LUT University
School of Energy Systems
Master's Programme in Circular Economy

Mari Eronen

Determinants of Sustainable Agroforestry in Ethiopia

Examiners: Professor Helena Kahiluoto, Janne Kaseva

Supervisors: Professor Helena Kahiluoto, Janne Kaseva

TIIVISTELMÄ

LUT-yliopisto

School of Energy Systems

Master's Programme in Circular Economy

Mari Eronen

Kestävän agrometsätalouden määrittävät tekijät Etiopiassa

Diplomityö

2021

27 sivua, 4 kuvaa, 6 taulukkoa

Työn tarkastajat: Professori Helena Kahiluoto, Janne Kaseva

Hakusanat: agrometsätalous, kestävyys, ilmastonmuutos, ruokaturva

Strategioita ilmastonmuutokseen sopeutumiseen ja maankäyttöön tarvitaan, jotta voidaan turvata ruuantuotanto ja pienviljelijöiden toimeentulo erityisesti kehittyvissä maissa. Agrometsätalous tarjoaa ratkaisuja ruokaturvan ja tuloturvan edistämiseen samalla kun hiilensidonta hillitsee ilmastonmuutosta. Näihin kolmeen ulottuuteen kuitenkin vaikuttavat useat tekijät, joiden keskinäinen vuorovaikutus täytyy ymmärtää, jotta voidaan mahdollistaa synergiat ja välttää kompromissit. Tämä tutkimus pohjautuu empiirisiin havaintoihin Etiopian neljältä eri alueelta ja 15 etiopialaiselta tilalta, jotka harjoittavat kerroksellista agrometsätaloutta. Kvantitatiivista ja kvalitatiivista analyysimenetelmää käytettiin ruokaturvan määrittävien tekijöiden tunnistamiseksi. Lisäksi arvioitiin näiden tekijöiden vaikutusta tuloturvaan ja hiilensidontaan. Tulokset osoittivat, että keskikokoisten puiden osuus lisäsi hiilensidontaa kasvillisuuteen ja paransi samalla ruokaturvaa. Myytävien tuotteiden monipuolisuus paransi sekä tulo- että ruokaturvaa. Puiden tiheys puolestaan vaikutti positiivisesti maaperän hiilensidontaan, mutta heikensi ruokaturvaa. Kotitalouksien tuloilla näyttää olevan vahva yhteys ruokaturvaan. Keskittyminen useampien myytävien tuotteiden viljelyyn näyttää parantavan kotitalouksien ravitsemuksen tasoa enemmän kuin pyrkiminen omavaraisuuteen ruokakasvien suhteen. Puut parantavat maaperän ominaisuuksia lisäten sadontuottoa ja tarjoavat lisätulon lähteitä, mutta hiilituloa selvästi tarvitaan kompromissien välttämiseksi.

ABSTRACT

LUT University
School of Energy Systems
Master's Programme in Circular Economy

Mari Eronen

Determinants of Sustainable Agroforestry in Ethiopia

Master's Thesis

2021

27 pages, 4 figures, 6 tables

Examiners: Professor Helena Kahiluoto, Janne Kaseva

Keywords: agroforestry, sustainability, climate change, food security

Strategies for climate change adaptation and land management are needed to secure food production and income of the smallholder farmers especially in developing countries. Agroforestry can offer solutions for enhancing food security and income security while also mitigating climate change by carbon sequestration. However, there are several factors in agroforestry systems which affect these three dimensions. Their interdependences have to be understood to enable synergies and avoid trade-offs. This case study relied on empirical findings from four Ethiopian regions and 15 smallholder farms practicing multistrata agroforestry. The key determinants of food security were identified by using quantitative and qualitative analytical methods. Furthermore, the contribution of these factors to carbon sequestration and income security was estimated. The main results showed that the proportion of plants with middle-sized basal diameter increased aboveground carbon sequestration and enhanced food security. Richness of the sold product categories was found to be co-beneficial for income security and food security. Tree density caused the most significant trade-off increasing soil carbon sequestration while decreasing food security. It is concluded that households' income is strongly connected with food security. Cultivation of several cash crops instead of self-sufficiency in food production improves households' nutrition level. Trees may improve soil quality thus increasing crop yields and do provide additional income, but carbon revenue is clearly needed to avoid trade-offs.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AFS	Agroforestry system
AGBC	Aboveground biomass carbon
C	Carbon
FCS	Food consumption score
GHG	Greenhouse gas
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
N	Nitrogen
PCA	Principal Component Analysis
PLS	Partial least squares
SOC	Soil organic carbon
SSA	Sub-Saharan Africa
SDG	Sustainable Development Goal

1 INTRODUCTION

Food insecurity and malnutrition are constantly increasing in the global level. It has been recently estimated that there are 690 million hungry people in the world. This development is mainly contributed to by greater number of conflicts, which are often exacerbated by climate-related shocks, such as drought and flooding. The impacts are most serious in developing countries, like in Sub-Saharan Africa, where 235 million people are undernourished. (FAO 2020.) According to the IPCC report (2018), the negative impact of climate change on global food security is expected to increase in the future due to decline in the production of staple food crops and increasing cereal prices. Deforestation and conversion to crop land are decreasing vegetation cover and disturbing natural ecosystems, which causes soil degradation and erosion. This leads to depletion of soil fertility, as the concentrations of soil organic matter and available nitrogen pools are declining (Mulugeta et al. 2005). Strategies for climate change adaptation and land management are needed to secure food production and income of the smallholder farmers. Especially in agrarian countries like Ethiopia, where majority of the population relies on agriculture, solutions need to be found quickly.

Before the growing demand for efficient production of crops drove agriculture into monoculture cultivation, farming of multiple species mixed with trees was very common worldwide (Stafford Smith and Mbow 2014). Transforming monocropping systems back into agroforestry could have multiple benefits. This has been acknowledged in Ethiopia, where agroforestry practice was included in the country's food safety program (Productive Safety Net Program) launched in 2005. The case study conducted by Woolf et al. (2018) showed that the program had significant co-benefits in climate change mitigation by building carbon stocks in a large scale. The most remarkable synergy was discovered on agroforestry sites, where non-timber forest products were introduced to enhance diet and livelihood diversification while also boosting carbon stocks through increased tree cover. In addition, improved carbon sequestration could provide potential carbon income for farmers (Waldén et al. 2019). This could be a significant driver, as the climate change mitigation may not have very important role in smallholder farmers' decision making (Mbow et al. 2014).

However, agroforestry is not a unified concept, as there are number of different practices. This study concentrates on multistrata homegarden agroforestry system, which is common in most tropical and subtropical countries. It is the prevalent farming practice in southern Ethiopia and is also expanding in northern parts of the country. Multistrata homegardens are complex, tree dominated land use systems, with two or more layers of trees and shrubs. In this system, multipurpose trees are planted and managed together with annual or perennial agricultural crops and livestock (Nair 1991). Multistrata homegardens provide multiple services for the household, such as timber, fuelwood, fodder and crops. Ecological benefits include carbon sequestration, biodiversity conservation, soil enrichment, improved air and water quality in addition to enhanced climate change resilience. (Kuyah et al. 2019.) The other examples of commonly practiced agroforestry systems are parklands, live fences, fodder banks, improved fallow, plantation in pasture, alley cropping and hedgerows (Bayala et al. 2014; Kuyah et al. 2019; Theobald et al. 2014).

Food security is defined as a situation, where all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO 2008). During the last 50 years, intensification of agriculture by improved seed varieties, synthetic fertilizers and mechanization has been able to increase the world's cereal supply remarkably (DeFries et al. 2015). Despite the increasing productivity, conventional agricultural practices are unable to meet the Sustainable Development Goal on zero hunger. Agroforestry systems can play important role in enhancing food and nutrition security by providing more nutritionally balanced diets and delivering ecosystem services for crop production. Fruits and other edible tree products provide micro-nutrients and vitamins thus complementing the cereal based diets. (Bayala et al. 2014.) Perennial crops and crop diversity help to reduce variation in food supply and income of smallholder farmers, thus enhancing resilience (Nguyen et al. 2013; Thangata & Hildebrand 2012). According to the recent studies, the key determinants for food security in farming and forest-based households in Nigeria, Kenya and South Africa were household size (Kabir et al. 2020; Oduniyi & Tekana 2020) and gender of the household's head (Kabir et al. 2020). In Ethiopia, food security has been significantly determined by rain shock, lack of off-farm income and region of the households. (Abegaz 2017.)

Trees and shrubs provide soil cover, reducing erosion and buffering impacts of climate change, and seem to have a positive contribution to soil carbon content (Bayala et al. 2014). Trees fix carbon from atmosphere in the photosynthesis and store it in biomass and soil. Nitrogen fixing trees, i.e., legume trees, are commonly used in agroforestry systems to help offset potential soil nitrogen deficiencies and increase overall biomass productivity (FAO 1992). Agroforestry systems can be used to build soil carbon stocks, though the estimations of sequestration potential vary. According to Lal (2004), the carbon sequestration potential of soil depends on soil texture and structure, rainfall, temperature, farming system and soil management. On smallholder farms in Western Kenya, carbon sequestration was found to be determined by farm size, tree density and the average size of trees (Reppin et al. 2019). Negash et al. (2021) had similar findings from Ethiopian farms. The main determinants of soil carbon sequestration were duration of agroforestry, tree density and the proportion of plants with a high basal diameter (>25 cm). Very high proportion of legumes slightly increased soil C/N ratio. The key determinants of aboveground carbon sequestration were basal area, diversity of basal area, dominant species and proportion of legumes, while the most important predictor was middle-sized basal diameter (>10 cm). In the areas, where enset was dominant plant, the effect of diversity of basal area was increasing, whereas the effect of basal area >10 cm was decreasing.

Agroforestry systems can enhance income security through improved soil fertility and providing additional products from trees, such as fruits and timber wood. Based on literature, there are many factors affecting the productivity of agroforestry systems, such as multistrata composition, diversity, climatic parameters and management intensity (Rahman et al. 2013; Alam et al. 2012; Gómez et al. 2015). Melaku et al. (2014) discovered that size of landholding, distance to market and distance of the forest from the residence were significant variables determining the income of the households in Ethiopian farms. According to Walden et al. (2021), the key determinants affecting the net income of the Ethiopian smallholder farmers were farm size, proportion of legume trees, richness of the sold product categories and fertilizer use. The only significant negative correlation was found with the proportion of legume trees, which decreased income by 7 % when the proportion of legume trees increased by 10 % units. In addition to environmental benefits, improved carbon sequestration of soil could offer monetary benefits from the carbon market. This could have significant impact on motivating farmers to convert to agroforestry. The amount of carbon revenue depends on the accumulation rate and the market price of the carbon (Waldén et al. 2019). Even without carbon revenues agroforestry was four times as profitable as the dominant monoculture systems. When the carbon revenue was included, the profitability of agroforestry could be increased by 150 % on average. Perennial trees and shrubs contributed over 70 % of the AFS revenue.

Agroforestry practices can be co-beneficial for food security, carbon sequestration and income security, but there can also be trade-offs. For example, shading trees can affect negatively on crop yields and there can be competition for water and nutrients, if the trees are not pruned (Kuyah et al. 2019). The study conducted in Western Kenya showed significant trade-off between income generation and climate change mitigation, as the farmers were focusing on fast growing timber trees, such as Eucalyptus (Reppin et al 2019). In their meta-analysis, Kuyah et al. (2019) found synergies with food security and carbon sequestration. AF practice seemed to significantly increase crop yields, which could be explained by improved soil fertility, water regulation, microclimate and soil physical properties. It was also discovered that AF improved total N, available P and SOC compared to controls. According to Lal (2004), one ton increase of soil carbon pool of degraded cropland can increase wheat yields by 20-40 kg/ha.

Defining the sustainable agroforestry practice requires understanding the interactions between the determinants affecting food security, carbon sequestration and income security. The recent empirical studies conducted in Ethiopia showed that duration of agroforestry, tree density and proportion of plants with a high basal diameter (>25 cm) were the key determinants for soil carbon sequestration. For the aboveground carbon stock, the key determinants were basal area (diameter >10 and 25 cm), diversity of basal area, dominant species and the proportion of legumes**.** Income security was determined by farm size, proportion of legume trees, richness of the sold product categories and fertilizer use (Negash et al. 2021; Waldén et al. 2021). To enable synergies and avoid trade-offs, it has to be estimated how these factors contribute to food security. The aim of this case study was to identify the determinants of agroforestry system affecting food security, as well as possible synergies and trade-offs with carbon sequestration and income security. The study relied on empirical findings from multistrata agroforestry systems of smallholders in four Ethiopian regions. The results are based on quantitative and qualitative analyses.

2 MATERIALS AND METHODS

This study was based on data collection from four regions located in southern, northern and central Ethiopia. The economic survey included 135 households in northern and southern parts of the country, from which 27 participated in the carbon sequestration study. The diet survey was conducted in 40 households in southern, northern and central Ethiopia. Finally, there were 15 households, whose data could be used to identify the determinants of multistrata agroforestry system affecting food security, carbon sequestration and income security.

2.1 Description of the study regions

Ethiopia is an agrarian country located in the horn of Africa, close to the equator. Agriculture has a significant role in providing livelihood for rural communities. The empirical study was conducted in four different regions in northern, southern and central parts of the country. In the selected regions, multistrata agroforestry systems dominate as traditional cropping systems and are significantly enhancing self-sufficiency of the smallholder farmers. These sites were selected, because they represent important cultivation areas with relatively high agricultural productivity and a broad range of variation within the multistrata agroforestry system. The climate in the areas is characterized as moist to sub-humid warm subtropical and the altitude is approximately 2000 m above the sea.

The agroforestry sites in Gedeo and Sidama are the most densely populated areas of Ethiopia, 1300 persons/km^2 (Mebrate 2007). The population density is lower in north and also the farms are larger there than in the south. The study regions have different history of agroforestry and farming practices. In Gedeo and Sidama, agroforestry evolved from natural forests by removing trees and intensifying land use. Some native trees and shrubs were retained. In Fenote-Selam, agroforestry formed through intensification of previous mixed farming that combined cereal-based cropping with grazing animals (Negash et al. 2012; Asfaw & Ågren 2007). In south, multistrata homegarden is the prevalent farming practice, whereas in north, farmers have agroforestry plots in addition to monoculture farming. Fertilizers are only used in monoculture farming. Green manure and crop residues are used in south.

The tree density was higher in the north than in the south. In Fenote-Selam, *Cordia Africana* and *Coffea arabica* are the dominating species. Also, some exotic N-fixing trees (e.g., *Sesbania sesban*) have been integrated. Plant species in Gedeo are mainly composed of N-fixing native trees (e.g., *Millettia ferruginea, Erythrina brucei*) and in Sidama, not N-fixing trees (e.g., *Cordia Africana*, enset). (Negash et al. 2021.) Enset, which is a perennial, herbaceous monocarpic banana-like plant, is the dominating staple food crop in Sidama and Gedeo. In Fenote-Selam, multistrata homegarden contains cereal crops, teff grain being the most prevalent food crop. Coffee, khat and chili pepper are cultivated as cash crops.

2.2 Carbon sequestration

The carbon sequestration study (Negash et al. 2021) was conducted in Haru-Gedeo (Gedeo) in southeastern Ethiopia, Bokansa-Wonsho-Sidama (Sidama) in southcentral Ethiopia and Menekus-Abdoguma-Fenote-Selam in northwestern Ethiopia. The practiced agroforestry system in the study areas is multistrata homegarden, with broad variation in the characteristics that could have impact on soil organic carbon and nitrogen stock (duration, tree density, proportion of legumes, species diversities of abundance and basal diameters above 10 and 25 cm, plant species composition, soil depth, texture, pH, altitude). From each study area, 21 agroforestry plots aged from 10 to 54 years were selected. An inventory of perennial species and soil sampling were conducted in each plot. The C stock in aboveground biomass was calculated based on a product of the biomass dry matter and C content. It was assumed, that C contents for trees and shrubs were 48 % (Kuyah et al. 2012), for coffee 49 % (Negash & Starr 2013) and for enset 48 % (Negash et al. 2013). The total C and N concentrations of air-dried soil samples were determined by dry combustion. The SOC and N stocks were primarily calculated using the fixed depth method by multiplying the concentrations of soil C or N by the bulk density and the depth of the sampled soil.

2.3 Economic determinants

The economic data for the income security study (Waldén et al. 2021) was collected by interviewing farmers and key informants from Fenote Selam in northwestern Ethiopia, Haru-Gedeo in southwestern Ethiopia and Wonsho-Sidama in southcentral Ethiopia. The financially responsible persons of the farms were interviewed. The key informants were selected from a group of community recommended farmers who had general knowledge about the farming practices and agricultural economy of the study area. Information was gathered about socio-economic attributes (size of landholding, education level and farmers' age, size of livestock holdings), annual data about crop yields, revenues (crops, woody species, livestock), cost of production inputs (seedlings, seeds, fertilizers, pesticides, herbicides, irrigation) and labor intensity. Also, diversity of the plant species, including tree density (number of stems) and richness (number of species) were surveyed. To evaluate the impact of carbon revenue on the income of the farmers, the carbon sequestration rates were obtained from the carbon stock data collected from the farms, that participated in the household survey (Negash et al. 2021). The interviews were conducted during the same time period when the carbon sequestration rates were measured.

2.4 Diet study

The diet study areas were Mankusa in northern Ethiopia, Oromia in central Ethiopia and Sidama and Gedeo in southern Ethiopia. Agroforestry systems (multistrata homegarden in north and south, parkland in central) were compared to monocropping systems. Ten households (5 AF + 5 non-AF) from each site were included in the survey. The data were collected from seven days on four production seasons (surplus, enough supply, low supply, deficit). The timing of the study periods and the level of food supply are described in table 1. The documented parameters were type of the food, ingredients and the quantity of use.

Table 1. Study periods: four production seasons.

	Food supply	**Months**
Week 1	Deficit	June - August
Week 2	Surplus	September - November
Week 3	Enough	December - February
Week 4	Low	March - May

Food Consumption Score (FCS) was used as the indicator for food and nutrition security. According to UNWFP (2008), FCS is a "composite score based on dietary diversity, food frequency, and relative nutritional importance of different food groups". The consumed food items were divided into eight food groups, that were weighted by their nutritional value. This way the FCSs for each household could be calculated and further classified in three categories: poor (0-21), borderline (21,5-35) and acceptable (≤35). Additional data were collected by interviewing men and women about nutrition, income and costs; changes in diet; the role of AF in diet; costs and income for the cash crop; food supply and its use, and other use of the harvest. Qualitative analysis was based on the interviews. The possible determinants for food security, income security and carbon sequestration were identified and color coded.

Quantitative analysis was done to identify the key determinants for food security and to form a synthesis over all three dimensions. The average FCSs from four study periods (weeks) were used. Data collected from 15 households, who had participated in all the three studies (carbon sequestration, income and diet) were included in the analysis. The number of determinants used in the analysis was relatively high compared to the number of observations, which may lead to inconclusive or contradictory results (Button et al. 2013; Colditz et al. 1995; Ioannidis et al. 2005). There are no accurate directions about the minimum number of observations used in analyses. According to Jenkins and Quintana-Ascencio (2020), minimum N = 25 is recommended in regressions, but with very low variance clear data shape can be identified at minimum N = 8. Partial least squares (PLS) was selected for the main analysis method, because it is appropriate tool for finding a few underlying predictive factors that explain most of the variation in the response (SAS 2019). Principal component analysis was also used as a supportive analysis method.

2.5 Hypothetical determinants

The hypothetical determinants for food security were based on the results of former studies, in-depth interviews of the farmers participated in the survey, and the key determinants of carbon sequestration (Negash et al. 2021) and income security (Waldén et al. 2021). The hypothetical determinants used in the analysis were duration of agroforestry in years, tree density (number of stems ha^{-1} regardless of the species), proportion of legumes (%), proportion of stems with basal diameter >10 or >25 cm (%) and species diversity based on plant basal diameter ($H_b = -\Sigma P_i (P_i)$ i=1, where p_i is the proportion of basal diameter of the ith species, diameters < 2.5 cm excluded) (Negash et al. 2021). The determinants related to households' income were total net income, income richness and income diversity. Income diversity was evaluated according to variability and proportionality of income sources. This composition was divided into following categories: (1) annual crops, (2) woody plants, (3) herbaceous perennials, (4) livestock, or as follows by their intended use: (1) staple food crops, (2) nutritionally important crops, (3) animal products, (4) wood products and (5) cash crops (Waldén et al. 2021).

3 RESULTS

3.1 Food Consumption Scores

The results showed remarkable differences in the households' FCSs among the study regions, but also among the households within the same regions. In addition, some differences between the study periods could be noticed. Especially week 3 (enough supply) seemed to differ from the others.

In Gedeo, all of the households' food consumption status was on borderline or acceptable level throughout the year (Figure 1). All of them were harvesting staple food crops for own consumption only without using fertilizers. Four households cultivated coffee as the main cash crop and additional income was obtained by selling wood products, fruits and animals. The household 24 did not have coffee production. They had the smallest income, which consisted mainly of selling sheep. However, their FCSs were similar to the households 6 and 32. The food security in the household 15 varied also, but to opposite direction. That household had the highest income, but the household was also the largest. The household 11 was the only one with flat curve, meaning that their food consumption status appeared to be even throughout the year. They mentioned in the interview, that they had always something to harvest.

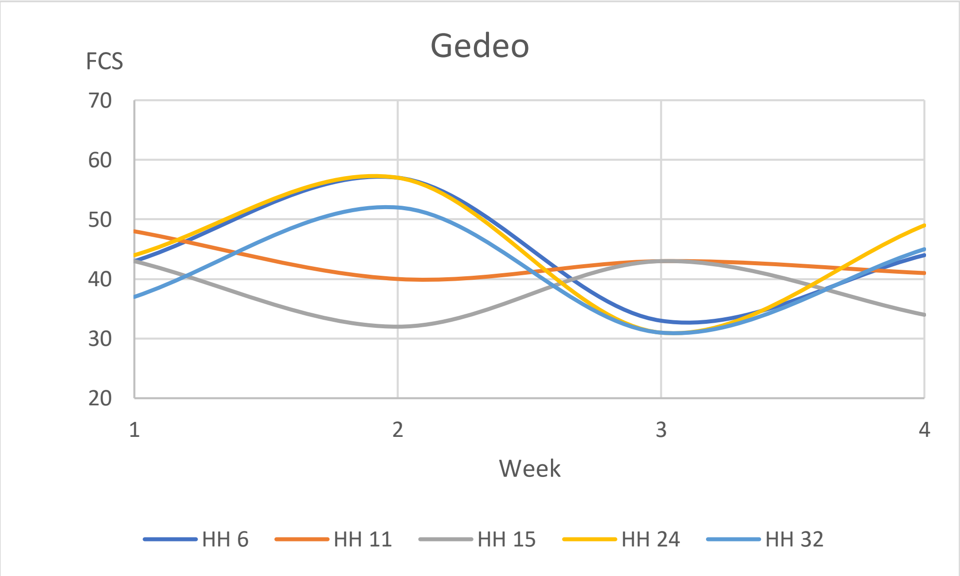

Figure 1. Food consumption scores of the households in Gedeo.

Sidama had the highest variation in FCSs among the households (Figure 2). The households with higher FCSs were consuming milk, which improved their food security significantly by providing vitamins and nutrients. Other animal-based foods were not consumed during the study periods. Richness of the staple food crops and self-sufficiency in food production were relatively high in the farms in Sidama.

In the households 3 and 35, the food consumption status was on an acceptable level throughout the year, whereas in the households 12 and 25, it was on poor or borderline level at the best. Both households 3 and 35 had *Cordia* trees as their main source of income. The households 12 and 25 were cultivating khat as the main crop. They both reported not having anything to harvest in April, and nothing to sell in June or from August to September. The household 25 had the highest income and the largest farm size. The household 12 had the highest production of khat. The largest changes were happening in the food consumption level of the household 31. This was the only household who did not use fertilizers or have legume trees on their farm. They had the smallest income and production of crops, and also the lowest diversity in sold products. They cultivated khat and coffee as cash crops, khat being the main crop. All the cultivated food crops were harvested for own consumption. They did not have anything to harvest from March to April or anything to sell from August to September.

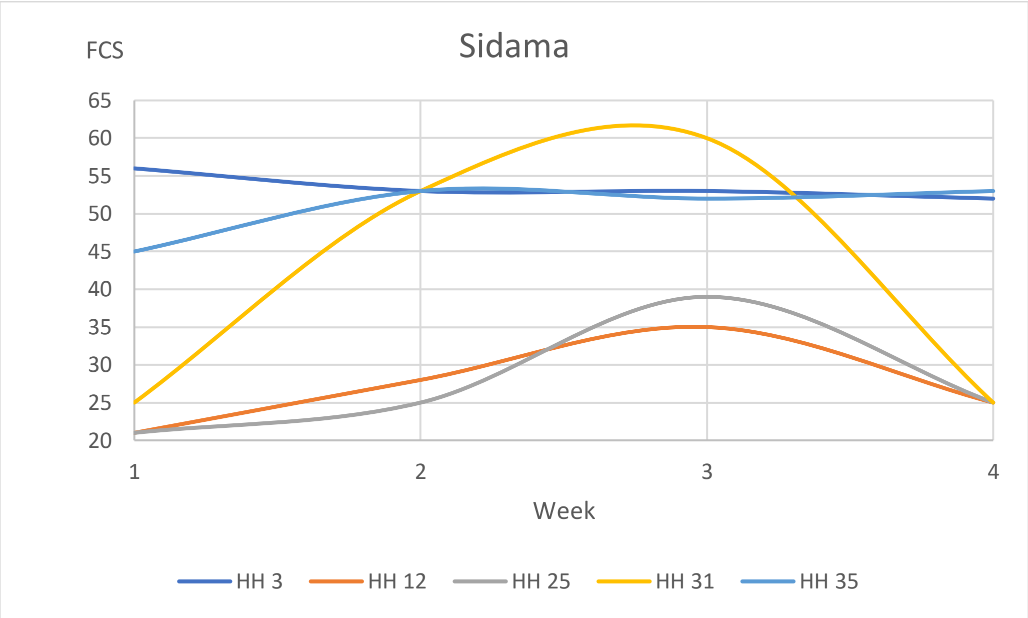

Figure 2. Food consumption scores of the households in Sidama.

The five households in Mankusa had food consumption scores much higher than in the southern study regions (Figure 3). All of the households' food consumption status was on an acceptable level throughout the year and they had also significantly higher net income. The production on the farms was mainly focused on cash crops, only few staple food crops were cultivated. Thus, a large share of the consumed food products was purchased from the market.

For the households 18 and 40, the curve was decreasing steadily. Both of them were cultivating chili pepper as the main crop. The household 40 had the highest income and they reported that they had always something to sell. However, the household 18 had the highest food consumption scores. The households 7 and 29 had clear rise in the curve during week 3. They also cultivated chili pepper as the main crop. Additional income was obtained from selling coffee, maize, teff and animals. The household 24 had the lowest FCSs with very little variation. Their income consisted mainly of selling oxen, but coffee and chili pepper were also cultivated as cash crops. Their diet contained mainly food items, that were produced in the farm, so they appeared to be highly self-sufficient. The only animal-based products in their diet were eggs. Meat was not used.

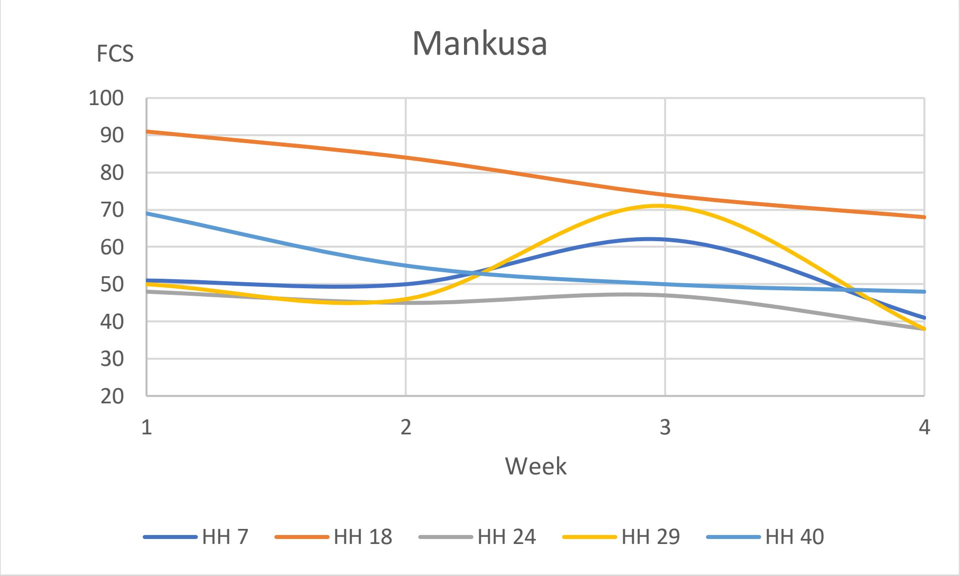

Figure 3. Food consumption scores of the households in Mankusa.

3.2 In-depth interviews (qualitative analysis)

Gedeo, Sidama (South)

The interviewed farmers. considered agroforestry as a beneficial farming practice, because it increases the farmer's income and food security by providing food and wood products for sale and for own consumption. The decreased income of coffee and other cash crops can be compensated by selling tree products or animals. Coffee yields have been increased as a result of improved soil fertilization. However, AF practice may also have negative effects, if the trees are planted in dense arrangement and are competing for growth resources with crops.

Location of the farm and distance from the markets seem to affect on the farmers' economic situation. The price fluctuation of cash crops, e.g., coffee and khat, is very common. The decreased income also weakens food security, since the farmers cannot afford to buy all the needed food items. The price of the food products in market can also be very high. The government does not interfere in the market, so the price of cash crops depends highly on the traders, who are commonly used to reach the consumers. The price would be higher in bigger cities, but it is easier for farmers to sell the products in the local markets. However, the export of coffee has been seen beneficial for the country's economy.

The dominating species in AF system clearly have impact on income security and food security, but topography may be limiting the options for cultivated crops and farming practices. Main cash crops cultivated in Gedeo and Sidama are coffee and khat. The challenges related to coffee production are high costs and yield losses caused by diseases and drying coffee beans. Allocating more land for khat production has increased the farmers' income. Also, khat is harvested several times a year, coffee only once. However, the large expansion of khat production has reduced tree species, due to its light demanding feature. This development has had negative impact on soil productivity, as well as animal feed and fuel production. In addition, khat production undermines food security, since the land area for food production has decreased and food is not as accessible as it used to be. The farmers have become dependent on the food from the market. Enset is considered as food security crop, but it takes several years to produce yield. Diversification is seen very important for future development, instead of converting land to monoculture farming of cash crops.

The impact of tree species included in the AF system came up during the interviews. High valued *Eucalyptus* is grown on many of the farms, but it competes for growth resources with food crops and should not be intercropped with grass land. *Cordia africana*, *Erythrina abyssinica* and *Millettia ferugenea* are leguminous trees and are used for fertilizing soil. *Eucalyptus* and *Cordia* trees are mainly sold as timber, whereas *Milletia* trees are sold as firewood. Rotation age of trees used as timber wood impacts highly on the income, since the farmers get better price for older trees with larger stem diameter. The supply of plant nutrients (fertilizers/residues/legumes) was seen sufficient in Gedeo. In Sidama, shortage of farmyard manure and fertilizing trees was reported as a problem.

Menkusa, Abdegoma (North)

In the north, AF is also considered as beneficial farming practice. Diversity in cultivated crops is important for compensating income losses caused by low prices or yield losses. Hence, there is more likely something to sell. According to the farmers, they are highly self-sufficient. Mainly cooking oil and spices are purchased and it is not common to buy imported food items. Improved seeds (maize, pepper, teff) are seen as beneficial technology, but the supply of seeds is low. There are problems with land resources, soil erosion and low soil fertility. Artificial fertilizers are used, but their price is high and untimely distribution causes challenges. Better irrigation system is also needed, because rain fed agriculture is considered unreliable. The major disadvantage of AF is the competition of trees with coffee growth. Trees are also serving a good habitat for monkeys and birds, which are damaging the crops. Biodiversity conservation has increased the monkey population, causing yield losses of vegetables, coffee, fruits and sugarcane.

Location and distance from markets were mentioned in many of the interviews. Same as in the south, there is a challenge with market price fluctuation of cash crops (coffee, pepper) in the northern study sites. The farmers are told that the variation is linked to international price fluctuation, but they have some doubts about that. The market price is dominated by traders. The closest market is located in Mankusa (3 km), where the products are also sold directly to the consumers. It is easier for farmers to sell food crops in Mankusa, but the price would be higher in Fenote-Selam, which is a bigger city located 15 km from the village. However, transport is costly, and it is difficult to find suitable traders. Some farmers have also a strategy to wait until the price is better, usually after main yield seasons, though there is no guarantee for that.

Tree species and stem diameter of trees could be recognized as determinants of income security and carbon sequestration. The coffee shade trees in the system include *Cordia Africana, Albizia gummifera, acacia species, sesbania* species. *Cordia* and *Eucalyptus* trees have high value, and they are used as timber wood. Trees are also kept as an insurance for "bad times." Farmers can get higher price for older and bigger trees. For example, for *Cordia* trees this means felling in the age of 15 to 20 years. However, coffee yields under the big trees are lower, which decreases the income.

Table 2. Determinants of food security, carbon sequestration and income security based on the in-depth interviews.

Food security	**Carbon sequestration**	**Income security**
- Distance from the markets - Main crops - Farm size - Fertilizers - Tree density - Richness of the sold products[1]	- Stem diameter of trees - Tree density - Dominating plant species	- Farm animals - Tree density - Distance from the markets - Stem diameter of trees - Tree species - Main crops - Fertilizers - Farm size - Richness of the sold products[1]

[1] Multiple products for sell.

3.3 Food security (quantitative analysis)

PLS procedure aims to find few PLS factors that explain most of the variation in both predictors and responses (SAS 2019). In this case, three extracted factors explained 65 % of the response variation and 56 % of the predictor variation (Table 3).

Table 3. Percent variation accounted for by PLS factors.

Percent Variation Accounted for by Partial Least Squares Factors				
Number of Extracted Factors	Model Effects		Dependent Variables	
	Current	Total	Current	Total
1	23,0	23,0	41,6	41,6
2	22,4	45,4	15,6	57,2
3	10,7	56,1	7,9	65,1

Correlation loading plot (Figure 4) summarizes the features of this model. Based on the loadings, it can be seen how much variation in each variable is accounted for by the factor 1 (horizontal axis) and factor 2 (vertical axis). Third dimension (factor 3) is also marked in the figure, although it cannot be seen so straightforward. The distance of the corresponding point from the origin shows the joint effect of the variables. It can be seen that the determinants related to income of the households are clearly grouped. Also, the proportion of plants with high basal diameter and duration of the AF seem to be strongly connected. The third group is formed by the proportion of plants with middle-sized basal diameter and the share of legumes, and tree density which is located in the opposite direction. The variables can also be observed individually by the distance for the projections of this point onto the horizontal and vertical axes. It can be seen that income richness (category 1) is separated from the other determinants related to income. Diversity of basal area is located very close to origin and does not seem to have significant impact on FCS.

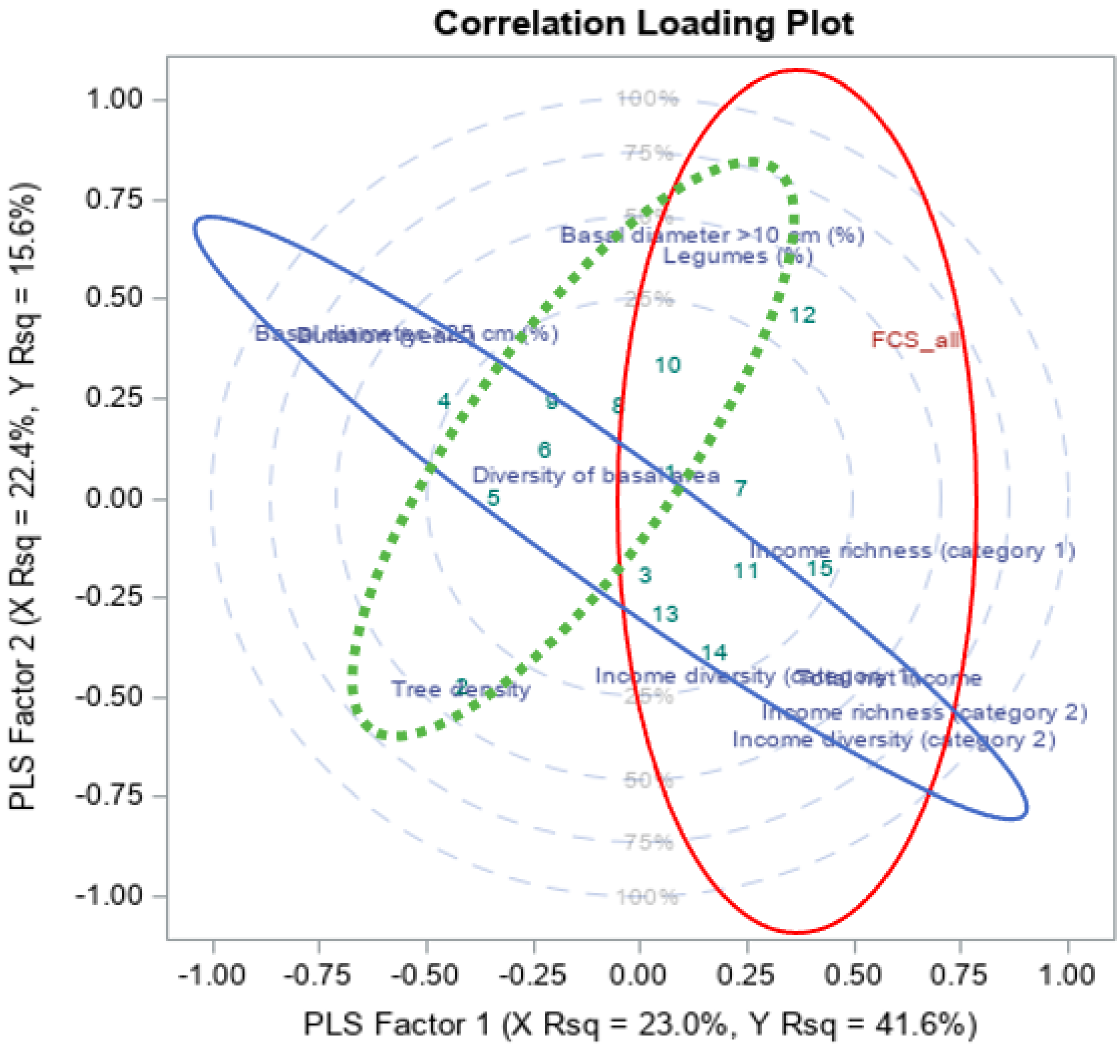

Figure 4. Correlation loading plot of determinants for combined food consumption scores (FCS) of the households.

Rotated factor pattern supports the interpretation of the correlation loading plot (Table 4). It also describes the interrelationships of the determinants. Factor 1 is clearly formed by the proportion of plants with high basal diameter and duration of the AF, and total net income which have strong negative loading. The most significant determinants of factor 2 are income richness and income diversity categories. The proportion of plants with middle-sized basal diameter and the share of legumes form factor 3, which can also be seen from correlation loading plot. Correlation coefficients of the determinants and FCS can be seen from correlation matrix (Table 5).

Table 4. Principal component (PC) loadings of the Varimax rotated principal component analysis (PCA) matrix of the determinants for food consumption scores (FCS) of the households. The proportions of the variance explained by the PCs are presented for each PC in the bottom row.

Rotated Factor Pattern				
	Factor 1	Factor 2	Factor 3	Total
Basal diameter >25 cm (%)	**0,91**	0,12	0,06	
Duration (years)	**0,75**	-0,21	-0,08	
Income richness (category 2)	**-0,63**	**0,52**	-0,41	
Total net income	**-0,74**	0,21	-0,15	
Income diversity (category 1)	0,04	**0,86**	-0,08	
Income richness (category 1)	-0,17	**0,84**	0,08	
Income diversity (category 2)	-0,48	**0,71**	-0,31	
Legumes (%)	-0,01	-0,10	**0,86**	
Basal diameter >10 cm (%)	0,28	0,16	**0,71**	
Diversity of basal area	0,01	-0,07	0,41	
Tree density	0,41	0,36	-0,46	
Variation explained	26 %	23 %	18 %	**66 %**

Table 5. Correlation matrix.

Pearson Correlation Coefficients and their p-values (H0:|r|=0), N = 15												
Determinant	**FCS_all**	**Duration (years)**	**Basal diameter >25 cm (%)**	**Basal diameter >10 cm (%)**	**Diversity of basal area**	**Tree density**	**Legumes (%)**	**Total net income**	**Income richness (category 1)**	**Income richness (category 2)**	**Income diversity (category 1)**	**Income diversity (category 2)**
FCS_all	1	0,5879	0,5566	0,2491	0,667	0,1726	0,4036	0,4555	0,0923	0,2403	0,7662	0,5452
Duration (years)	-0,152	1	0,004	0,917	0,619	0,921	0,828	0,099	0,454	0,144	0,655	0,050
Basal diameter >25 cm (%)	-0,165	0,694	1	0,128	0,775	0,302	0,763	0,042	0,822	0,073	0,802	0,219
Basal diameter >10 cm (%)	0,317	0,029	0,411	1	0,529	0,839	0,090	0,550	0,939	0,231	0,716	0,747
Diversity of basal area	-0,121	0,140	0,081	0,177	1	0,696	0,525	0,557	0,724	0,485	0,868	0,513
Tree density	-0,372	0,028	0,286	-0,057	-0,110	1	0,250	0,512	0,922	0,848	0,343	0,313
Legumes (%)	0,233	-0,061	-0,085	0,453	0,178	-0,317	1	0,272	0,997	0,166	0,634	0,238
Total net income	0,209	-0,442	-0,529	-0,168	0,165	-0,184	-0,303	1	0,401	0,010	0,561	0,048
Income richness (category 1)	0,450	-0,210	-0,064	-0,022	-0,100	0,028	-0,001	0,234	1	0,042	0,003	0,060
Income richness (category 2)	0,323	-0,396	-0,476	-0,329	-0,196	0,054	-0,377	0,639	0,530	1	0,240	0,000
Income diversity (category 1)	-0,084	-0,126	0,071	-0,103	-0,047	0,264	-0,134	0,163	0,712	0,323	1	0,041
Income diversity (category 2)	0,170	-0,514	-0,337	-0,091	-0,183	0,280	-0,325	0,519	0,495	0,865	0,532	1

Considering the small size of data, further analysis was made to improve the reliability of the conclusions. The predictors were centered and scaled to estimate their impact on food consumption scores. The most important determinants for food security appeared to be the proportion of plants with middle-sized (>10 cm) basal diameter, income richness (category 1), income diversity (category 2) and tree density (Table 6).

Table 6. Parameter estimates for centered and scaled data.

Parameter Estimates for Centered and Scaled Data	
	FCS_all
Intercept	0
Duration (years)	0,121
Basal diameter >25 cm (%)	0,025
Basal diameter >10 cm (%)	**0,385**
Diversity of basal area	-0,231
Tree density	**-0,309**
Legumes (%)	0,103
Total net income	0,065
Income richness (category 1)	**0,525**
Income richness (category 2)	0,316
Income diversity (category 1)	**-0,362**
Income diversity (category 2)	0,015

3.4 Synergies & trade-offs

The main determinants of soil carbon sequestration were duration of agroforestry, tree density and proportion of plants with high basal diameter (>25 cm). Tree density was also identified as one of the key predictors of food security with negative correlation. Thereby, trade-offs between food security and soil carbon sequestration can be detected. The results of qualitative analysis also support this. The aboveground carbon stock was determined by middle-size diameter (>10 cm) plants, dominant species and legumes. (Negash et al. 2021). The proportion of middle-sized plants was also the most important predictor of food security. Thus, there is a synergy between food security and carbon sequestration in aboveground biomass.

Determinants increasing the income of the farmers were farm size, richness of the sold product categories and fertilizer use. Richness of the sold product categories appeared to be a key determinant of food security also. The findings from qualitative analysis support this. Fertilizer use was excluded from the analysis because of the uncertainty about the cause-effect relationship. The households with better income are more capable for purchasing fertilizers than others. Also, the need for fertilizers is highly dependent on the main crop. For example, chili pepper requires high amounts of fertilizers, whereas in cultivation of organic coffee they are not allowed at all. On the other hand, farmers can get higher price for organic coffee. Farm size was also excluded, because this study concentrated on the characteristics that are manageable for the farmers.

The only negative impact on income security was found with the proportion of legume trees (Walden et al. 2021), which in turn is important for the persistence of soil carbon and for soil productivity. According to Negash et al. (2021), the proportion of legumes may increase N availability while also reducing soil C concentration. Based on the results of the quantitative analysis, legumes did not seem to have significant impact on food security. However, the share of legumes is strongly connected with the proportion of plants with middle-sized basal diameter, which was one of the key determinants.

4 DISCUSSION

The results of this study showed that the proportion of plants with middle-sized (>10 cm) basal diameter increased aboveground carbon sequestration and enhanced food security**.** Richness of the sold product categories was found to be co-beneficial for income security and food security. Tree density seemed to form the most significant trade-off between the determinants reducing food security while increasing soil carbon sequestration.

4.1 Reliability and generalizability

This case study was conducted by using triangulation method to enhance the reliability of the results. Proper designing of AF systems is highly important for enabling synergies and avoiding trade-offs. This requires integrated approach and involving environmental, economic, statistical and nutritional expertise. The same research question was examined from multiple aspects. Both quantitative and qualitative analyses were used for a broader perspective. Data were collected comprehensively by empirical studies, questionnaire and interviews. Additional information was gathered from the literature and former studies.

The uncertainties were mostly related to the small number of observations used in the quantitative analysis. However, this was a case study considering 15 households. Additional studies are needed for wider observations. Possible inaccuracies in data collection may also affect on the reliability of the results. Data were collected during different years by different people conducting the interviews. The farmers may not had have the exact information about the number of trees, cultivated plants or animals on their farms. This could affect the analysis results of the contribution of trees on food security, or the conclusions about their self-sufficiency in food production. Also, translations may have been incorrect, or the farmers could have been insecure about telling the truth for fear of the consequences.

The results of this case study can be applied for multistrata agroforestry systems practiced in similar agroecological environments in east Africa. Environmental characteristics, such as plant diversity and biomass production (Dossa et al. 2013), accumulation and decomposition of litter (Berg & Laskowski 2006), and climatic factors (Mehta et al. 2014) have influence on carbon sequestration rate, as well as the crop production. The options for cultivated crops and farming practices can also be limited by topography. Location of the farm, distance from markets and the market prices of the sold products have clear impact on the income generation and food security. The results of this case study showed that the farmers' income and richness of the sold product categories strongly determine food security. The households with higher income can diversify their diet by purchasing food from the market. However, this requires that they get decent price from the sold products, the market is located in achievable distance and the price of the food is affordable.

4.2 The key determinants of food security

The proportion of middle-sized trees was one of the key determinants of food security. The findings from the in-depth interviews support the results of the quantitative analysis, as the farmers reported that trees were perceived to improve soil productivity and increase the crop yields. The former studies have shown that improving soil quality by soil carbon sequestration is highly important for achieving food security. According to Lal (2004), one ton increase of soil carbon pool of degraded cropland can increase wheat yields by 20-40 kg/ha, maize yields by 10-20 kg/ha and cowpea yields by 0,5-1 kg/ha. However, high density and large size of trees causes competition for growth resources. Decreasing yields are weakening economic situation and food security of the households. The results of the quantitative analysis showed strong negative correlation with tree density and food security. This was also mentioned in the interviews and recognized as one of the key determinants.

Although, the quantitative analysis did not show strong correlation between total net income and FCS, income security and food security appear to be strongly linked. Both were significantly determined by richness of the sold product categories, which helps to compensate possible yield losses, as the farmers have more likely something to sell. However, the income and the food consumption status of the households in Mankusa were significantly higher compared to Gedeo and Sidama. This could be explained by higher production of cash crops and higher prices. Since the number of cultivated food crops was small, a large share of consumed food products was purchased. This would suggest that income from cash crops is more important for enhancing food security than achieving self-sufficiency in food production. The similar results were also found in Western Kenya, where households with high on-farm food plant richness and diversity were not more food secure than households managing species-poor farms (Ng'endo et al. 2015). On the other hand, Kuria et al. (2019) discovered that specialization on few high-value cash crops led to food-insecurity in Rwanda. They concluded that food security policies should instead promote crop diversity.

In addition, having animals on farm appears to have impact on food security. In Sidama, the households had very similar diets, but two of them were consuming milk regularly and had much higher FCS than the those, who did not consume milk at all. One of the households consumed milk only during week 3, which led to a significant rise in their food consumption status. Milk products are weighted same as meat and fish, because of the highest quality protein, micro-nutrients, vitamin A and energy content. This can be misleading, if milk is consumed in very small amounts. (WFP 2008.) However, milk was the only animal-based food in the households' diet during the study periods and therefore it can be considered to improve their food security.

4.3 Enabling synergies and avoiding trade-offs

The most significant trade-off was caused by tree density and the proportion of large trees, which are increasing soil carbon sequestration while decreasing food security. Trade-offs usually occur, as certain tree species (e.g., *Eucalyptus*) or densely growing trees are reducing the crop yields. According to Bayala et al. (2014), the competition for growth resources may be reduced by tree management practices, such as crown pruning, root pruning and use of shade tolerant crops. Tree products, such as fruits may also compensate the loss in cereal production thus enhancing income security as well as food and nutrition security. Fruits also complement the cereal-based diet, which improves nutrition security (Bayala et al. 2014). In the long term, including agroforestry tree crops in seasonal agriculture may improve the systems' overall economic performance, even while understory crop production is reduced, as Rahman et al. (2016) discovered. However, short-term losses of agricultural income occurred. Carbon revenue is clearly needed to compensate income losses. According to Waldén et al. (2019) the carbon revenue was highest for the plot which contained *Coffea arabica L.*, fruits and vegetables. The plot with the lowest revenue was the plot with trees, such as *Jatropha curcas L., Sesbania sesban (L.) Merr.* and *Acacia Mill. spp*. Perennial trees and shrubs contributed, however, by more than 70 % of AFS revenue.

Plant species in AF system may have significant impact on possible synergies and trade-offs. *Eucalyptus* is a high value cash crop used for example for fuelwood, building material, medicine and honey production. Hence, it is contributing positively to income security of the farmers. Because of the consistent market, *Eucalyptus* trees yield more money for smallholder farmers than other tree crops. Also, selling leaves supports the livelihood of poor women. Trees are fast growing and survive in marginal environments, but also have remarkable consumption of water and nutrients. Therefore, it may out-compete agricultural crops for soil nutrients and is not recommended for intercropping with annual crops. (Parrotta 1999.) Synergies can be enabled by considering the utilization purpose of wood products. If trees are used as construction material instead of firewood, the carbon is stored for many years in the durable products. Usually, the price is better for timber, which improves the farmers' income security in a long term. (Reppin et al. 2019.)

Agro-environmental trade-offs could also be reduced by sustainable livestock intensification options. According to Paul et al. (2019), *Napier grass* can be cultivated on-farm and it can replace crop residues as a fodder. This improves milk production, which could have significant impact on household's food security, as was detected in Sidama. The crop residues can be left to the field, which leads to lower GHG emissions and improved N balances. *Calliandra calothyrsus* is fast growing fodder tree, that is tolerant to frequent pruning and droughts, and can be intercropped with *Napier grass* without depressing grass yields (Nyaata et al. 1998). In Kenya, hedges combining *Napier grass* and *Calliandra* reduced runoff and soil erosion while not reducing adjacent maize yields (Mutegi et al. 2008). Dried leaves can be fed to livestock and used as substitute for soybeans. *Calliandra* may increase milk and butterfat production of cows thus enhancing the farmers' income and food security (Place et al. 2009; Paterson et al. 1999). Also, it has been discovered to increase meat production effectively when fed to sheep and goats (Ebong et al. 2009).

Faidherbia albida is also a good example of a species with multiple benefits. It is leguminous nitrogen-fixing acacia-like species, which is indigenous all over Africa. It is dormant during wet seasons and drops leaves to fertilize associated crops. During the dry seasons, leaves grow providing fodder for livestock. There are approximately 500 000 farmers in Malawi, Tanzania and Zambia, who are cultivating crops under *Faidherbia* trees. The maize yields are reported to be doubled or tripled. (World Agroforestry Centre 2020.)

4.4 The way forward

This was a case study considering 15 households practicing multistrata agroforestry in northern and southern Ethiopia. The results can be applied in similar agroecological environments in east Africa. Out scaling for wider areas requires additional studies. Based on the overall results of this study, it can be deduced that households' income has significant impact on food security. Richness of the sold product categories determined both income security and food security. It did not have significant difference, how the categories were divided. However, additional studies are required to observe in more detail, how does diversity of the sold product categories affect food security. The quantitative analysis of this study showed negative correlation with food security, when the sold products were divided by botanical categories. Division into categories by intended use did not seem to have significant impact. Considering the small quantity of observations used in quantitative analysis these details should not have very much weight. Also, the contribution of legume trees should be analyzed more. Since legumes are used for increasing N availability, a larger share of legumes could be expected to increase yield production. Yet it did not seem to affect food security and had negative correlation with income security.

Conclusions

The sustainable agroforestry system, that is favourable for carbon sequestration, income security and food security was determined in this study. Households can improve their food security by focusing on farming several cash crops instead of striving to achieve self-sufficiency in staple food crops. Richness in sold product categories helps to compensate yield losses and effects of the price fluctuation. Also, keeping animals on farm and sustainable livestock intensification support economic situation and nutrition level of the households. Larger proportion of middle-sized trees on farms enhances carbon sequestration in aboveground biomass and improves crop yields. However, proper tree management practices should be applied to avoid competition between trees and crops. High tree density and larger share of trees with high basal diameter contribute positively to climate change mitigation but have negative impact on farmer's income and food security. Carbon revenue is needed to avoid trade-offs. In addition, utilization of wood products as timber instead of fuelwood should be preferred to prolong carbon sequestration.

REFERENCES

Abegaz, K.H. 2017. Determinants of food security: evidence from Ethiopian Rural Household Survey (ERHS) using pooled cross-sectional study. Agriculture and Food Security 6, 70 (2017). [Retrieved March 3, 2021]. From: https://doi.org/10.1186/s40066-017-0153-1

Alam, M. 2012. Valuation of tangible benefits of a homestead agroforestry system: A case study from Bangladesh. Human Ecology, 2012, 40, 639–645. [Retrieved March 3, 2021]. From: https://doi.org/10.1007/s10745-012-9512-5

Asfaw, Z. and Ågren, G.I. 2007. Farmers' local knowledge and topsoil properties of agroforestry practices in Sidama, southern Ethiopia. Agroforestry Systems, 2007, Vol. 71, 35-48. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s10457-007-9087-0

Bayala, J., Sanou, J., Teklehaimanot, Z., Kalinganire, A. and Ouédraogo, SJ. 2014. Parkland for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Current Opinion in Environmental Sustainability 2014, Vol. 6, 28-34. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.cosust.2013.10.004

Berg, B., Meentemeyer, V. and Johansson, M-B. 2000. Litter decomposition in a climatic transect of Norway spruce forests. Climate and lignin control of mass loss rates. Canadian Journal of Forest Research, 2000, Vol. 30, 1136-1147. DOI: 10.1139/cjfr-30-7-1136

Button, K.S., Ioannidis, J.P., Mokrysz, C., Nosek, B.A., Flint, J. and Robinson, E.S. 2013. Power failure: why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience, 2013; Vol. 14, 365. [Retrieved March 3, 2021]. From: https://doi.org/10.1038/nrn3475 PMID: 23571845

Colditz, G.A., Burdick, E. and Mosteller, F. 1995. Heterogeneity in meta-analysis of data from epidemiologic studies: a commentary. Am. J. Epidem, 1995, Vol. 142, 371–382. PMID: 7625401. DOI: 10.1093/oxfordjournals.aje.a117644

DeFries, R., Fanzo, J., Remans, R., Palm, C., Wood, S. and Anderman, T.L. 2015. Global nutrition. Metrics for land-scarce agriculture. Science, 2015, Vol. 349, 238-240. [Retrieved March 3, 2021]. From: https://www.researchgate.net/publication/280117533

Dossa, G.G.O., Paudel, E., Fujinuma, J., Yu, H., Chutipong, W., Zhang, Y., Paz, S., Harrison, R.D. and Swenson, N.G. 2013. Factors determining forest diversity and biomass on a tropical volcano, Mt. Rinjani, Lombok, Indonesia. PLoS one, 2013, Vol. 8, e67720. [Retrieved March 3, 2021]. From: http://dx.doi.org.ezproxy.cc.lut.fi/10.1371/journal.pone.0067720

Ebong, C., Byenkya, S.G. and Ndikumana, J. 2009. Effects of substituting Calliandra leaf meal for soybean meal on intake, digestibility, growth and feed efficiency in goats. Journal of Applied Animal Research, 2009, Vol. 16, 211-216. [Retrieved March 3, 2021]. From: https://doi.org/10.1080/09712119.1999.9706284

FAO. 2020. Food and Agriculture Organization of the United Nations. 2020. The state of food security and nutrition in the world 2020. Food and Agriculture Organization of the United Nations. [Retrieved March 3, 2021]. From: http://www.fao.org/3/ca9692en/online/ca9692en.html#

FAO. 2008. Food and Agriculture Organization of the United Nations. An Introduction to the Basic Concepts of Food Security. Food and Agriculture Organization of the United Nations. [Retrieved March 3, 2021]. From: http://www.foodsec.org/docs/concepts_guide.pdf

FAO. 1992. Mixed and pure forest plantations in the tropics and subtropics. FAO Forestry Paper 103. Food and Agriculture Organization of the United Nations, Rome. pp. 152. [Retrieved March 3, 2021]. From: http://www.fao.org/3/ap421e/ap421e00.pdf

Franzel, S., Carsan, S., Lukuyu, B., Sinja, J. and Wambugu, C. 2014. Fodder trees for improving livestock productivity and smallholder livelihoods in Africa. Current Opinion in Environmental Sustainability 2014, 6:98-103. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.cosust.2013.11.008

Gómez Cardozo, E., Mavisoy Muchavisoy, H., Rocha Silva, H., Zelarayán, Corrêa Zelarayán, M.L., Alves Leite, M.F., Rousseau, G.X. and Gehring, C. 2015. Species richness increases income in agroforestry systems of eastern Amazonia. Agroforestry Systems, 2015, Vol. 89, 1-16. [Retrieved March 3, 2021]. From: https://doi.org/10.1007/s10457-015-9823-9

Ioannidis, J.P. Why most published research findings are false. PLOS Medicine. 2005, Vol. 2, e124. [Retrieved March 3, 2021]. From: https://doi.org/10.1371/journal.pmed.0020124 PMID: 16060722

Intergovernmental Panel on Climate Change (IPCC). 2018. Special Report. Climate Change and Land.

Jenkins, D.G., Quintana-Ascencio, P.F. 2020. A solution to minimum sample size for regressions. PLoS ONE 15(2): e0229345. [Retrieved March 3, 2021]. From: https://doi.org/10.1371/journal.pone.0229345

Kabir, G.B., Azeez, F.A., Arowolo, O.V. and Nosiru, M.O. 2020. Determinants of Food Security among Forest-Based Households in Oyo State, Nigeria. Journal of Applied Sciences and Environmental Management 2020, Vol. 24, 1293-1298. [Retrieved March 3, 2021]. From: https://dx.doi.org/10.4314/jasem.v24i7.25

Kuria, A., Pagella, T., Muthuri, C. and Sinclair, F.L. 2019. Decreasing crop diversity leads to food insecurity and off-farm food reliance and varies with land degradation status. 4th World Congress on Agroforestry. Montpellier, France. 20-22 May 2019. [Retrieved March 3, 2021]. From:

https://www.alphavisa.com/agroforestry/2019/documents/Agroforestry2019-Book-of-Abstract-v1.pdf

Kuyah, S., Dietz, J., Catherine, M., Jamnadassa, R., Mwangi, P., Coe, R. and Neufeldt, H. 2012. Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agriulture, Ecosystems & Environment 2012, Vol. 158, 216– 224. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.agee.2012.05.011

Kuyah, S., Withney, C. W., Jonsson, M., Sileshi, G.W., Öborn, I., Muthuri, C.W. and Luedeling, E. 2019. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agronomy for Sustainable Development, 2019, Vol. 39. https://doi-org.ezproxy.cc.lut.fi/10.1007/s13593-019-0589-8

Lal, R. 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. American Association for the Advancement of Science, Washington, 2004, Vol. 304, 1623-1627. [Retrieved March 3, 2021]. From: https://ezproxy.cc.lut.fi/scholarly-journals/soil-carbon-sequestration-impacts-on-global/docview/743448360/se-2?accountid=27292

Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, E., Minang, P.A. and Kowero, G. 2014. Agroforestry solutions to address food security and climate change challenges in Africa. Current Opinion in Environmental Sustainability, 2014, Vol. 6, 61–67. [Retrieved March 3, 2021]. From: http://dx.doi.org/10.1016/j.cosust.2013.10.014

Mebrate, B.T. 2007. Agroforestry practices in Gedeo zone Ethiopia a geographical analysis. PhD Dissertation, Panjab University, Chandigarh.

Mehta, N., Pandya, N.R.V, Thomas, O. and Krishnayya, N.S.R. 2014. Impact of rainfall gradient on aboveground biomass and soil organic carbon dynamics of forest covers in Gujarat, India. Ecological Research, 2014, Vol. 29, 1053–1063. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s11284-014-1192-8

Melaku, E., Ewnetu, Z. and Teketay, D. 2014. Non-timber forest products and household incomes in Bonga forest area, southwestern Ethiopia. Journal of Forestry Research, 2014, Vol. 25, 215-223. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s11676-014-0447-0

Mulugeta, L., Karltun, E. and Olsson, M. 2005. Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia. Agriculture, Ecosystems & Environment, 2009, Vol. 109, 9-19. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.agee.2005.02.015

Mutegi, J., Mugendi, D., Verchot, L., Kung'u, J. 2008. Combining napier grass with leguminous shrubs in contour hedgerows controls soil erosion without competing with crops. Agroforestry Systems, 2008, Vol. 74, 37–49. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s10457-008-9152-3

Nair, P.K.R. 1991. State-of-the-art of agroforestry systems. Forest Ecology and Management, 45, 5–29. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/0378-1127(91)90203-8

Negash, M., Kaseva, J. and Kahiluoto, H. 2021. Determinants of carbon and nitrogen sequestration in multistrata agroforestry. (Submitted)

Negash, M. and Starr, M. 2013. Litterfall production and associated carbon and nitrogen fluxes of seven woody species grown in indigenous agroforestry systems in the Rift Valley escarpment of Ethiopia. Nutrient Cycling in Agroecosystems, 2013, Vol. 97, 29–41. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s10705-013-9590-9

Negash, M. 2013. The indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia: Their biodiversity, carbon stocks, and litterfall. Tropical forestry reports no. 44. Doctoral thesis, University of Helsinki.

Negash, M., Yirdaw, E. and Luukkanen, O. 2012. Potential of indigenous multistrata agroforests for maintaining native floristic diversity in the south-eastern Rift Valley escarpment, Ethiopia. Agroforestry Systems, 2012, Vol. 85, 9–28. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s10457-011-9408-1

Ng'endo, M., Keding, G.B., Bhagwat, S. and Kehlenbeck, K. 2015. Variability of on-farm food plant diversity and its contribution to food security of smallholder farming households in Western Kenya. Agroecology and Sustainable Food Systems, 2015, Vol. 39, 1071-1103. [Retrieved March 3, 2021]. From: http://dx.doi.org/10.1080/21683565.2015.1073206

Nguyen, Q., Hoang MH., O'born, I. and Noordwijk, MV. 2013. Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. Climatic Change 2013, Vol. 117, 241-257. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1007/s10584-012-0550-1

Nyaata, O.Z., O'Neil, M.K. and Roothaert, R.L. 1998. Comparison of Leucaena leucocephala with Calliandra calothyrsus in Napier (Pennisetum purpureum) fodder banks. In Leucaena-adaptation quality and farming systems, ACIAR Proceedings, Vol. 86. Proceedings of a workshop held in Hanoi, Vietnam, 9–14 February. Edited by Shelton HM, Gutteridge RC, Mullen BF, Bray RA. 1998:257–260.

Oduniyi, O.S. and Tekana, S.S. 2020 Status and socioeconomic determinants of farming households' food security in Ngaka Modiri Molema district, South Africa. Social Indicators Research, 2020, Vol. 149, 719–732. [Retrieved March 3, 2021]. From: https://doi.org/10.1007/s11205-020-02266-2

Parrotta, J.A. 1999. Productivity, nutrient cycling, and succession in single- and mixed-species plantations of Casuarina equisetifolia, Eucalyptus robusta, and Leucaena leucocephala in Puerto Rico. Forest Ecology and Management, 1999, Vol. 124, 45-77. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/S0378-1127(99)00049-3

Paterson, R.T., Kiruiro, E. and Arimi, H.K. 1999. Calliandra calothyrsus as a supplement for milk production in the Kenya Highlands. Tropical Animal Health and Production, 1999, Vol. 31, 115-126. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1023/A:1005119808090

Paul, B., Groot, J., Birnholz C., Nzogela, B., Notenbaert, A., Woyessa, K., Sommer, R., Nijbroek, R. and Tittonell, P. 2019. Reducing agro-environmental trade-offs through sustainable livestock intensification across smallholder systems in Northern Tanzania. International Journal of Agricultural Sustainability, 2019, Vol. 18, 35-54. [Retrieved March 3, 2021]. From: https://doi.org/10.1080/14735903.2019.1695348

Place, F., Roothaert, R., Maina, L., Franzel, S., Sinja, J. and Wanjiku, J. 2009. The impact of fodder shrubs on milk production and income among smallholder dairy farmers in East Africa and the role of research undertaken by the World Agroforestry Centre. Occasional Paper 12. World Agroforestry Centre, 2009.

Rahman, S.A., Baldauf, C., Mollee, E.M., Pavel, M.A.A., Mamun, M.A.A., Toy, M.M., Sunderland, T. 2013. Cultivated plants in the diversified homegardens of local communities in Ganges Valley, Bangladesh. Science Journal of Agricultural Research & Management, 2013, 1–6. [Retrieved March 3, 2021]. From: https://doi.org/10.7237/sjarm/197

Rahman, S.A., Sunderland, T., Kshatriya, T., Roshetko, J.M., Pagella, T. and Healey, J.R. 2016. Towards productive landscapes: trade-offs in tree-cover and income across a matrix of smallholder agricultural land-use systems. Land Use Policy. 58: 152-164. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.landusepol.2016.07.003

Reppin, S., Kuyah, S., De Neergaard, A., Oelofse, M. and Rosenstock, T.S. 2019. Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. Agroforestry Systems, 2020, Vol. 94, 203-220. [Retrieved March 3, 2021]. From: https://doi.org/10.1007/s10457-019-00383-7.

Richards, M.B. and Mendez, V.E. 2013. Interactions between carbon sequestration and shade tree diversity in smallholder coffee cooperative in El Salvador. Conservation Biology, 2014, Vol. 28, 489-497. [Retrieved March 3, 2021]. From: https://doi-org.ezproxy.cc.lut.fi/10.1111/cobi.12181

SAS Institute Inc (SAS). 2019. SAS/STAT User's Guide. The PLS Procedure. [Retrieved March 3, 2021]. From: https://documentation.sas.com/?cdcId=pgmsascdc&cdcVersion=9.4_3.4&docsetId=statug&docsetTarget=statug_pls_examples.htm&locale=en

Stafford Smith, M. and Mbow, C. 2014. Editorial overview: Sustainability challenges: Agroforestry from the past into the future. Current Opinion in Environmental Sustainability, 2014, Vol. 6, 134-137. [Retrieved March 3, 2021]. From: http://dx.doi.org/10.1016/j.cosust.2013.11.017

Thangataa, PH. and Hildebrand PE. 2012. Carbon stock and sequestration potential of agroforestry systems in smallholder agroecosystems of sub-Saharan Africa: mechanisms for 'reducing emissions from deforestation and forest degradation' (REDD+). Agriculture, Ecosystems & Environment, 2012, Vol. 158, 172-183. [Retrieved March 3, 2021]. From: https://doi.org/10.1016/j.agee.2012.06.007

Theobald, T.F.H., Mussgnug, F. and Becker, M. 2014. Live fences – a hidden resource of soil fertility in West Kenya. Journal of Plant Nutrition and Soil Science. 2014, Vol. 177, 758–765. [Retrieved March 3, 2021]. From: https://doi.org/10.1002/jpln.201300232

United Nations World Food Programme. 2008. Food Consumption Score. Calculation and use of the food consumption score in food security analysis.

Waldén, P., Negash, M., Kaseva, J. and Kahiluoto, H. 2021. Determinants of the economy in multistrata agroforestry. (Manuscript)

Waldén, P., Ollikainen, M. and Kahiluoto, H. 2019. Carbon revenue in the profitability of agroforestry relative to monocultures. Agroforestry Systems, 2020, Vol. 94, 15–28. [Retrieved March 3, 2021]. From: https://doi.org/10.1007/s10457-019-00355-x

United Nations World Food Programme (UNWFP). 2008. Food consumption analysis. Calculation and use of the food consumption score in food security analysis. Technical Guidance Sheet.

World Agroforestry Centre. 2020. Faidherbia Albida - Keystone of Evergreen Agriculture in Africa. [Retrieved March 3, 2021]. From: https://www.worldagroforestry.org/sites/default/files/F.a_keystone_of_Ev_Ag.pdf

Woolf, D., Solomon, D. and Lehmann, J. 2018. Land restoration in food security programmes: synergies with climate change mitigation. Climate Policy, 2018, Vol. 18, 1260-1270. [Retrieved March 3, 2021]. From: https://doi.org/10.1080/14693062.