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Carbon revenue in the profitability of agroforestry relative to monocultures

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Abstract The impact of carbon revenue on the profitability of agroforestry systems in comparison to monocultures is unexplored in regard to Sub-Saharan Africa. This study creates a multivariate model to evaluate the impact of carbon revenue on the profitability of agroforestry relative to the dominant monocultures in Ethiopia by using stylized plots. Yields and carbon stock changes of eight agroforestry systems were modeled based on data from agroforestry plots in the Ethiopian Central Rift Valley. According to our model, agroforestry was, on average, four times more profitable than the main monoculture systems (wheat, barley, maize, teff, sorghum, sugarcane and lentil) even when carbon revenues were excluded, primarily due to the higher prices of fruit produce. Carbon revenues were estimated using a plausible carbon price ranging from US\$8/tCO2e to \$40/tCO2e and carbon sequestration rates of 0.59 to 17.2 Mg C ha^{-1} $year^{-1}$. The possibility of receiving carbon revenue increased the profitability of agroforestry by 0.5% when using the lowest utilized carbon price and carbon sequestration rate, by 20% when using the carbon price of \$20 and the average carbon sequestration rate, and by 70% when using the highest price and highest sequestration rate of carbon. On average, carbon revenue increased the profitability of agroforestry by 150% in comparison to monoculture farming. We conclude that carbon income may have significant potential to motivate smallholders to convert to agroforestry when there is a proper management system, a sufficiently high carbon price and effective institutional support to mitigate the transition and transaction costs.

Keywords Cropping systems · Smallholder · Carbon sequestration · Carbon trading · Ethiopia · Modeling

Introduction

There is a need for new practices and policies to mitigate climate change. Such practices and policies should also facilitate adaptation in local communities in developing countries. Agroforestry systems (AFSs) may be able to accomplish both goals, i.e., to mitigate climate change while improving food security and the local economy. An AFS is a cropping system that includes trees and shrubs and thus sequesters more carbon into the soil and into vegetation than a monoculture farming system (Rimhanen et al. 2016). Increased carbon stock can provide environmental

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services, social benefits, and potentially monetary benefit from the carbon market through carbon revenue. An AFS as a carbon sink represents untapped potential to feasibly deliver benefits from carbon schemes to poor smallholders in developing countries and to lower the emission-reduction costs of developed countries. Carbon revenue could also be an incentive for the adoption of sustainable agricultural practices, increasing soil productivity while restoring degraded drylands and abating climate change. Sub-Saharan Africa has the highest rate of land degradation in the world due to low amounts of soil organic carbon and nutrients leading to low yields and reduced food security.

At present, the Clean Development Mechanism (CDM) includes afforestation and reforestation as mechanisms to increase carbon sinks in developing countries, whereas soil carbon sequestration and the prevention of deforestation are excluded. However, reforestation and forest preservation, while beneficial from an emission-reduction perspective, conflict with the need to increase food security for growing populations. An AFS could offer one solution to this conflict as it has the potential to sequester carbon and simultaneously increase food production. In an AFS, carbon is sequestered in above- and underground vegetation and in soil. The sequestration potential depends on climate conditions, site characteristics, plant species, stand age and cultivation methods (Nair et al. 2009). Thus, estimates of carbon sequestration potential in AFSs vary considerably. According to Nair et al. (2009), the range of AFS aboveground carbon sequestration is 0.29–15.21 Mg C ha^{-1} -$year^{-1}$, and belowground it is 30–300 Mg C ha^{-1} up to 1-m depth in the soil.

The monetary value of annually sequestered carbon depends on the carbon accumulation rate and the market price of the carbon. The price of carbon has varied during past trading periods from a high of $30 to lower than $1 per tCO_2e (EEX 2016), and the carbon price depends on the many economic, technological and political factors that impact the demand for and supply of carbon credits. In Ethiopia, Kassa (2015) and Linger (2014) compared revenues of agroforestry and monocultures and according to their research, agroforestry was 2–6 times more profitable. In West African Mali, Takimoto et al. (2008) researched two types of agroforestry systems, live fences and fodder banks, and found that carbon revenue increased net profits by approximately 15% at a carbon price of $42/tCO2e. González-Estrada et al. (2008) report that carbon revenues in West Africa could increase agroforestry net profits by 2–32%. However, there are no studies that compare profitability of AFSs with added carbon revenue to the revenue of monocultures.

This paper evaluates the economic impact of carbon revenue on the profitability of multistrata smallholder AFSs, and its impact relative to the dominant monocultures found in Ethiopia. This evaluation was done by modeling, drawing on available empirical values from the area in order to address inherent uncertainty, as there are many site and system specific characteristics that vary and independently affect the profitability of a farm plot and carbon sequestration. Eight stylized AFSs were developed by closely approximating monitored cases in the Ethiopian Central Rift Valley in Sire and by using mean values of the gathered empirical data whenever available. An economic model that incorporated actual soil carbon measurements from AFS plots in the area, crop yields, and prices was used to compare AFS profits with and without carbon income with those of monocultures. Since carbon sink benefits vary between AFS plots and future carbon prices are uncertain, the monetary benefit was determined with three different carbon sequestration rates and at three different plausible carbon prices.

Theoretical framework

This section develops a framework for the empirical assessment and comparison of AFSs and monocultures with and without carbon policies. Consider first a smallholder farmer cultivating monoculture crops in a given land area. Denote the typical crops cultivated in monoculture by j (j = 1…n). The farmer chooses a vector of inputs × to produce crop j according to the (concave) production function $y_j = f_j(x)$. Let c denote the respective vector of input prices, and K the fixed costs of production. Then, the profits from monoculture cultivation of any crop j can be expressed as follows:

$$\pi^{M} = p_j f_j(x) - cx - K, \tag{1}$$

where p_j denotes the price of the crop j. The maximum revenue from monoculture, as a result of the optimal choice of inputs subject to exogenous variables, is defined by

$$\pi^{M} = \pi^{M}(x^{*}(p, c). \tag{2}$$

Depending on the use of inputs, monoculture may or may not produce carbon benefits. The carbon benefits are, however, omitted here, as carbon sequestration allocated to AFS cultivation is the amount of carbon in excess of that under monoculture. Consider next the optimal cultivation of crops under AFSs. Recall that the farmer may combine a number of crops in a given land area based on the type of AFS and anticipated crop prices. Let the number of crops in a given AFS land area be i, $i = 1\ldots$k (in the empirical part $k = 8$). Using previous notation but letting L denote the fixed costs, the profits from cultivating a given AFS land area with a given set of crops in the absence of carbon revenue is:

$$\pi^{AFS} = \sum_{i=1}^{k} (p_i f_i(x) - cx_i) - L. \tag{3}$$

Unlike in the monoculture, the farmer optimizes cultivation over k crops. Again, the maximum revenue from the optimal choice of inputs and subject to exogenous parameters and the specific features of the AFS plot is given by

$$\pi^{AFS}\left(\sum_{i=1}^{k} x^{*}(p, c)\right). \tag{4}$$

To include the carbon price in the analysis, denote the total amount of carbon sequestered as an aggregate of sequestration in the soil and in vegetation aboveground by $C = C_{\text{aboveground}} + C_{\text{soil}}$. Let the price of carbon be q. It is a unit price per ton of CO_2-equivalent emissions (one ton of C equals 3.7 tons of CO_2.). It is assumed that the carbon price is a result of either domestic climate policy incorporating agriculture as a voluntary sector or international mechanisms created by the Paris 2015 agreement. Profits from AFS cultivation can now be expressed as:

$$\pi^{AFS(q)} = \sum_{i=1}^{k} (p_i f_i(x) - cx_i) - L + qCO_2 - eq. \tag{5}$$

As far as the farmer can promote carbon sequestration in the cultivation with the choice of inputs, the maximum profits from the optimal choice of inputs in the presence of carbon prices are defined by:

$$\pi^{AFS(q)}\left(\sum_{i=1}^{k} x^{*}(p, c, q)\right). \tag{6}$$

The future price of CO_2-equivalent emissions is uncertain, and measurement of carbon sequestration is subject to uncertainty as well. Hence, various levels of carbon prices and sequestration rates are employed in the empirical analysis. More specifically, carbon revenue (R) is determined using three different carbon sequestration amounts of CO_2 (minimal, average and maximum) and three different carbon prices q_i (1 = \$8.40, 2 = \$22.30 and 3 = \$40.20).

$$R = \begin{cases} q_i * CO_2 - eq.\ emissions(\min) \\ q_i * CO_2 - eq.\ emissions(mean), \\ q_i * CO_2 - eq.\ emissions(\max) \end{cases} \quad i = 1, 2, 3 \tag{7}$$

The model facilitates comparison of AFS cultivation to monoculture as well as AFS cultivation in the presence and absence of the carbon market. While the hypothesis concerning monoculture versus AFS with carbon prices is $\pi^{M} > (<)\pi^{AFS(q)}$, for AFS cultivation, it is $\pi^{AFS(q)} > \pi^{AFS}$. Empirical analysis in the next section shows the relative profitability of the three cases in Ethiopia's Sire.

Materials and methods

Description of the study area

The study area was the Sire district in Ethiopia. Sire is situated in the Arsi Zone of the Oromia region in the central part of the African Great Rift Valley (CRV) (Fig. 1). The most cultivated plants are teff, barley and maize. In Sire, as throughout Ethiopia, the vast majority of farmers (95%) are smallholders, i.e., with a land holding of up to 2 hectares (World Bank 2003). Unlike in the northern parts of Ethiopia, arable cultivation in the CRV started only a few decades ago, and therefore, the soils are less degraded than in the north. The region is an important food supplier. However, as generally in Ethiopia, most agriculture in

Fig. 1 Location of the studied plots, Sire Ethiopia (Google Maps 2018)

Sire is rain-fed and uses little external inputs and therefore is low-yielding and dependent on weather conditions (Demeke et al. 2011). Sire represents an agroecological zone that can be characterized as cool subhumid. The mean annual temperature and precipitation are 15–20°C and 532–1123 mm, with a mean of 868 mm, respectively.

Modeled AFS plots

The simulated multistrata, homegarden type AFS plot sizes and vegetation were modeled by applying the empirical data of the 6–20-year old AFS plots studied by Rimhanen et al. (2016). The plot area was divided into 50% food crops and 50% cash crops and timber trees, based on the study by Abele et al. (2010). Plant species were categorized into food and cash crops as follows. Food crops in AFSs were *Ensete ventricosum* (Welw.) Cheesman, *Persea americana* L., *Musa acuminata* Colla, *Phaseolus vulgaris* L., *Zea mays* L., *Solanum tuberosum* L. and *Brassica oleracea* L. Cash crops were *Coffea arabica* L., *Carica papaya* L., *Mangifera indica* L., *Citrus limon* L., *Saccharum officinarum* L., *Citrus sinensis* L., *Olea africana* Mill., *Catha edulis* Forsk. and *Eucalyptus globulus* Labill. The relative production areas of each plant species were based on the mean value of the 144 farms documented by Abele et al. (2010) in Southern Ethiopia. The area covered by individual plants of each species originated from several studies (Appendix, Table 4). Composition of the plant species and the ratio of the plant cover of the eight agroforestry plots (I–VIII) are presented in Fig. 2.

Empirical carbon sequestration data

In this study, we utilized data from Rimhanen et al. (2016), who estimated that in Ethiopian multistrata AFSs in Sire, the average sequestration amount into soil was 1.2 Mg C ha^{-1} $year^{-1}$ (95% CI 0.3–2) higher than in the adjacent monoculture plots. Rimhanen et al. (2016) obtained the underground sequestration amounts from AFS plots that were 6 to 20 years old and with the species composition applied in the

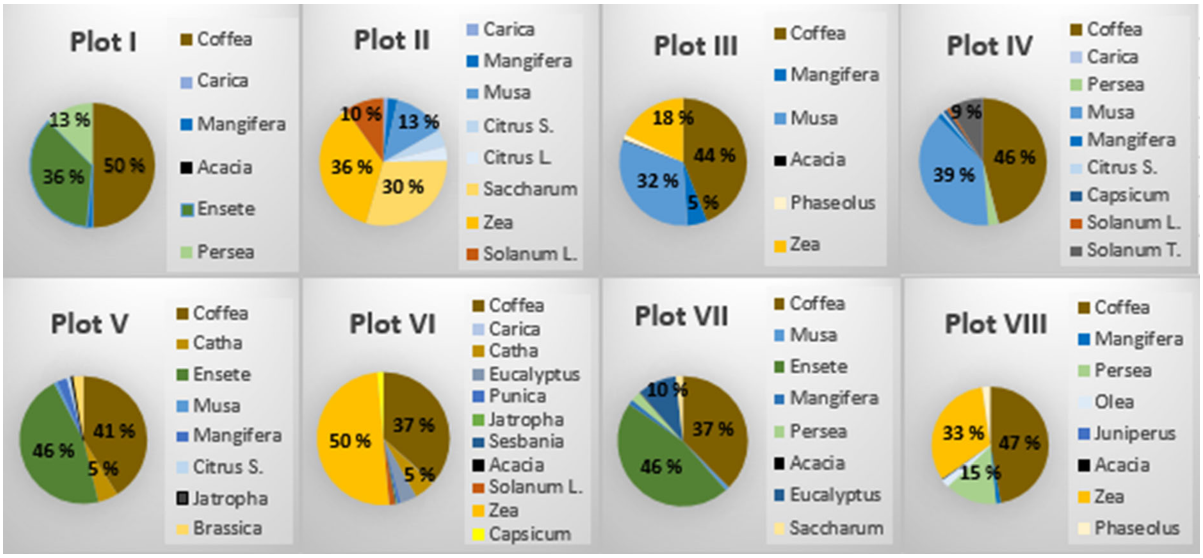

Fig. 2 Eight constructed 0.2 hectare AFS plots (I–VIII) based upon plant species composition data from Ethiopia's Sire (Rimhanen et al. 2016) and the relative plant cover of AFSs in Southern Ethiopia (Abele et al. 2010)

stylized plots. For aboveground carbon sequestration amounts, research by Nair et al. (2009) was utilized, as there is no available plant-specific sequestration data. Nair et al. (2009) stated that the global range of the aboveground carbon sequestration in AFSs is 0.29 to 15.21 Mg C ha^{-1} year^{-1} (average 8 Mg C ha^{-1} year^{-1}). Consequently, the sum of the aboveground and soil-sequestered carbon results in three different carbon sequestration rates: low (0.59 Mg C ha^{-1} year^{-1}), average (9.2 Mg C ha^{-1} year^{-1}), and high (17.2 Mg C ha^{-1} year^{-1}). The sum is calculated by adding the aboveground and underground sequestration amounts together from lowest to the highest. The amount of carbon sequestered aboveground by annual cereal monocultures is assumed to be zero.

Yield data

The approximate yield for each AFS plot was calculated by summing the total yield for each plant type according to the coverage of that plant type in the plot. Yield data for each plot is presented in Table 1. The total yield for each plant type was calculated based on previously published empirical yield data from Ethiopia (Table 2). Empirical yield data from the most common monocultures in Ethiopia based upon field survey data collected in 2012 and from the literature were utilized (Table 2). The reported annual yields were of average volume for the area. Monoculture yields per 0.2 hectare area were of maize (*Zea mays* L.) 540 kg, barley (*Hordeum vulgare*) 500 kg, sorghum (*Sorghum bicolor*) 460 kg, wheat (*Triticum* spp.) 440 kg, teff (*Eragrostis tef* (Zucc.) Trotter) 260 kg, lentil (*Lens culinaris*) 100 kg and highly productive sugarcane (*Saccharum officinarum* L.) 1020 kg.

Cost and prices

Product prices and production costs were obtained from the literature (Kassa 2015; Table 3). The net profit of the plot was determined based on the aggregate yield of crops and timber. The cost of production of the AFS was derived from Kassa's research (2015) performed in the study area. According to Kassa (2015), cost of production for the AFS is approximately 30% of the total revenue, wherein costs for monocultures are estimated to be between 40% and 70% in regard to smallholders. Cost of production of the monoculture was selected to be the minimum 40% of the total revenue, and 30% was selected for the constructed AFS plots. Market prices were obtained from a market survey in the capital of Ethiopia, Addis Ababa, in 2013 and from the literature (Table 3). The exchange rate of US$1.00 per 20.5ETB was used. The carbon price range applied was: EU Emission

Table 1 Modeled crop yields (Y) and revenues (R) for the composition of the plant species of the eight agroforestry plots (I–VIII) documented by Rimhanen et al. (2016) and yields in AFSs (kg/0.2 ha/year) (Table 2) and typical plant species densities in Ethiopian multistrata AFSs (Table 3)

Plot I				Plot II				Plot III				Plot IV			
Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $
Coffea	17	233	853	*Carica*	4	228	112	*Coffea*	15	209	765	*Carica*	1	38	19
Carica	1	38	19	*Mangifera*	2	50	20	*Mangifera*	4	100	39	*Coffea*	16	214	783
Mangifera	1	25	10	*Musa*	12	231	113	*Musa*	28	555	272	*Persea*	1	66	26
Acacia	1	*		*Citrus S.*	6	240	142	*Acacia*	1	*		*Musa*	33	666	326
Ensete	22	438	127	*Citrus L.*	6	300	147	*Phaseolus*		5	3	*Mangifera*	1	25	10
Persea	5	330	129	*Saccharum*		306	150	*Zea*		97	47	*Citrus S.*	1	50	25
Timber*			2	*Zea*		195	96	Timber*			2	*Capsicum*		4	3
				Solanum L.		108	87					*Solanum L.*		8	7
				Timber*			2					*Solanum T.*		84	45
												Timber*			2
Total	0.2		1140	Total	0.2		869	Total	0.2		1128	Total	0.2		1246

Plot V				Plot VI				Plot VII				Plot VIII			
Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $	Crop	pcs	Y kg	R $
Coffea	14	190	696	*Carica*	1	38	19	*Coffea*	13	174	637	*Coffea*	17	226	828
Catha		22	27	*Coffea*	13	174	637	*Musa*	1	18	9	*Mangifera*	1	25	10
Ensete	28	552	160	*Catha*		22	28	*Ensete*	28	553	160	*Persea*	6	396	154
Musa	1	15	7	*Eucalyptus*	13		3	*Mangifera*	1	25	10	*Olea*	1	25	51
Mangifera	2	50	20	*Punica*	1	13	6	*Persea*	1	66	26	*Juniperus*	1	*	
Citrus S.	2	100	49	*Jatropha*	1	*		*Acacia*	1	*		*Acacia*	1	*	
Jatropha	1	*		*Sesbania*	1	*		*Eucalyptus*			8	*Zea*		177	87
Brassica		48	21	*Acacia*	1	*		*Saccharum*		16	8	*Phaseolus*		7	5
Timber*			2	*Solanum L.*		15	12	Timber*			2	Timber*			2
				Zea		270	132								
				Capsicum		6	4								
				Timber*			2								
Total	0.2		982	Total	0.2		843	Total	0.2		860	Total	0.2		1137

Acacia (*Acacia Mill.* spp.), *Brassica* (*Brassica oleracea* L.), *Capsicum* (*Capsicum annuum* L.), *Carica* (*Carica papaya* L.), *Catha* (*Catha edulis Forsk.*), *Citrus* L. (*Citrus limon* L.), *Citrus S.* (*Citrus sinensis* L.), *Coffea* (*Coffea arabica* L.), *Ensete* (*Ensete ventricosum* (*Welw*)*.Cheesman*), *Eucalyptus* (*Eucalyptus globulus Labill*), *Jatropha* (*Jatropha curcas* L.), *Juniperus* (*Juniperus procera L*), *Mangifera* (*Mangifera indica* L.), *Musa* (*Musa acuminata Colla*), *Olea* (*Olea Africana Mil*L.), *Phaseolus* (*Phaseolus vulgaris* L.), *Pennisetum* (*Pennisetum purpureum Schumach.*), *Persea* (*Persea americana* L.), *Punica* (*Punica granatum* L.), *Saccharum* (*Saccharum officinarum* L.), *Sesbania* (*Sesbania sesban* (L.) *Merr.*), *Solanum* L. (*Solanum lycopersicum* L.), *Solanum T.* (*Solanum tuberosum* L.) *and Zea* (*Zea mays* L.)

*Timber production in homegarden is estimated at 1.5 m per year (Table 2)

**Jatropha plants yield estimate is 0.5 kg and revenue is $0.1 (Tables 2, 3)

Allowance $8.40/tCO2e (17.6.2015), price collar $22.30/tCO2e (Knopf et al. 2014) and the social cost of carbon, i.e., $40.20/tCO2e (Tol 2011). The costs do not include opportunity costs, other transition costs or transaction costs but are for 6–20-year-old AFS plots.

Results

Depending on the monoculture (*Saccharum officinarum* L., *Zea mays* L., *Hordeum vulgare*, *Sorghum bicolor*, *Triticum* spp., *Eragrostis tef* (Zucc.) Trotter and *Lentil culinaris*), total revenue varied between $145 and $500 per 0.2 hectare. The highest revenue was obtained from sugarcane and wheat, and the lowest from lentil monoculture.

The total revenue of the AFS plots varied between $843 and $1245 (Table 1). The revenue was highest for the plot which contained *Coffea arabica* L., fruits and vegetables (plot 4). The plot with the lowest revenue was the plot with trees, such as *Jatropha curcas* L., *Sesbania sesban* (L.) Merr. and *Acacia* Mill. spp. (plot VI). Perennial trees and shrubs contributed over 70% of AFS revenue. The average total revenue of AFS plots was $1025, whereas monoculture plots had an average revenue of $289.

The net revenue of AFS plots varied between $590 and $870 without carbon revenue, and the net revenue of the monocultures varied between $90 and $300. The average net revenue for the AFS plots was approximately $720 and for monoculture plots, it was approximately $175. The average net revenue of AFS plots was twice that of monocultures with sugarcane; three times that of wheat; four times that of maize, teff and barley; five times that of sorghum and seven times that of lentil.

The carbon revenue varied for 0.2-hectare plots between $4 and $512 depending on the price of carbon and the annual amount of sequestrated carbon. Figure 3 presents the average per hectare net revenue divergence without carbon revenue between AFS and monocultures, and carbon revenues with different carbon sequestration rates and carbon prices.

When the carbon revenue was added to the ordinary agricultural revenue of the AFS plots (0.2 ha), the net revenue of the AFS varied between $600 and $1385. The percent increases of the net revenue of the AFS plots after adding the carbon revenue were as follows: 0.5–15% at a carbon price of $8.40, 1–40% at a carbon price of $20.30, and 3–73% at the highest modeled carbon price of $40.20, depending on the sequestration rate of 0.6/9.2/17.2 Mg C ha^{-1} year^{-1}.

Transaction costs (e.g., implementing, measuring and monitoring) were considered to be zero in this study. Thus, the carbon revenue was considered as the net revenue, because transaction costs in AFS projects are usually covered by a third party such as a trust fund (Scolel Te 2007). When the impact of the carbon revenue from the AFS was analyzed in relation to the net revenue of monocultures with a low sequestration rate of 0.6 Mg C ha^{-1} year^{-1}, the net revenue of the AFS increased as follows: by 2% at a carbon price of $8.40, by 6% at $20, and by 10% at $40. With the average carbon sequestration rate of 9.2 Mg C ha^{-1} year^{-1}, the net revenue of the AFS increased as follows: by 30% at a carbon price of $8.40, by 90% at $20, and by 160% at $40. With the highest carbon sequestration rate of 17.2 Mg C ha^{-1} year^{-1}, the net revenue of the AFS increased as follows: by 60% at the carbon price of $8, by 165% at $20, and by 295% at $40 in comparison to the net revenues of monoculture cultivation. When the sequestration rate was high and the carbon price was at its peak, $40 Mg CO_2e, the carbon revenue ($500) alone was higher than the net revenue of any monoculture plot. The carbon revenue

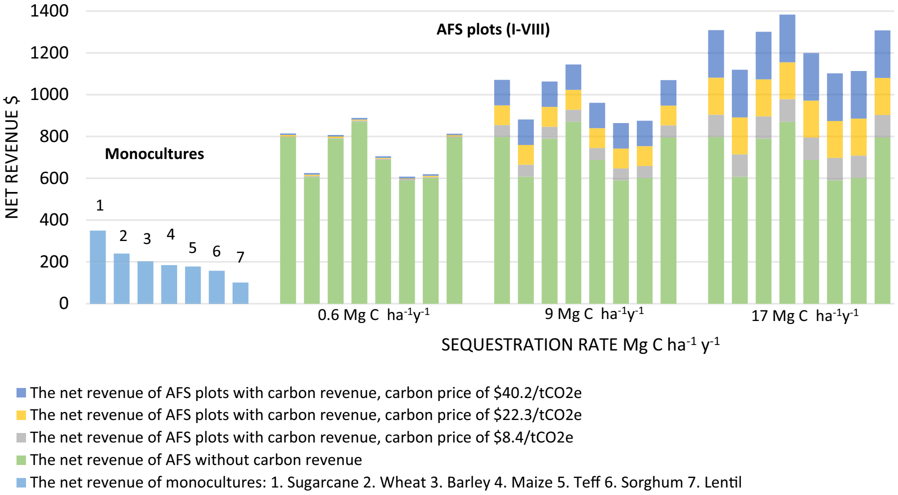

Fig. 3 Carbon revenue in agroforestry systems (AFSs) relative to monocultures. AFS benefit (difference of average net revenue in AFS and monocultures) without carbon revenue, and carbon revenue at three carbon sequestration rates and three carbon prices

increased the profitability of the AFS plots most significantly when compared with a monoculture of lentil (5–590%), which had the lowest net revenue. The carbon revenue had the least impact when compared with a monoculture of sugarcane (1–170%), which had the highest net revenue.

The sensitivity of the profitability of AFSs in comparison to monocultures was examined in regard to the revenue and cost structures of the model. A twofold increase in the costs of AFSs and a fourfold decrease in the costs of monocultures did not change the overall result. The overall results of this study are no longer valid when the revenue of AFSs was halved and when the costs were twofold. The results of the sensitivity analysis are presented in the Appendix, Table 5.

Discussion

Our findings indicate that the AFSs were more profitable than the dominant monocultures. When carbon revenue was added, the revenue gap between monoculture and agroforestry farming widened.

Generality and reliability of the findings

The applicability of our results on the profitability of AFSs relative to monocultures is contingent on how anomalous the used empirical data is and how typical the site characteristics were as the basis for the plot construction. This uncertainty has been addressed by the use of multiple sequestration amounts and by using the average to minimum annual yields documented from the area. According to Nair et al. (2009), it seems that agroforestry in the arid and semiarid climate and degraded land sites has lower sequestration potential than sequestration in the tropics. It seems plausible that the lowest aboveground sequestration amounts are applicable for the arid or semiarid part of Ethiopia, whereas the highest amounts are most applicable for the tropical areas.

The empirical yield data and plant species ratios have been derived from mosaic patch-pattern AFSs (Abele et al. 2010); thus, the amount of biomass might differ slightly in an AFS with no dominant crop patches. Because the yields and revenues were modeled based on empirical data from an Ethiopian food production area, the results are valid for Ethiopia and can be generalized to similar agroecological conditions on the hills of the Rift Valley crossing East Africa in regard to smallholders. The results are not directly applicable to mechanized agriculture due to scalability of labor costs in regard to large monoculture fields. Since two constant values of the documented average costs that Kassa (2015) reported have been used (one for monocultures and one for AFSs), the actual costs might vary depending on the site characteristics and management practices.

The results of this study apply to carbon sequestration of food production by multistrata -type agroforestry, and the results thus cannot be applied directly to other kinds of AFSs due to potential differences in plant cover areas.

This study used yield data of monocultures from all over Ethiopia, as there is a lack of reliable research data on yields of agroforestry. The spatial yields were adjusted through empirical plant species-specific plant cover data and species ratios in AFSs of the country. However, based on the sensitivity analysis, the yield uncertainty of the differences between monocultures and agroforestry is not high enough to change the overall results of this study. Instead, a radical change to coffee prices might change the results, as coffee was the most prevalent cash crop, contributing on average 70% of the revenue of the eight applied plots except for one plot that had no coffee. The sequestration amounts of agroforestry are generalizable for different conditions as the range for the sequestration rates used was broad, even if conflicting evidence is presented as to whether the rates higher than the average rate used are actually achievable in the case study area of Sire (Nair et al. 2009; Keith et al. 2009). The impact was calculated using a broad plausible range of carbon prices. Thus, the carbon revenue is generally applicable; however, the relative profitability of the carbon revenue applies to the Rift Valley in East Africa, because costs, prices and yield amounts are for the area.

Profitability of AFSs relative to the dominant monocultures

In our study, AFSs were found to be many times more profitable than monocultures due to the higher price of fruit produce. A study done in the Wondo district by Kassa (2015) similarly concluded that the net revenue of fruit tree-based agroforestry was two to four times higher than that of monocultures (sugarcane, tomato + maize, potato + maize). Other studies report up to three to six times greater profits from AFSs relative to monocultures (Linger 2014; Peiris et al. 2003). Multiple studies have arrived at the same conclusion, namely, that investing in an AFS is more profitable than investing in a monoculture (Neupane and Thapa 2001; Rahman et al. 2007; Magcale-Macandog et al. 2010). Even research that takes into account social prices (tax, transaction costs and informal charges) still reaches the conclusion that intercropping provides more monetary benefit (Santos-Martin and Van Noordwijk 2011). Thus, the practical incentive to transition to an AFS from a monoculture appears to be contingent on the transition costs, i.e., the amount of work needed, possible lost produce, growing time of trees, etc., and the upfront costs might be a significant barrier.

Role of carbon revenue in the profitability of AFSs relative to monocultures

Based on our study, carbon revenue increases the profitability of agroforestry in comparison to monocultures by 2% ($8.50) to 300% ($40). With the lowest sequestration rate studied, the carbon revenue did not have a significant impact on the profitability of agroforestry relative to monoculture, but when the sequestration rate was high and the price for carbon was at the highest value studied ($40 Mg CO_2e), the carbon revenue was higher than the net revenue of any monoculture plot. Thus, with peak values, the carbon revenue could be the primary incentive for a transition to agroforestry in addition to other incentives, such as increased yield, food security and land rejuvenation. However, these monetary incentives are contingent on the transition costs from monocultures into agroforestry and from the transition and transaction costs of agroforestry into a viable project in the carbon credit markets. The transaction costs are especially relevant to small projects, but they can be reduced through farm cooperatives (Tefera et al. 2017). Transaction and transition costs seem to be the only disincentives and can be a barrier to entry, especially for smallholders.

Role of the carbon sequestration rate and carbon price in the profitability of AFSs

Our results indicate that carbon income could increase the profitability of agroforestry by 0.5–70%, depending on the price and sequestration rate of carbon. With high carbon sequestration values, the profitability of agroforestry increased from 15–70% by carbon income. Values higher than 10 Mg C ha^{-1} $year^{-1}$ (above the average rate used here) have been measured in humid tropical conditions in mixed species stands and agroforestry woodlots in Puerto Rico (Parrotta 1999) and cacao agroforestry in Costa Rica (Beer et al. 1990). In Sub-Saharan Africa, approximately 6 Mg C ha^{-1} $year^{-1}$ sequestration rates have been obtained in a shaded coffee system in Togo (Dossa et al. 2008) and from cacao agroforestry in Cameroon (Duguma et al. 2001). This sequestration rate would increase the profitability of this study's AFSs by 15% at a price of $22/tCO2e, which is in line with the West African study by González-Estrada et al. (2008) that found an increase in farm net profit from 2% to 32%. According to Luedeling et al. (2011), AFSs such as parklands, homegardens, and live fences in Sub-Saharan Africa sequester carbon in aboveground biomass only in the range of 0.2 $year^{-1}$0.8 Mg C ha^{-1} $year^{-1}$. This is the lowest sequestration rate used in this study and resulted in a profit increase for agroforestry of 0.5% ($8) to 2% ($40).

The price of carbon in the international market varies greatly depending on the market situation and political circumstances. The recent carbon price is just a few cents per ton of CO_2e and therefore Clean Development Mechanism projects are not profitable. The low price of carbon does not work as an incentive to motivate actions towards goals that mitigate climate change. This study uses the price range of $8–$40. The highest carbon price used is the social cost of carbon ($40/t$CO_2$e) by Tol (2011); however, some studies estimate that the social cost of carbon is actually even as high as $220 (Moore and Diaz 2015). Most analyses indicate that if an average carbon price of $80 to $120 is attained by 2030, then that would be sufficient to limit global warming to 2°C (IPCC 2014).

Some studies (De Jong et al. 2000; Masera et al. 2001; Makundi 2001; Ravindranath et al. 2001) have estimated the cost of carbon sequestration with forestry and agroforestry projects to be US$0.39 to $40 per ton of carbon (tC) in the tropics. These costs vary depending on the project size, site characteristics, cost of labor and amount of training and planning required, and whether the costs include opportunity costs. Study of on-the-ground carbon sequestration projects by De Jong et al (2004) arrived at costs (US$/tC) for different AFSs in Mexico as follows: live fence $8.76, improved fallow $7.92, and plantation in pasture $9.73. For the area studied in this work, it is safe to approximate that the breakeven point can be exceeded with a carbon price of $10 per tC, as labor costs in Ethiopia can be assumed to be cheaper than in Mexico, as long as the project is of a sufficient size and the amount sequestered is similar. However, as carbon projects in the form of agroforestry contain multiple inconstant variables, such as labor costs, unique site characteristics and project size, the final cost per tC can vary considerably and further research is required for a more precise cost approximation.

Conclusions

Our study concludes that carbon income may have a significant potential to motivate the conversion of arable land to agroforestry by East African smallholders when there is proper management, a sufficiently high carbon price, and efficient institutions. AFSs vary in their potential to sequester carbon, especially depending on the climate and soil, plant species composition and diversity, and overall management. Research is therefore needed on the key determinants of the carbon sequestration potential of AFSs. Further, to incentivize a transition to sustainable agroforestry practices, it is essential to ensure that the carbon income directly and fully benefits the resource-limited smallholder communities. Since the direct measurement of carbon sequestration of each agroforestry plot of smallholders is not feasible, models, such as those demonstrated by the current study that calculate the attainable carbon sequestration, the carbon revenue and the total revenue for an agroforestry plot with known characteristics, might facilitate upscaling carbon trading by smallholder communities. New knowledge is required on the transition and transaction costs and on potential barriers to the entry to the market by smallholders in various local and national contexts. Consequent solutions need to be co-created for the appropriate cross-scale institutions for monitoring agroforestry and trading carbon credits and for cooperative means to facilitate the market access and the gains by smallholder communities in Sub-Saharan Africa.

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Appendix

See Tables 4, and 5.

Table 2 Yield data with references

Crop	Yield kg/ha	Reference
Brassica oleracea L.	9466	Bernard et al. (2013)
Capsicum annuum L.	1975	Bernard et al. (2013)
Carica papaya L.	95,000	Bose et al. (1992)
Catha edulis Forsk.	2174	Bernard et al. (2013)
Citrus limon L.	40,000	FAO (2002)
Citrus sinensis L.	25,000	FAO (2002)
Coffea arabica L.	2378	Bernard et al. (2013)
Eragrostis tef (*Zucc.*) *Trotter*	1300	Rimhanen (2012)

Table 2 continued

Crop	Yield kg/ha	Reference
Ensete ventricosum Welw.Cheesman	6146	Bernard et al. (2013)
Hordeum vulgare	2500	Rimhanen (2012)
Jatropha curcas L.	125	Von Maltitz et al. (2016)
Lens culinaris	500	Rimhanen (2012)
Mangifera indica L.	10,000	Light (1997)
Musa acuminata Colla	8759	Bernard et al. (2013)
*Olea Africana Mil*L.	25/tree	Haifa. Nutritional recommendations for olives pp. 1–83 http://www.haifa-group.com/files/Guides/Olive_Booklet.pdf
Persea americana L.	14,000	MOFA. Ministry of food and agriculture republic of Ghana. https://mofa.gov.gh/site/?page_id=14099 Avocado production, Ghana
Phaseolus vulgaris L.	1700	Rimhanen (2012)
Punica granatum L.	13/tree	Dhanumjaya and Subramanyam (2009)
Saccharum officinarum L.	5100	FAOSTAT (2013)
Solanum lycopersicum L.	6000	Yeshiwas et al. (2016)
Solanum tuberosum L.	4886	Bernard et al. (2013)
Sorghum bicolor	2300	Rimhanen (2012)
Timber	1–2 m	Fernandes et al. (1984)
Triticum spp. L.	2200	Rimhanen (2012)
Zea mays L.	2700	Rimhanen (2012)

Table 3 Price data with references, USD1.00 = 20.5ETB

Crop	USD/kg	Reference
Brassica oleracea L.	0.44	Hagos (2013)
Capsicum annuum L.	0.65	Rehima and Dawit (2012)
Carica papaya L.	0.49	Hagos (2013)
Catha edulis Forsk	1.25	Hagos (2013)
Citrus limon L.	0.49	Hagos (2013)
Citrus sinensis L.	0.59	Hagos (2013)
Coffea arabica L.	3.66	Hagos (2013)
Eragrostis tef (*Zucc.*) *Trotter*	0.98	Hagos (2013)
Ensete ventricosum Welw.Cheesman	0.29	Hagos (2013)
Hordeum vulgare	0.58	Hagos (2013)
Jatropha curcas L.	0.15	Hagos (2013)
Lens culinaris	1.45	Hagos (2013)
Mangifera indica L.	0.39	Hagos (2013)
Musa acuminata Colla	0.49	Hagos (2013)
*Olea Africana Mil*L.	2.05	Hagos (2013)
Persea americana L.	0.39	Hagos (2013)
Phaseolus vulgaris L.	0.67	FAO (2015)
Punica granatum L.	0.8	POMASA. Pomegranate association of south Africa. http://www.sapomegranate.co.za/wp-content/uploads/2013/11/POMASA-Technical-Production-Manual.pdf
Saccharum officinarum L.	0.49	Investment Office ANRS (2008)
Solanum lycopersicum L.	0.81	Hagos (2013)
Solanum tuberosum L.	0.54	Hagos (2013)

Table 3 continued

Crop	USD/kg	Reference
Sorghum bicolor	0.49	Hagos (2013)
Timber	1/GJ	Asfaw and Dimissie (2012)
Triticum spp.	0.78	Hagos (2013)
Zea mays L.	0.49	Hagos (2013)

Table 4 Plant spacing data with references

Crop	Spacing	Reference
*Acacia Mil*L. *spp.*	2 m × 2 m	FAO (1993)
Carica papaya L.	2 m × 2 m	Bose et al. (1992)
Citrus limon L.	6 m × 6 m	Gonzales-Molina et al. (2008)
Citrus sinensis L.	5 m × 3 m	Wheaton et al. (1995)
Jatropha curcas L.	2 m × 4 m	Von Maltitz et al. (2016)
Mangifera indica L.	5 m × 5 m	Gaikwad et al. (2017)
Musa acuminata Colla	2 m × 2 m	Bose et al. (1992)
*Olea Africana Mil*L.	8 m × 5 m	Haifa. Nutritional recommentations for olives pp. 1–83 http://www.haifa-group.com/files/Guides/Olive_Booklet.pdf
Persea americana L.	7 m × 7 m	Shumeta (2010)
Punica granatum L.	5 m × 3.5 m	Shanmugasundaram and Balakrishnamurthy (2015)

Table 5 Sensitivity analysis

AFS						AFS (Net revenue decrease -50%)					
Production costs (%)	±	+ 10%	+ 20%	+30%	+40%	Production costs (%)	±	+ 10%	+ 20%	+30%	+40%
Monoculture											
	276	237	197	158	118	− 30%	138	118	99	79	59
− 20%	310	266	222	177	133	− 20%	155	133	111	89	67
− 10%	355	304	253	203	152	− 10%	177	152	127	101	76
±	**414**	355	296	237	177	±	207	177	148	118	89
+ 10%	497	426	355	284	213	+ 10%	248	213	177	142	106
+ 20%	621	532	444	355	266	+ 20%	310	266	222	177	133
+ 30%	828	710	591	473	355	+ 30%	414	355	296	237	177

The profitability of AFSs relative to monocultures when production costs of AFSs decrease or increase (%) and if AFS revenue decreases by 50%. Modeled yields and revenues for the composition of the plant species of the eight agroforestry plots (I–VIII) documented by Rimhanen et al. (2016) and typical plant species densities in Ethiopian multistrata AFSs (Table 3) and yields in AFSs (kg/0.2 ha/year) (Table 2). Agroforestry was, on average, four times more profitable than the main monoculture systems (wheat, barley, maize, teff, sorghum, sugarcane and lentil). Baseline (414) is bolded

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