Home expenditure (Food, cloth etc)	
2	School payment	
3	Payments for social affaires	
4	Tax payment	
5	others	

22) Asset developed as a result of practicing Coffee-Fruit tree-Enset based Agroforestry

	Type of asset developed	Year developed this asset			Amount of money according to current price
		Last 10 years	last 5 years	This year	
1	Better house				
2	kitchen				
3	store				
4	Motorcycle				
5	Bicycle				
6	cart				
7	Radio				
8	Singer machine				
9	refrigerator				
10	Bee hive				
11	Irrigation pump				
12	Weaving tools				
13	Mill				
14	Water harvesting well				
15	Animals (like Goats, sheep, Ox, cow)				

23) are there saving organizations in your locality?

1) Yes 2) No

24. If your answer for Q23 is yes, which type of saving organizations do you have?

1) Formal 2) Informal

25) Do you have access to market?

1) Yes 2) No

26) Problems and challenges of the three components of agroforestry

A) What problems and challenges do you face during crop production? Please mention three main ones and rank them according to their severity

B) What problems and challenges do you face during fruit production? Please mention three main ones and rank them according to their severity

C) What problems and challenges do you face during livestock production? Please mention three main ones and rank them according to their severity

SYNONYMS AND ACRONYMS

AF	Agroforestry
AGB	Aboveground Biomass
AIC	Akaike information criterion
ANOVA	Analysis of Variance
asl	meter above sea level
BGB	Belowground Biomass
BS	Base saturation
C	Carbon
CaCl2	Calcium dichloride
CBD	Convention of Biological Diversity
CDM	Clean Development Mechanism
CEC	Cation exchange capacity
C-Ft-E	Coffee Fruit tree Enset
CH_4	Methane
cm	Centimeter
C:N	Carbon Nitrogen ratio
CO_2	Carbon dioxide
DBH	Diameter at breast height
DBMC	Dry biomass carbon
TDBMC	Total dry biomass carbon
E-C	Enset-Coffee
ETB	Ethiopian Birr
FAO	Food and Agricultural Organization of the United Nations
g	gram
GHGs	Greenhouse Gases
GPS	Global positioning system
GRDAO	Gedeo Rural Development and Agricultural Office
Gt	Giga tne
ha	Hectare
HFCs	hydrofluorocarbons
H_2O	Dihydrogen oxide
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometer
ICRAF	International Centre for Research in Agroforestry
IPCC	Intergovernmental Panel for Climate Change
IUCN	International Union for Conservation of Nature
LOI	Loss-On-Ignition
LSD	Least Square Difference
m	meter
mg	milligrams
Mg	Mega grams (1 Mg=106 grams)
Mha	Million hectares
MoARDE	Ministry of Agriculture and Rural Development of Ethiopia
N_2O	Nitrous oxide
OM	Organic matter
O_3	Trioxygen (Ozone)
Pg	Peta grams (1 Pg=10^{15} grams=1 billion tonne)
REDD	Reducing Emission from Deforestation and Forest Degradation
SE	Standard error of the Mean
SD	Standard Deviation

SNNPRs	Southern Nations, Nationalities' and Peoples' Regional State
SOC	Soil Organic Carbon
t	Tonne
TN	Total nitrogen
UNFCC	United Nations Framework Convention on Climate change
USDA	United states department of agriculture

SYMBOLS

C	Carbon
Ca	Calcium
ca	crown area
ch	crown height
cw	crown width
D	Index of agreement
d_{10}	basal diameter at 10 cm height
d_{30}	stump diameter at 30 cm height
d_{40}	stump diameter at 40 cm height
d	diameter at breast height
di	diameter of the ith stem at breast height or stump height
Dmg	Margalef's richness index
h	total height
H′	Shannon diversity index
J	Pielou's evenness (Equitability)
K	Potasium
l	Length
Mg	Magnesium
Mn	Manganise
N	Nitrogen
P	Phosphorus
Ss	Sorensen's similarity coefficient
w	width
yr	year

Curriculum vitae Personal data

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