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Determinants of the economy in multistrata agroforestry in Ethiopia

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ABSTRACT

Agroforestry represents a potentially multi-beneficial approach to land management as it may enhance a farming household's income and income stability simultaneously with nutrition security and climate change mitigation. However, our comprehension of the specific characteristics within agroforestry systems that bolster economic productivity remains limited, exacerbating the challenges of land management for smallholder livelihoods. This complexity is compounded by the potential influence of carbon revenue, adding an additional layer of intricacy to the equation. This paper aimed to identify the key economic determinants of multistrata agroforestry in sub-Saharan Africa with and without potential carbon revenue. A quantitative survey of 135 farmers was performed regarding their multistrata agroforestry systems with contrasting histories in three regions of Ethiopia. The carbon sequestration rate and carbon stocks in agroforestry were assessed on one-fifth (27) of the farms. The relative importance of hypothetical determinants of agroforestry systems' economic performance was modeled using descriptive statistics and generalized linear models. Farm size and fertilizer usage were the primary drivers of the farm economy, but farm net income was also highly influenced by the richness and diversity of the income sources. In addition, tree diversity had a positive impact on the net income, whereas the proportion of legume trees and trees with a large diameter correlated negatively with the income. Potential carbon revenue at prices of US\$40 tCO_2^{-1} and US\$100 tCO_2^{-1} increased income for multistrata agroforestry farms without significantly changing the magnitude of the identified key determinants. This suggests that the most economically viable agroforestry systems inherently possess a strong capacity for carbon sequestration, effectively serving as carbon sinks. Consequently, carbon revenue serves as a compelling financial incentive for the adoption of these agroforestry systems. Ultimately, this research underscores the pivotal role of biological and product diversity in shaping economic productivity within multistrata agroforestry systems. Moreover, it highlights the accessibility of diversity management for smallholder farmers, even under conditions of resource constraints.

1. Introduction

Agriculture is the main source of employment and income in sub-Saharan Africa (SSA), like in many developing economies. For example, in Ethiopia, agriculture provides the livelihood for approximately 75% of the population but suffers from the shrinkage and degradation of arable land as well as from a lack of relevant agricultural technology and inputs (USAID, 2022; Sanchez, 2015). Despite relatively high economic growth (African Development Bank Group, 2022) and efforts to improve farmers' living standards, poverty and food insecurity remain common especially in rural areas (Hansen et al., 2019). Thus, new insights into agriculture are needed to enhance livelihoods and food security in SSA and elsewhere in the developing world.

Agroforestry shows promise as a means to enhance yields and farmers' income (Hansen et al., 2019; Martinelli et al., 2019a; Waldén et al., 2019; Leakey, 2010; Verchot et al., 2007; Garrity, 2006) as well as food security (Duffy et al., 2021; Bayala et al., 2014; Mbow et al., 2014). Agroforestry also can maintain a notable part of forest carbon and nitrogen stocks (Negash et al., 2022a) and possesses the highest carbon sequestration rates and carbon stocks of food production systems in the

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tropics (Toensmeier, 2017; Rimhanen et al., 2016). Thus, agroforestry has the potential to be one of the most effective ways to increase agricultural productivity and income in rural areas, while also contributing to climate change mitigation (Martinelli et al., 2019b; Jose, 2009). Furthermore, carbon sequestration increased by agroforestry could allow carbon income in case of access to carbon markets (Waldén et al., 2019; Roshetko et al., 2007).

Multistrata agroforestry systems are complex tree-dominated land use systems with two or more strata of trees, shrubs, and herbaceous plants, and commonly practiced in most tropical and subtropical countries. These intensive land management systems can either originate from a native forest or be planted adding a range of under- and overstorey species and be managed with or without livestock. Multistrata agroforestry commonly produces timber or fuelwood, fodder for livestock, and fruits, vegetables, legume crops, grains, and stimulants for sustenance and income. The diversity of plants and products in addition to malleable harvest times provide flexibility and continuity for income generation and can prevent crop losses caused by pests, diseases, and drought (Núñez et al., 2023; Wan et al., 2016). Agroforestry can thus provide resilience to climate change as well as to market price volatility.

Climatic and edaphic conditions, plant species composition and diversity, in addition to management intensity influence the productivity and economic performance of multistrata agroforestry (Gómez et al., 2015; Rahman et al., 2013; Alam, 2012). Cardozo et al. (2015) discovered that an increase in species richness and diversity positively affected the net income of agroforestry farms in eastern Amazonia. According to Neupane and Thapa (2001), especially multifunctional trees could enhance the profitability of an agroforestry system. Additionally,

Fig. 1. a) The three study regions (Google map), and pictures of multistrata agroforestry in b) Fenote-Selam, c) Wonsho-Sidama, d) Haru-Gedeo.

socio-economic attributes such as the size of landholding and livestock (Sadeghi et al., 2001) as well as the farmer's education level and age have been found to influence the income of the farms practicing agroforestry (Safa, 2004; Phandanouvong, 1998). While some sporadic determinants of income from agroforestry have been shown, the relative importance of potential determinants, including aspects of diversification and potential access to carbon markets, and the profitability of multistrata agroforestry have not been systematically investigated to date (Waldén et al., 2019).

To ensure the vitality of multistrata agroforestry systems and to create incentives for smallholder communities to maintain or convert to these systems, it is essential to understand the current economic determinants and potential economic impact of carbon revenue. Since this knowledge is lacking, the objective of this study was to empirically identify the key determinants of income generation from multistrata agroforestry systems in the subtropical highlands of eastern Africa.

2. Materials and methods

2.1. Study regions

The study was conducted in three Ethiopian regions, northwestern Fenote-Selam (10°40′–10°42′ N, 37°11′–37°15′ E), southeastern Haru-Gedeo (5°50'– 6° 12' N, 38° 03'–38°18'E) and southcentral Wonsho-Sidama (7°00′–7°06′N, 38°34′—38°37′E) (Fig. 1). The three study regions were purposively selected for spatial representativeness of mid-altitude (1885–2065 m), sub-humid, subtropical multistrata agroforestry with contrasting multistrata agroforestry histories, traditions, and

Table 1
Characteristics of the studied farms and their agroforestry systems in the three regions.

a. Social farm characteristics.

Variable	Haru-Gedeo			Wonsho-Sidama			Fenote-Selam		
	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max
Age of respondent[1] (years)	43.6	13.9	20–84	43.5	13.1	25–78	47.9	11.7	24–75
Gender[2] of respondent[1]	1.13	0.34	1–2	1.38	0.49	1–2	1.18	0.39	1–2
Education level[3]	1.73	0.89	1–4	2.42	0.87	1–3	2.02	1.71	0–6
Household size (number of members)	7.71	3.42	2–20	7.29	2	4–13	6.84	2.39	2–11
Cash crop cultivation method[4]	2	0	2–2	1.65	0.48	1–2	1.55	0.48	1–2

b. Farm resources.

Variable	Haru-Gedeo			Wonsho-Sidama			Fenote-Selam		
	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max
Farm size (ha)	0.68	0.73	0.1–3.5	0.61	0.37	0.25–2	1.27	0.63	0.4–4
Labor (monthly)[5]	1.44	1.49	1–10	2.04	1.17	1–6	1.2	0.76	0–3
Labor (main harvest)[5]	3.98	3.92	0–20	3.76	4.6	1–32	3.91	1.95	1–10
Fertilizer use (kg)[6]	3.29	11.27	0–50	38.4	48.5	0–200	507	268	0–1500
Livestock holding[7]	6.11	4.23	0–16	8.02	11.8	0–80	12.7	12.9	1–88
Production richness[8]	9.47	2.91	1–14	10.2	2.43	5–15	8.18	1.98	4–11
Production diversity[9]	1.55	0.53	0–2.24	1.38	0.45	0–2.1	1.48	0.29	0.42–2.06

c. Bio-physical characteristics of the agroforestry systems.

Variable	Haru-Gedeo			Wonsho-Sidama			Fenote-Selam		
	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max
Altitude (m)[10]	1941	15.4	1913–193	2043	22.7	2001–2062	1891	3.9	1886–1899
Duration (years)[10]	37.6	11.3	10 – 45	45.4	7.9	32 – 54	26	5.4	19–35
Tree density (stems ha^{-1})[10]	367	150	200 – 667	200	72.7	100–300	785	429	400–1667
Tree species richness	6.4	1.8	2 – 9	4.6	1.76	1 – 8	4.89	1.57	1–8
Tree species diversity	1.47	0.33	0.41–1.99	0.81	0.5	0–1.81	0.64	0.43	0–1.37
Legume trees (%)	39.8	18.4	1.74–85.7	12.7	19.5	0 – 100	5.55	11.6	0–47.4
Diversity of basal area[10]	0.71	0.27	0.24–0.94	0.43	0.14	0.2–0.65	0.61	0.32	0–1.03
Basal diameter >10 cm[10]	0.47	0.3	0–0.89	0.42	0.31	0.13–0.97	0.44	0.32	0–0.84
Basal diameter >25 cm[10]	0.77	0.16	0.59–0.99	0.97	0.05	0.83 – 1	0.7	0.23	0.25–0.97

d. Economic characteristics of the agroforestry systems.

Variable	Haru-Gedeo			Wonsho-Sidama			Fenote-Selam		
	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max	Mean	Std Dev	Min-Max
Annual income (US$)	377	343	14.4–1943	480	423	0–2069	2314	1582	505–6688
Main crop income (US$)									
Coffee	407	351	47–1943	348	293	116–849	-	-	-
Chili pepper	-	-	-	-	-	-	2326	1603	505–6688
Khat	-	-	-	438	436	0–2069	-	-	-
Other	141	110	14–290	648	419	0–1291	2065	1447	1042–3088
Annual costs (US$)	3.61	8.9	0–39.8	30.3	33.6	0–134	374	141	100–742
Income categories richness (intended use)[11]	3.18	1.07	1–4	2.96	1.21	0–5	3.69	1.04	1–5
Income categories richness (biology)[11]	2.02	0.66	1–3	2.13	0.89	0–4	3.71	0.63	1–4
Income categories diversity (intended use)[11]	0.7	0.39	0–1.24	0.63	0.39	0–1.29	0.72	0.3	0–1.25
Income categories diversity (biology)[11]	0.34	0.27	0–0.81	0.43	0.34	0–1.31	0.89	0.3	0–1.35

[1] Financially responsible for the farm; [2] Male =1, female=2; [3]Illiterate=1, vocational=2, senior=3, tertiary=4.
[4] Cash crops cultivated separately=1, in mixtures with trees (multilayer) =2.
[5] Number of household members;[6] Di-ammonium phosphate; [7] Number of animals; [8] Number of the sold products; [9] Shannon-Diversity index of the sold products.
[10] Hypothetical determinants of the income in the analysis including potential carbon revenue.
[11] Categories of the sold products (see Table 2).

proximity to markets. The agroforestry systems in Haru-Gedeo and Wonsho-Sidama evolved by gradually and selectively removing trees from natural forests and intensifying land use (Negash et al., 2012; Asfaw and Ågren, 2007), while deliberately retaining some native trees and shrubs. In Fenote-Selam, trees and shrubs are added to mixed-farming that combines cereal-based cropping with grazing animals, and multistrata agroforestry appears either spatially fully integrated or with the different strata spatially separated within the agroforestry farms.

The farms are managed by family labor (Table 1a) and the size of the farm holdings in the study area vary from 0.1 ha to 4 ha (Table 1b). Owing to the high population density in the southern Haru-Gedeo and Wonsho-Sidama regions, the farm holdings are smaller there than in the north. Coffee is the most prevalent cash crop on the three sites, as generally in Ethiopia, and it is mostly cultivated as an organic product. Farmers in Sidama also produce other cash crops such as khat (*Catha edulis* Forskal), and in Fenote-Selam chili pepper (*Capsicum* spp.). Teff grain is the most prevalent native food crop in the Fenote-Selam, and enset (*Ensete ventricosum* (Welw.) Cheesman), known as the false banana, in Haru-Gedeo and Wonsho-Sidama regions, due to its robustness to weather extremes and high starch content of all the plant organs (Brandt et al., 1997) as well as due to local culinary habits. The agroforestry systems in Haru-Gedeo are structurally the most complex ones in Ethiopia (Bishaw et al., 2013) and unlike in other agroforestry systems, annual and perennial food crops and fruit trees are cultivated together in several strata. In Wonsho-Sidama approximately one-third and in Fenote-Selam about half of the agroforestry farmers' cash crops are cultivated on separate plots.

The tree density (stems ha^{-1}) in the agroforestry of Fenote-Selam is two to four times higher than in Haru-Gedeo and Wonsho-Sidama, respectively (Negash et al., 2022b). Inorganic fertilizer (di-ammonium phosphate) use is most common in Fenote-Selam and is mainly applied for separate chili pepper and cereals (maize, teff, wheat) plots. Fertilizers are used to some extent in Wonsho-Sidama primarily for separate maize plots. Synthetic fertilizers are not applied in most of the studied farms in Haru-Gedeo. Organic residues such as crop and house residues, and slashed weeds, in addition to enset and tree foliage, are used in all the study sites. Agriculture in the selected sites, as generally in Ethiopia, is mostly rainfed; irrigation was found only in Fenote-Selam.

The annual net income in the northern study area, Fenote-Selam, is significantly higher than in the other regions. This was mainly due to the sale of chili pepper and other products rather than cash crops such as coffee and khat which were less prevalent in this area (Table 1d). Fenote-Selam also has the highest average richness (number) of the income categories both based on biology and the intended use of the products (Table 2). The most noticeable variation in the annual net income between the farms in the same study area can be found in Wonsho-Sidama.

2.2. Hypothetical determinants

In the first phase where the carbon revenue was not assumed, we used multiple regression analyses to estimate the relationship between the farms' net income and hypothetical determinants, i.e., potential explanatory variables. The hypothetical determinants were the social farm characteristics, farm resources and the bio-physical and economic characteristics of the agroforestry systems as presented in Table 1. The recorded income characteristics were the revenue and cost of the products, the composition of income sources and dominant income sources. To analyze the impact of the income source diversity in more detail, we divided the farms' products into five categories by their intended use, and into four categories by their biology (Table 2). Income richness represents the number of categories, while income diversity was evaluated accounting for both the richness and evenness (the proportions of the categories) using the Shannon diversity index.

To identify the determinants of the farms' net income including

Table 2
The income source categories for the sold products. The income sources of the farms were divided into different categories based on the intended use and biology of the products. Income richness (number of the categories) and income diversity (number and proportions of the categories) were used as hypothetical determinants in the analysis of the net income.

Criteria	Categories	Products
Intended use	Staple food crops	Maize, enset, teff (*Eragrostis teff*), wheat (*Triticum spp. L*)
	Nutritionally important crops (vegetable, fruit, legume)	Haricot beans (*Phaseolus vulgaris L.*), millet (*Eleusine coracana L. Garten*), sunflowers (*Helianthus annuus L.*), avocados *(Persea americana)*, bananas, gishta (*Annona spp.*), grawa (*Vernonia amygdalina)*
	Animal products (eggs, milk, meat)	Sheep, cows, goats, chickens, oxen
	Cash crops	Coffee, khat, chili pepper
	Wood products (firewood & timber)	*Cordia africana*, eucalyptus, *Millettia ferrugnia*
Biology	Annual crops/cereal crops	Maize, teff (*Eragrostis teff*), wheat (*Triticum spp. L*), millet (*Eleusine coracana L. Garten)*, sunflowers (*Helianthus annuus L.*)
	Woody plants	Khat, coffee, grawa (*Vernonia amygdalina), Cordia Africana, Millettia ferrugnia*, gishta (*Annona spp.*, avocados *(Persea americana)*, eucalyptus
	Herbaceous perennials	Enset, chili pepper, bananas
	Livestock	Sheep, cows, goats, chicken, oxen

potential carbon revenue, we added the determinants that were known to affect carbon stocks of the carbon sample farms (Negash et al., 2022b). These hypothetical determinants added during the analysis were as follows: the duration of agroforestry in years; the tree density (number of stems); the proportion of stems with basal diameter >10 cm and >25 cm (%); the species diversity based on plant basal diameter ($H_b = -\sum p_i \ln(p_i)$, i=1,…, N, where p_i is the proportion of basal diameter of the *i*th species, diameters <2.5 cm excluded); the soil texture; the pH; and the altitude (Table 1c).

2.3. Data collection

2.3.1. Financial data

We collected all socioeconomic data via semi-structured interviews with open questions by interviewing the persons financially responsible for each farm (male 104, female 31). We interviewed a total of 135 (45 ×3 sites) randomly selected households practicing agroforestry and 15 (5 ×3 sites) key informants during the years 2014, 2015 and 2016. Production and economic data from at least two years were utilized. The said years' data depended on the harvesting and marketing season of each product and study site.

The key informants were selected based on the number of recommendations using the snowball sampling method from a group of community-recommended farmers. The key informants were defined as those who had general knowledge about the farming practices and agricultural economy of each study site. To identify individual farmers who could pinpoint key informants, a guided tour of the village was conducted with the chairmen and development agents from selected Kebeles, which are the smallest administrative units in Ethiopia. During the guided tour, at least five individual farmers were randomly asked to give the names of six key informants based on the stated criteria. Finally, 30 key informants were identified including five key informants with the highest scores per kebele (site).

2.3.2. Carbon sequestration

The carbon sequestration of 27 randomly selected farms (9 farms x 3 sites), representing one-fifth of the 45 farms at each site, was assessed.

The methods and data are presented in full detail in Negash et al. (2022b). The potential carbon sequestration rate for the agroforestry plots was calculated by comparing the carbon stock of each agroforestry plot (which was assessed by averaging the carbon stock of three sub-plots, each with ten samples) to the baseline carbon stock of an adjacent plot of a similar size that was dominated by monocultures in each region. This value was then divided by the duration of the agricultural practice currently in place. The agricultural practice was represented by the monocropped plot in Wonsho-Sidama and Haru-Gedeo and by the agroforestry plot in Fenote-Selam. The monocropped adjacent plot was in the case of Wonsho-Sidama represented by khat, in Haru-Gedeo by maize and in Fenote-Selam by maize, wheat, and pepper. The duration of the sampled agroforestry systems varied from 10 to 54 years across the selected sites and from 20 to 72 years for the adjacent monocropped plots.

The agroforestry plots were selected to represent the available range within the hypothetical determinants. Within each agroforestry plot, three plots (10 m x 10 m) were randomly assigned for sampling. These plots served both perennial species inventory and soil sampling. The location of the plot was assigned using an ocular method to divide the farm into ten grid points. Then, the sample point was selected by lottery through assigning a random number to each grid point. For the agroforestry plots, all woody species ≥2.5 cm in breast-height diameter (1.3 m) and ≥1.5 m in height growing on the plots were inventoried. For both agroforestry and adjacent monocropping, five sub-plots (1 m × 1 m) were laid down at the corners and center of a bigger plot (10 m x 10 m) for soil sampling (0–20 cm and 20–40 cm layers) and a random number was assigned to each sub-plot among which three sub-plots were randomly selected using a lottery system. The collected composite soils were used to assess soil organic matter (SOC). Furthermore, soil samples for bulk density analysis were separately collected from each sub-plot and both soil depths.

The aboveground biomass of trees and shrubs was assessed following the allometric equation developed by Kuyah et al. (2012). A biomass C content of 48% was used for trees and shrubs grown in agroforestry systems (Kuyah et al., 2012), 49% for coffee (Negash et al., 2013a), and 47% for enset (Negash et al., 2013b). The primary SOC calculation (t ha^{-1-1}) was done by using the fixed depth method where the concentrations (%) of soil C or N were multiplied by the bulk density and the depth of the sampled soil, i.e., SOC or SON, Mg ha^{-1} = C or N (%) × ρ × z × 100 (Solomon et al., 2002).

2.4. Assessment of net income and potential carbon revenues

The annual net income for multistrata agroforestry was expressed as follows,

$$NI = Rev - Exp$$

where *NI* denotes the annual net income for multistrata agroforestry, while *Rev* indicates the total revenues and *Exp* the total expenses.

The annual net income with carbon revenues was expressed as follows,

$$NI_{CR} = (Rev + CR_p) - Exp$$

where NI_{CR} denotes the annual net income with added carbon revenue, *Rev* indicates the total revenues, *CR* indicates the potential carbon revenues with the price of *p* and *Exp* indicates the total expenses.

2.5. Statistical analysis

Generalized linear models (GLMs) were used in the analysis of the farm net incomes with and without carbon revenues because the random effect of the study region was estimated to be zero in all cases. The sample size of carbon price data (N=27) was substantially smaller than in the main analysis (N=135). A natural log transformation was applied to net income and farm size due to skewed distributions. Four models were formed for both datasets, one for each alternative measure of diversity. All hypothetical determinants and their second-order interactions were included and excluded individually if no statistical significance was found in the models. Afterward, a stepwise method of the model selection procedures was used to check if all significant effects were included in the models. A significance level of α=0.10 was used in model selection, but the default option of α=0.15 in SAS for stepwise selection, respectively.

The possible multicollinearity issue of the determinants was studied through variance inflation factor (VIF), where values over 10 indicate a high correlation and can thus be considered as a cause of concern. The values 2.5 and 5 can also be used as more conservative limits. No violations were found even at these more conservative limits. The residuals were checked for normality using a boxplot and plotted against the fitted values, and they indicated that the assumptions of the models were adequate. R^2-values were calculated for each model. The interpretations of the significant determinants are presented in percentage change for the dependent variable, because of the logarithmic form of the models. The analyses were performed using the GLIMMIX, GLM and GLMSELECT procedures of the SAS Enterprise Guide 7.1 (SAS Institute Inc., Cary, NC, USA). The correlation matrix was plotted using R package psych (R Core Team, Version 4.0.2).

3. Results

3.1. Determinants of the net income

In the analysis of the 135 farms where a carbon income was not assumed, the highest positive correlation with the net income appeared with the richness and diversity of the income sources, farm size and fertilizer usage (Fig. 2). The strongest negative correlation appeared with the proportion of legume trees. The models for each alternative measure of income diversity consisted of four hypothetical determinants: farm size, the proportion of legume trees, fertilizer usage with its second-order polynomial and the chosen measure of diversity (Table 3). The models explained 73–77% of the variation in the net income. Diversity measures (richness/diversity) explained the farms' net income statistically significantly ($p<0.01$), except for biology-based income diversity with only a tendency to the significance ($p=0.109$).

The magnitude of the income increased as the number and variety of the income source categories grew. An increment of one unit in the number of intended use and biology categories increased the income by 29% and 42%, respectively. Due to every 10% increase in true diversity, the net income increased 4.6% and 2.9%, respectively, for the intended use and biology categorization.

Regarding the intended use of the products, the average was 3.3 categories per farm: 14% of households had two categories of income sources, 25% of households had three, 43% of households had four and 10% had all five categories of income sources (see Table 1d for the three regions). The three most common income categories were animal products, cash crops and staple food crops. The most common biological categories were woody plants, livestock, and herbaceous plants. Among the households, the average was 2.6 categories per farm: 40% had two categories of income sources, 17% had three and 30% of households had all four categories.

As shown in Table 3 and Fig. 3a and 3b, there were no remarkable differences between the models regarding the other key determinants' impact on the net income. However, the models where the richness of the income sources based on biology and intended use categories were used as diversity measures, explained the variation in the net income best.

3.2. Determinants of net income depending on carbon stock and prices

In the analysis of the 27 farms where the contribution of carbon

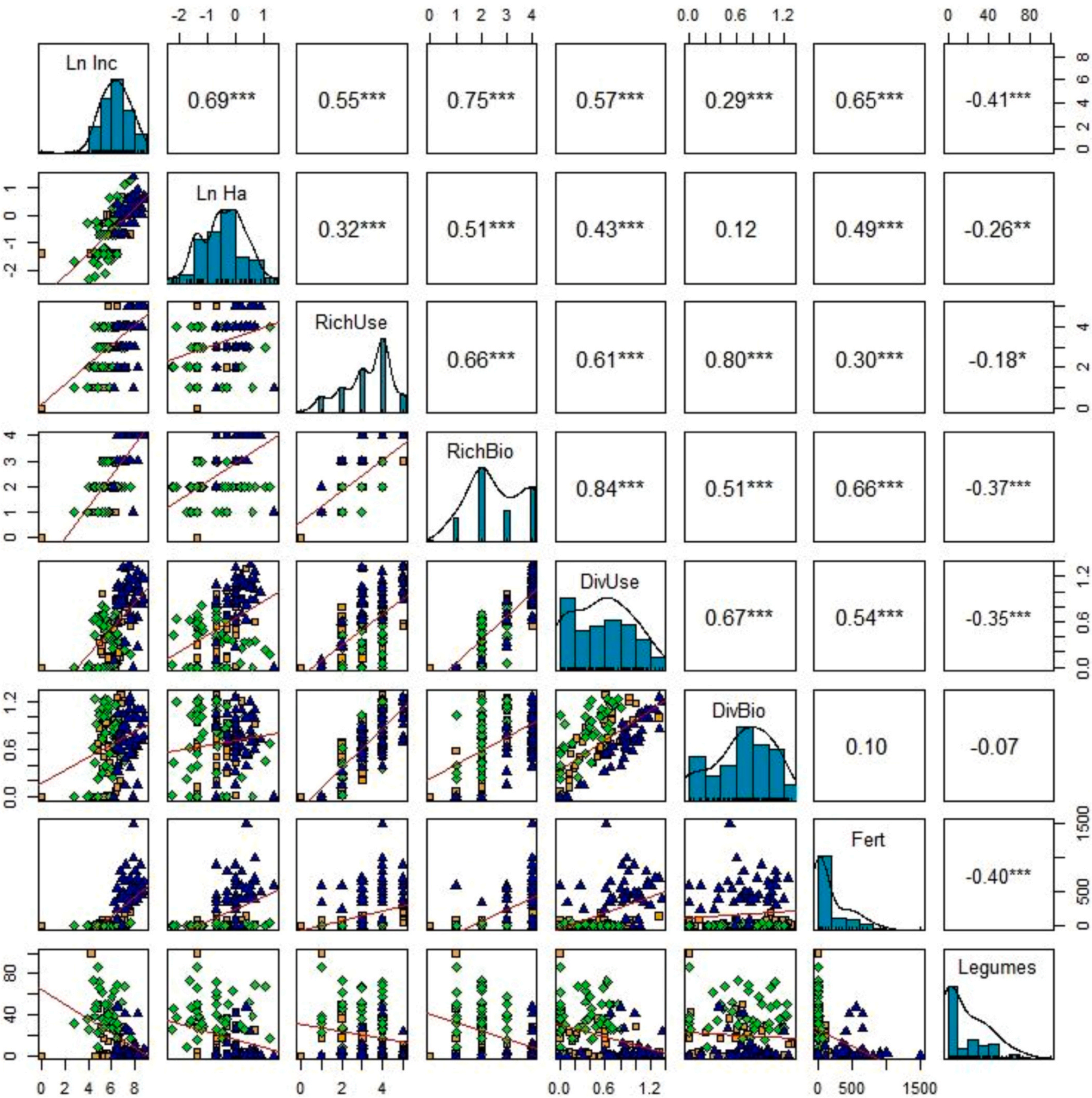


Fig. 2. Correlation matrix of the main continuous variables: the farm's net income (Ln Inc), farm size (Ln Ha), richness of the income source categories by intended use (RichUse), richness of the income source categories by biology (RichBio), diversity of the income source categories by intended use (DivUse), diversity of the income source categories by biology (DivBio) and fertilizer usage (Fert). The color codes of the study regions are as follows: blue=Fenote-Selam; green=Haru-Gedeo; orange=Wonsho-Sidama.

income (US\$0 vs. US\$40 vs. US\$100 tCO_2^{-1}) was compared, the data were significantly smaller since only one-fifth of the farms were representatively sampled for assessing the carbon stock. Since income diversity explained less of the variation and did not affect the net income statistically significantly, we only show two alternative models which differ by the richness of income sources in terms of a) biology and b) intended use (Table 4, Fig. 4). The variance explained by the models was 87–89%.

When the previously shown determinants of the carbon stock (Negash et al., 2022b; Table 1c) were added to the analysis where the net income was calculated (Table 4) excluding (A) or including carbon revenue of US\$40 tCO_2^{-1} (B) or of US\$100 tCO_2^{-1} (C), the tree diversity, and the proportion of trees with a basal diameter of >25 cm, were also found as determinants with statistical significance. However, no statistical significance of the basal diameter was found irrespective of the richness criterion (biology vs. intended use) with a carbon price of US\$100 tCO_2^{-1} ($p > 0.23$). Consequently, the negative impact of these determinants became less statistically significant as the carbon price increased.

The carbon revenue increased the average net income by 25% (US\$40) and by 63% (US\$100), respectively. Depending on the carbon price, a 10% growth in the farm size increased the net income by 8.9%-9.8%. There were no significant differences between the models. In model a, an increase of 100 kg in fertilizer usage increased the net

Table 3
Determinants of the net income from multistrata agroforestry systems (N=135; carbon income not assumed). The determinants of the net income according to four alternative models which differ regarding the diversity measure (richness/diversity). The diversity measure refers to two diversity and richness classifications (A-D). The models with the highest variance explained were selected including all statistically significant determinants. There were no statistically significant interactions. Due to log-transformed net income, the effects of determinants are shown on a logarithmic scale. Diversity indices are measured in logarithmic form, so when back-transformed to the original scale, their more interpretive exponential form, known as true diversity, was used in the interpretation. The percentage change in the net income by every 10% increase in diversity (models C-D) and farm size can be calculated as $(1.1^{estimate} - 1) \times 100\%$. For the other determinants, the percentage change in the net income by a one-unit increase in the determinant can be calculated as $(e^{estimate} - 1) \times 100$. R^2s are shown for each model (N=125). Statistical significance (H_0: $|b|=0$): ** $p<0.01$ and *** $p<0.001$.

	A) Richness (intended use)			B) Richness (biology)			C) Diversity (intended use)			D) Diversity (biology)		
Fixed Effect	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value
Intercept	5,5034		***	5,5431		***	6,0516		***	6.2348		***
Fertilizer use	0,0030		***	0,0020		***	0,0032		***	0.0029		***
(Fertilizer use)^2	-1,7E-06		***	-1,1E-06		0.029	-1,7E-06		***	-1.5E-06		**
Ln Farm size (ha)[a]	0,6024	5.8%	***	0,5908	5.9%	***	0,6590	6.5%	***	0.6473	6.4%	***
Legume trees (%)[b]	-0,0072	-0.7%	**	-0,0068	-0.7%	***	-0,0081	-0.8%	**	-0.0079	-0.8%	**
Diversity measure[ab]	0,2584	29.5%	***	0,3508	42.0%	***	0,4691	4.6%	**	0.2971	2.9%	0.109
Variance explained	77.2%			76.5%				74.1%			72.7%	

[a] For every 10% increase in the independent variable, the dependent variable change by xx.x% (see column Effect, original scale)
[b] A one-unit increase in the independent variable changes the dependent variable by xx.x% (original scale)

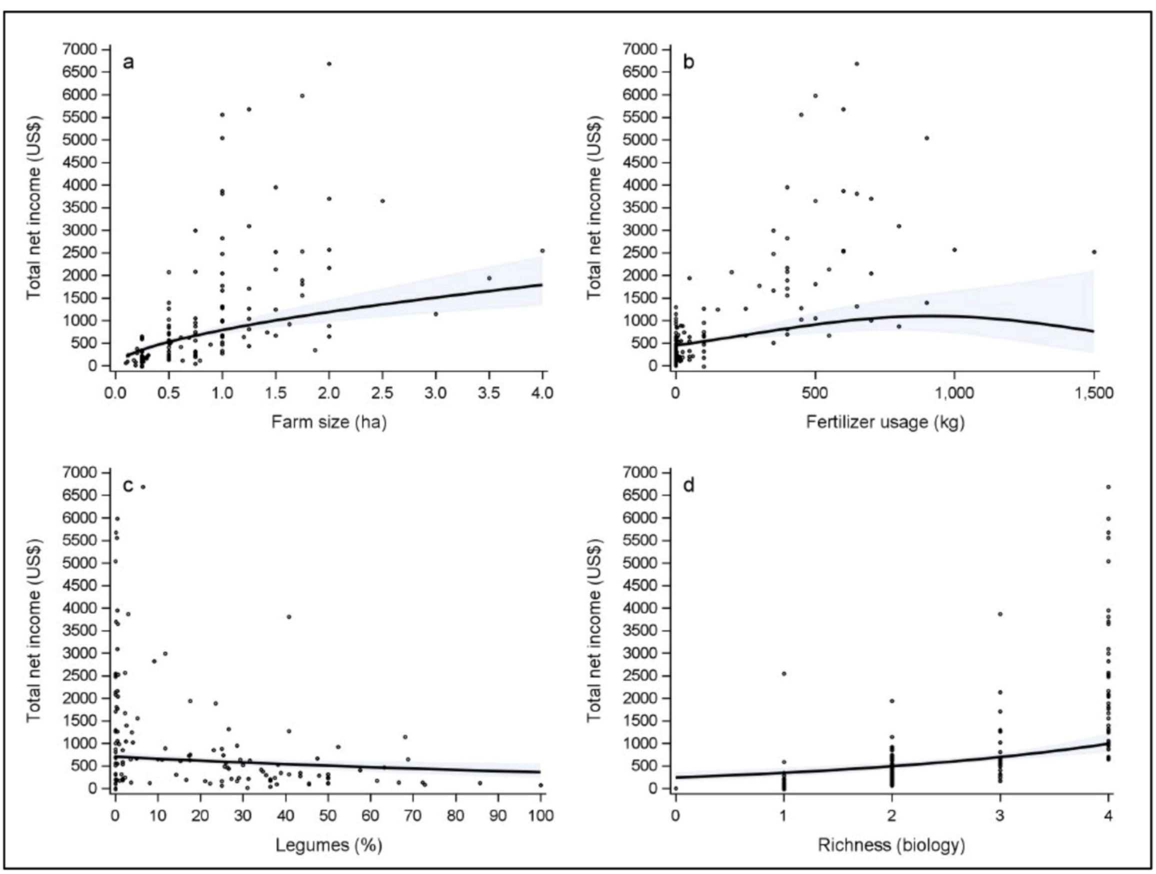


Fig. 3a. The impact of the key determinants on farms' net incomes when income sources were categorized by the biology of the products (B in Table 3). The richness represents the number of income categories. The back-transformed estimates with their 95% confidence intervals are shown.

income by 12–13%, with carbon prices of US$40-US$100 respectively. In model b, the increase in net income was slightly higher, from 14% to 16%. In both models, the impact of tree diversity on the net income declined with the higher carbon price. In model a, an increase of 10% in tree diversity increased the net income by 13% (US$40) or 10.6% (US $100), and in model b, 15% (US$40) or 12% (US$100). A unit increase in the richness in the biological categories increased the net income by 18% irrespective of the carbon price. When the categories were divided

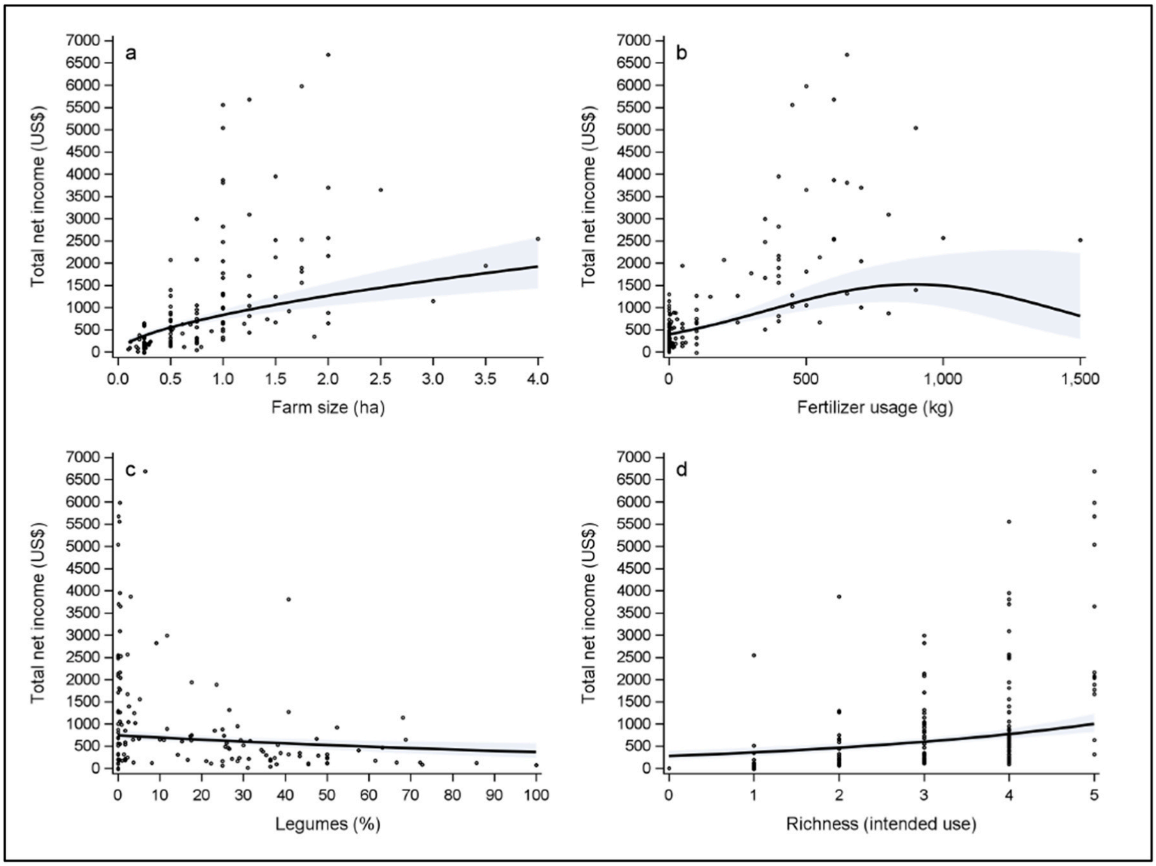


Fig. 3b. The impact of the key determinants on farms' net income when income sources were categorized by the intended use of the products (A in Table 3). The richness represents the number of income categories. The back-transformed estimates with their 95% confidence intervals are shown.

by the intended use, the increase was 16% with US$40, but only 10% with US$100. The statistical significance of the proportion of legume trees and the proportion of trees with a high basal diameter weakened as the carbon prices increased. The results of both models are presented in Table 4a-b.

4. Discussion

Our findings indicate that, besides the farm size and fertilizer usage, richness and diversity of the income sources, the proportion of legume and large trees as well as tree diversity were the key determinants of farms' net income from agroforestry. Only an increase in the proportion of legume trees and trees with a high basal diameter reduced the net income. However, the negative impact of these determinants declined with higher carbon prices. While carbon revenues increased the farms' net income, the importance of tree diversity declined when the assumed carbon revenue increased.

4.1. Generality and reliability of the findings

Since the data were collected from three regions presenting the range of Ethiopian multistrata agroforestry in terms of history, practices and sites, the results are valid for Ethiopia. The results can be generalized to similar agroecological conditions in the mid-altitude subtropics regarding subsistence smallholders.

Since the carbon stock data set separately published (Negash et al., 2022b) represented one-fifth of the farms in all three sites, the data set including the potential carbon income was smaller than the entire farm data set. Consequently, the richness (number) of the income sources did not predict the farms' net income statistically significantly when the carbon revenue was assumed ($p>0.1$). However, it seems plausible to assume that the richness and diversity of income sources would appear as a determinant also in this case with a larger data set as they did explain the farms' net income when the analysis included the data of all farms ($p<0.01$). Since the study focused on income security, the monetary value of households' own consumption was not included in the assessment.

Fertilizer use was a key determinant of the economy, with the results dominated by the abundant fertilizer requirement and positive response of chili pepper. Chili pepper was cultivated as a major cash crop in the northern study site, which was reflected in the highest farm income reported in that region.

To increase the reliability of the results, we tested a wide range of hypothetical determinants. We further excluded the statistically non-significant interactions of the determinants from the model, which also facilitated the interpretation. Despite differences among the study sites, no statistically significant interactions with sites were found, indicating the uniformity of the data, and thus the appropriateness of the model used. Furthermore, the high explanatory powers imply that the used models were able to explain most of the total variation. No evidence of endogeneity of the explanatory variables (Abdallah et al., 2015) was found and, for example, while the farms with higher income might in some cases have better opportunities for diversifying their production, the variable costs of the diversification were included in the analysis thus avoiding the endogeneity.

While the three sites of the study are representative to the three most important agroforestry regions in Ethiopia, each with a different dominant agroforestry system, including more different regions with their agroforestry systems, elsewhere in East Africa or beyond, would of course further improve the generalizability of the results.

Table 4
Determinants of the net income excluding (A) and including (B, C) carbon revenue. The determinants of the net income are given according to two alternative models which differ by richness of income sources in terms of a) biology and b) the intended use. The models with the highest variance explained were selected including all hypothetical determinants which explained net income statistically significantly. There were no statistically significant interactions. Due to the log-transformed net income, the effects of the determinants are shown on a logarithmic scale. Diversity indices are measured in a logarithmic form, so when they are back-transformed to the original scale, their more interpretive exponential form, known as true diversity, was used in the interpretation. The percentage change in the net income by every 10% increase in diversity (models B-C) and farm size can be calculated as $(1.1^{estimate} - 1) \times 100\%$. For the other determinants, the percentage change in the net income by a one-unit increase in the determinant can be calculated as $(e^{estimate} - 1) \times 100$. R^2s are shown for each model (N=27). Statistical significance (H_0:|b|=0): ** $p<0.01$ and *** $p<0.001$.

a) Including richness of the income sources in terms of biology.

Fixed Effect	A) Carbon revenue of US$0			B) Carbon revenue of US$40			C) Carbon revenue of US$100		
	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value
Intercept	7.0531		***	6.6747		***	6.5206		***
Ln Farm size (ha)	0.7986	8%	***	0.8959	8.9%	***	0.9723	9.7%	***
Fertilizer use	0.0009	9.2%	0.106	0.0011	11.7%	0.036	0.0012	13.1%	0.027
Tree diversity	1.6165	17%	**	1.2836	13.0%	0.012	1.0557	10.6%	0.042
Legume trees (%)	-0.0108	-1.1%	0.027	-0.0080	-0.8%	0.077	-0.0069	-0.7%	0.137
Tree Ø >25 cm (%)	-1.9445	-1.9%	**	-1.1577	-1.2%	0.079	-0.5925	-0.6%	0.376
Richness (biology)	0.1434	15.4%	0.326	0.1619	17.6%	0.243	0.1661	18.1%	0.253
Variance explained	86.7%			88.6%			88.2%		

b) Including richness of the income sources in terms of intended use.

Fixed Effect	A) Carbon revenue of US$0			B) Carbon revenue of US$40			C) Carbon revenue of US$100		
	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value	Effect (log scale)	Effect (orig. scale)	P value
Intercept	6.8388		***	6.7024		***	6.7390		***
Ln Farm size (ha)	0.7795	7.7%	***	0.8935	8.9%	***	0.9832	9.8%	***
Fertilizer use	0.0010	11.0%	0.020	0.0013	14.3%	**	0.0015	16.2%	**
Tree diversity	1.8438	19.2%	***	1.4833	15.2%	**	1.2206	12.3%	0.022
Legume trees (%)	-0.0123	-1.2%	***	-0.0096	-1.0%	0.028	-0.0085	-0.8%	0.065
Tree Ø >25 cm (%)	-2.1551	-2.1%	**	-1.3734	-1.4%	0.032	-0.7982	-0.8%	0.231
Richness (intended use)	0.2000	22.1%	0.052	0.1479	15.9%	0.140	0.0969	10.2%	0.363
Variance explained	88.5%			88.6%			88.2%		

4.2. Richness and diversity of the income sources

The importance of the richness and diversity of income sources as key determinants of net income in multistrata agroforestry shown by the current study emphasizes the benefits for the livelihoods of smallholders by producing multiple products for sale. The importance of diversity of biological categories such as perennial and annual crops as well as livestock may reflect security against the variability of the weather. Previous studies suggest that income diversification is an important strategy for enhancing resilience against shocks such as droughts, pests and diseases, making the livelihood system more stable (Núñez et al., 2023; Wan et al., 2016; Watete et al., 2016; Meert et al., 2005; Niehof, 2004; Barrett et al., 2001; Guvele, 2001; Ellis, 1998). A more diverse farm ecosystem may facilitate a better microclimate, multiple ecological niches, and beneficial interactions between cultivated species. Farmers who diversify their agroforestry systems seem to be able to optimize the spatial resources at their disposal by producing in multiple layers.

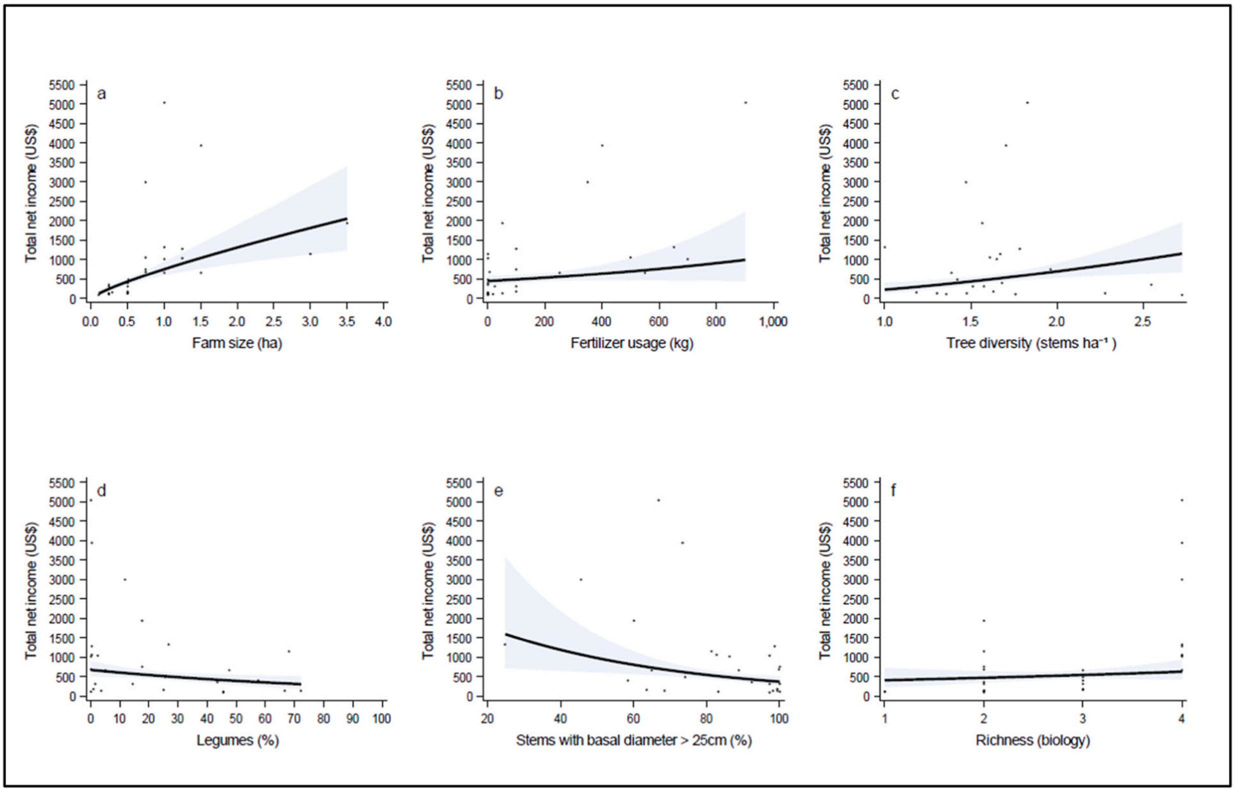
Not only biological diversification but also diversity in the intended use of the sold products, shown here as the key determinants of the economy in multistrata agroforestry, may also imply flexibility towards demand and volatility on the market. Diversification has been found to favor income generation (Cardozo et al., 2015; Alam, 2012; Faye et al., 2011) because diversified farms can better respond to demand when the general market supply is lower. Especially timber and livestock offer protection against the market saturation of crops as they can be sold when there is a sudden need for income. Annual crops are harvested approximately at the same time for all farmers, thus there can be a significant oversupply of produce, for example, the amounts of wheat, coffee, chili or khat affect the price during the harvest (Abebe et al., 2010). This can be a problem, especially for smallholders as they do not necessarily have the means to store their produce.

Empirical studies on income and production diversification have mainly focused on some income sources and paid less attention to spatial, species and product differentiation. However, such contextual knowledge is essential to comprehensively explain the key economic determinants of a well-performing smallholder agroforestry farm, because it functions as an interconnected ecological unit of production. Further empirical study is needed to better understand the subject, but it seems reasonable to assume that diversification as a determinant emerges from a complex combination of economic and ecological factors.

4.3. Farm size

Farm size was found to be positively correlated with the net income from agroforestry practices. The impact of this determinant is consistent with the findings of other studies of agroforestry (Zira and Gupa, 2020; Adane et al., 2019; Shonde, 2017; Zira et al., 2016; Regmi, 2003). This determinant is of note as most Ethiopian farms are fragmented in extremely small land areas, which can be especially harmful if the smallholders' primary sources of income and food security are contingent on the land, leaving them destitute if there is a disruption such as drought (Headey et al., 2014). The small size of landholdings can be a contributing factor to a loss of fertility as subsistence farmers need all their land area to produce at all times. Thus, they are unable to fallow their land or to apply other improved land management practices such as crop rotations and intercropping. Furthermore, farmers who are dependent on extremely small areas of land are unlikely to produce a surplus for investment for input purchase (fertilizers, improved seeds, etc.) and agricultural technology that significantly enhances the effectiveness of labor. According to Tesfaye (2008) and Desta (2015), a larger size of the farm may also enable farmers to increase the diversification of agroforestry, which increases income from the system as shown here.

a) Richness (biology) included.



b) Richness (intended use) included.

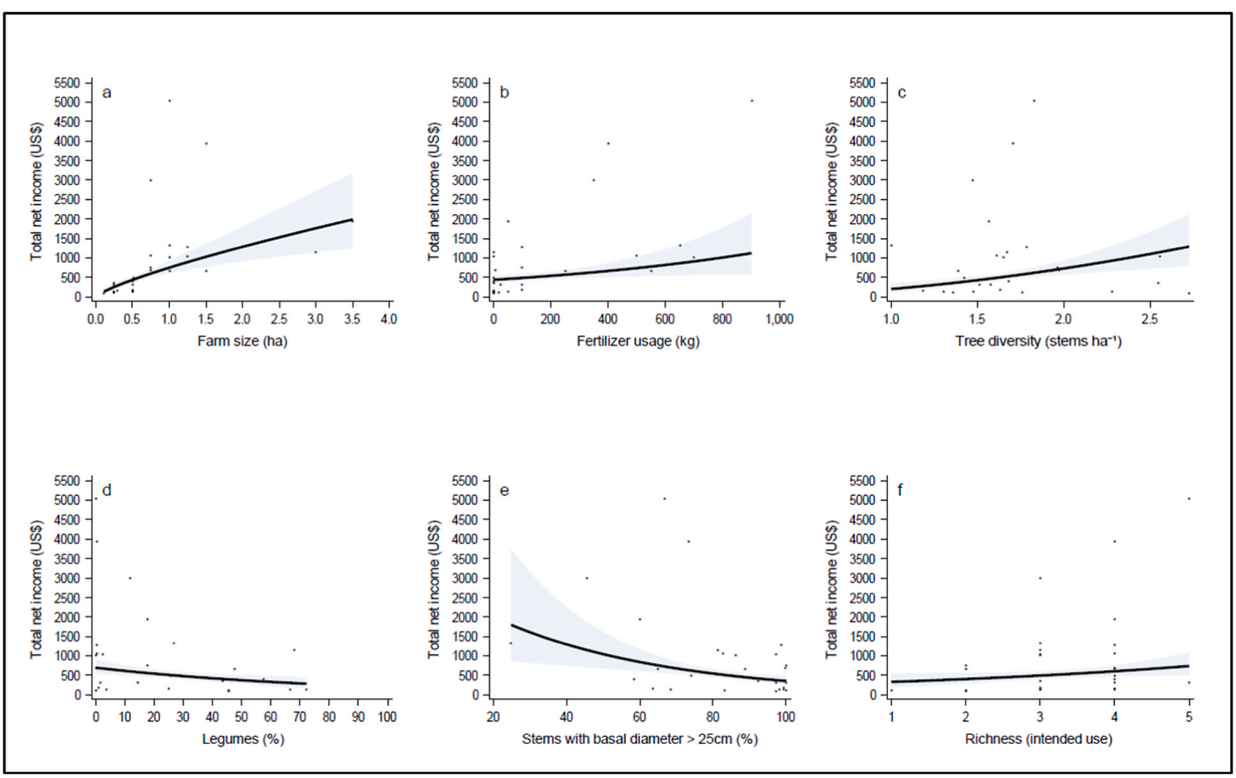


Fig. 4. The key determinants of farms' net income excluding potential carbon revenue (see Table 4a,b A). The back-transformed estimates with their 95% confidence intervals are shown. a) Model with richness (biology). The model includes the richness of the farms' income sources in terms of biology. b) Model with richness (intended use). The model includes the richness of the farm's income sources in terms of their intended use.

4.4. Fertilizer use and legume trees

While the intensity of fertilizer use has rapidly increased in other parts of the world, it has remained at a low level in sub-Saharan Africa (Kahiluoto et al., 2021). The impact of mineral fertilizer and its emergence as a key determinant of income might be enhanced by the macronutrients and several micronutrients reducing agricultural productivity (Gelgo et al., 2017). Additionally, chili peppers in the northern Fenote-Selam, wherein fertilizers were mostly used, seem to respond particularly well to fertilizers containing nitrogen (Mihretie et al., 2022; Stan et al., 2021).

According to our results, the input cost of the fertilizers is less than the monetary benefit from utilization with the 2015 market price of US $40 per 100 kg of di-ammonium phosphate (DAP) fertilizer (Statista Research Department, 2023) or with an average price of US$67 per 100 kg of DAP from our field survey. This suggests that fertilizer use is not optimized, resulting in much lower productivity than is economically viable in the studied regions. This might be due to factors such as some smallholders not having access to sufficient capital even for the most profitable inputs, unresponsive soil to fertilizers, as well as lack of recyclable nutrients due to the limited household wastes, manure used as fuel (Rimhanen and Kahiluoto, 2014) and no access to urban waste nutrients. Other explanations are logistical difficulties and lack of education which may lead to underutilization as well as excessive use of fertilizers. (van Dijk et al., 2020; Tittonell and Giller, 2013; Vanlauwe et al., 2011; Yirga and Hassan, 2006).

Even though fertilizer use is often seen as a universal solution to low productivity, other factors such as soil organic matter content, degradation of the soil and characteristics of the cultivated species must be considered. According to Sida et al. (2020), plant species in agroforestry have competitive and facilitative characteristics regarding nutrients which makes the spatial arrangement and species selection important factors when optimizing fertilizer use. Some soils are also unresponsive due to limited soil organic matter and biological functions which might cause fertilizer inputs to lose their cost effectiveness.

Soil organic matter is an important soil quality parameter, not only because fertilizer effectiveness is dependent on it, but as it is a key aspect of nutrient retention capacity, the structure of soil and better water holding capacity (Loveland and Webb, 2003). In Ethiopia, as elsewhere in sub-Saharan Africa, unsustainable agricultural management such as deforestation, the removal of crop residues, steep slope cultivation, and the use of animal manure (manure cake) as a source of energy for cooking (Rimhanen and Kahiluoto, 2014), as well as excessive livestock pressure, but also nutrient depletion, have led to a notable soil organic matter depletion. The carbon stock increase by agroforestry (Rimhanen et al., 2016) contributes to soil regeneration but requires nutrients (Kahiluoto et al., 2021) to make agriculture more sustainable and economically viable.

Nitrogen-fixing legume trees are also important for the persistence of soil organic matter and soil carbon as well as for soil productivity, in addition to providing green manure and livestock fodder (Negash et al., 2022b; Fornara and Tilman, 2008; FAO, 1992). Legumes have a crucial role in supporting sustainable agroforestry systems especially when recyclable nutrients or chemical fertilizers are not available or affordable for smallholders (Ribeiro-Barros et al., 2018; Dakora and Keya, 1997). Our finding on the reduced farm's net income by increased proportion of legume trees, similarly to trees with a large diameter, can be explained by the simultaneously reduced space for food and cash crops. Densely growing trees reduce crop yields due to competition for growth resources (Rahman et al., 2016; Bayala et al., 2014). This negative impact was, however, the smaller the higher potential carbon revenue was assumed. Hence, it is likely that the tree cover in the agroforestry sites with the greatest density of legume trees and trees with a larger diameter exceeded the critical threshold between beneficial and detrimental impact on farm's net income.

4.5. The role of carbon revenues

While carbon revenues, if implemented, appear to have the potential to notably increase the income of the studied multistrata agroforestry farms, the key determinants of the net income remained approximately the same whether carbon revenues were assumed or not. However, the biology-based richness of income sources maintained its importance as a determinant surpassing the impact of the product-based ("intended use") category when carbon income increased. This seems to indicate that the incentive to transition into the most profitable form of multistrata agroforestry that takes advantage of discovered key determinants, especially biology-based richness, does not necessarily need additional incentives that might come from carbon revenue. The incentive to transition into multistrata agroforestry from monocultures could, however, accelerate with access to carbon revenue.

While the impact of the proportion of large trees on net incomes was less negative when the carbon income increased, the results also seem counterintuitive. Namely, when the amount paid per ton of CO_2 increases, the amount of carbon-sequestering species, such as woody plants could become a key determinant. However, this does not seem to be the case with the carbon price range used in the analysis. This indicates that the most profitable diverse agroforestry farms already have good potential to sequester carbon and new radical measures to maximize profits from carbon income are not needed if carbon market becomes available. In terms of continuity, carbon payments should be considered as an additional income for the smallholder farmers without making them dependent on the payments (Roshetko et al., 2007). However, if carbon revenues become available, they need to be within the reach of smallholders as transaction and transition costs can be insurmountable barriers to entry. In addition to that, it is crucial to clarify the ownership of carbon stocks, especially in countries like Ethiopia where land is not privately owned. At present, there is no legal instrument in Ethiopia that defines 'carbon right' or specifies its ownership. It is essential that the monetary benefits from sale of carbon credits are allocated to the smallholder communities that are responsible for producing these stocks. This approach not only provides an incentive for these communities to increase their carbon stocks, but also has the potential to yield significant benefits for food security. This was the case in Ethiopia regarding the tree cover related clean development mechanism projects (Kahiluoto et al., 2012).

5. Conclusion

The findings of this study underscore the vital role income diversification plays in the multistrata agroforestry economy. For smallholders, the economic advantage lies in the production of a variety of product categories, each serving distinct purposes and representing diverse biological categories. This emphasis on diversity is particularly significant because smallholders, often constrained by limited resources, can more readily manage and implement diverse agricultural practices compared to addressing other beneficial factors like farm size and fertilizer usage. The diversity of income sources is also of great importance to smallholder communities' resilience to weather variability and climate change, as well as to market volatility, and thus for the income and food security.

Remarkably, the introduction of carbon revenue substantially boosted income levels while minimally impacting the key determinants. This suggests that multistrata agroforestry systems do not necessitate a complete overhaul when accessing the carbon market. Instead, it reveals that the most economically successful farms are already well-equipped for carbon sequestration and capitalizing on carbon revenue. Consequently, at the examined price levels, carbon revenue does not pose a threat to the diversification of farm ecosystems, provided subsistence smallholders maximize their profits through a deep understanding of income-determining factors.

However, further empirical and hypothesis-driven research is imperative to gain a nuanced understanding of the most effective forms of diversity in agroforestry, contingent on specific contextual factors. It is reasonable to conclude that diversification as a determinant of smallholder livelihoods arises from a multifaceted interplay of economic and ecological considerations. This necessitates ongoing exploration to inform sustainable practices in multistrata agroforestry systems.

CRediT authorship contribution statement

Pirjetta Waldén: Writing – original draft, Investigation, Data curation, Conceptualization. **Mari Eronen:** Writing – review & editing, Writing – original draft, Visualization. **Janne Kaseva:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation. **Mesele Negash:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Helena Kahiluoto:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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