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Crop vs. tree: Can agronomic management reduce trade-offs in tree-crop interactions?

Tesfaye Shiferaw Sida[a,b,*], Frédéric Baudron[c], Kiros Hadgu[d], Abayneh Derero[e], Ken E. Giller[b]

[a] International Maize and Wheat Improvement Centre (CIMMYT)-Ethiopia, Gurd Shola, c/o ILRI, P.O. Box 5689, Finfinne/Addis Ababa, Ethiopia
[b] Plant Production Systems, Wageningen University, P.O. Box 430, 6700AK Wageningen, Netherlands
[c] International Maize and Wheat Improvement Centre (CIMMYT), Southern Africa Regional Office, P. O. Box, MP 163, Mazowe Road, Harare, Zimbabwe
[d] World Agroforestry Centre (ICRAF)-Ethiopia, Gurd Shola, c/o ILRI, P.O. Box 5689, Addis Ababa, Ethiopia
[e] Ethiopian Environment and Forest Research Institute, Addis Ababa, Ethiopia

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ABSTRACT

Scattered trees dominate smallholder agricultural landscapes in Ethiopia, as in large parts of sub-Saharan Africa (SSA). While the inclusion of scattered trees could provide a viable pathway for sustainable intensification of these farming systems, they also lead to trade-offs. We carried out a study to: 1) explore the rationale of farmers to maintain on-farm trees beyond crop yield; 2) quantify the impact of agronomic practices on the outcome of tree-crop interactions; and 3) analyse partial economic trade-offs for selected on-farm tree species at farm scale. We recorded agronomic practices within the fields of 135 randomly selected farms from seedbed preparation to harvesting. A multivariate analysis showed that farmers maintained on-farm trees because of their direct timber, fencing, fuelwood, and charcoal production values. Trees generally had a significant negative effect on maize yield. Mean grain yields of 1683, 1994 and 1752 kg ha^{-1} under the canopies of *Cordia, Croton* and *Acacia,* respectively, were significantly lower than in their paired open field with mean yields of 4063, 3415 and 2418 kg ha^{-1}. Besides, more income from trees was accompanied by less income from maize, highlighting trade-offs. However, agronomic practices such as early planting, variety used, improved weed management, fine seedbed preparation and higher rates of nitrogen fertilizer significantly reduced yield penalties associated with trees. We found an inverse relationship between land size and on-farm tree density, implying that the importance of trees increases for land-constrained farms. Given the expected decline in per capita land size, scattered trees will likely remain an integral part of these systems. Thus, utilizing 'good agronomic practices' will be vital to minimize tree-crop trade-offs in the future.

1. Introduction

Scattered trees within crop fields are an integral part of smallholder agricultural landscapes in Ethiopia and large parts of sub-Saharan Africa (SSA) (Lengkeek et al., 2005; Endale et al., 2017). Fast population growth in the region is expected to cause greater demand for food, fuel and fibre, intensifying the pressure of agricultural production on the environment (Yu et al., 2012). The century-old practice of managing scattered trees on crop fields has been suggested as one of the pathways for sustainable intensification of smallholder agriculture in the region (Pretty et al., 2011). In addition to their direct provision of food, fibre and fuel (Alavalapati et al., 2004; Calvet-Mir et al., 2012), scattered on-farm trees are known to provide multiple ecosystem services (Asaah et al., 2011; Ango et al., 2014). Planted fast growing tree species or naturally grown scattered mature trees in crop fields, have been advocated as an affordable and sustainable means to improve and sustain soil fertility for smallholders in SSA (Glover et al., 2012). They can be used to minimize the problem of soil fertility decline (Akinnifesi et al., 2011), which is reported to have an indirect negative impact on household food security in Ethiopia (Haileslassie et al., 2005). Even under situations where short-term negative effects of on-farm trees on crop yield may prevail (Clough et al., 2011), they were reported to have long-term positive effects on the overall system productivity and sustainability (Malézieux, 2012).

By contrast, on-farm trees may compete with annual crops for resources. Their interactions with crops involve complex management decisions in order to maximize total farm-level benefits. Regardless of established ecological and provisioning contribution of trees (Bayala et al., 2002), their direct contribution to increased crop yield is often contested (Coulibaly et al., 2014) and context specific (Brandt et al.,

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[*] Corresponding author at: CIMMYT, Shola Campus, ILRI, P.O. Box 5689, Addis Ababa, Ethiopia.
E-mail address: tesfayesida@gmail.com (T.S. Sida).

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2012). Moreover, tree shade reduces light penetration to understory crops, limiting their rate of photosynthesis (Ong and Kho, 2015). While crop yield penalties are expected as a result of tree-crop competition for resources, farmers still maintain trees on their farms. This conforms with the findings of Boffa (2000) who suggested parkland trees are planted and maintained for their benefits in the overall farming system, not solely for their direct effects on crop yields. Den Biggelaar and Gold (1996) also showed that preferences for indigenous on-farm tree species are driven by context-specific values and their multiple uses rather than solely by financial and economic factors. On-farm trees are also maintained for their social and cultural values (Gustad et al., 2004). On the other hand, Kindt et al. (2004) found that woody species richness tended to increase with land size in smallholder systems, while Lengkeek et al. (2005) found that the number of on-farm trees declined with increasing land size. This is, perhaps, because managing trees with crops requires extra labour, forcing farmers with larger farms to manage relatively fewer trees. A recent study from the Oromia state of Ethiopia revealed that adoption of exotic tree species and maintenance of indigenous ones depended on farm assets such as total land size and income from livestock (Iiyama et al., 2017). Total land size affected positively the maintenance of indigenous tree species, while increased income from other farm enterprises had a negative influence on it.

Farmers potentially minimize tree-crop competition effects by managing both crops and trees. While many studies assessing the negative effects of tree-crop interaction have focused on management practices that manipulate the tree component such as root and canopy pruning (Bertomeu et al., 2011), studies exploring the potential impact of manipulating the crop component are scarce. Changes in crop planting schedules, and adaptations of crop genetic characteristics such as maturity class, competition tolerance, vulnerability to pests, and sensitivity to tree shade can be used to improve crop competitiveness with trees (Rosenzweig et al., 2004). Although the impact of these agronomic managements have been widely studied in the absence of trees (Kolb et al., 2012), it was seldom the case in tree-crop systems. On the other hand, differences in biophysical conditions resulted in different competition mechanisms, forcing farmers to practice different management options to minimize trade-offs in tree-crop production systems elsewhere (Huth et al., 2010). We expect that farmers may adapt agronomic practices such as field preparation, planting date, fertilization rate, variety selection, weeding, and cultivation in order to minimize trade-offs in tree-crop interactions. Thus, the overarching objective of the study was to understand farmers' motivations, impacts on crops and economic trade-offs from scattered trees in a semi-arid and two sub-humid agricultural landscapes in Oromia, Ethiopia. Specifically, we aimed: 1) to explore farmers' rationale of maintaining trees on-farm, beyond the effects on crop yield; 2) to quantify the impact of agronomic practices on the outcome of tree-crop interactions; and 3) to analyse partial economic trade-offs for selected on-farm trees at farm scale.

2. Materials and methods

2.1. *Study area*

We used a combination of household survey and field measurements in two contrasting agroecosystems (semi-arid and sub-humid) in Ethiopia (Table 1). We selected two sites from a sub-humid agroecoregion and one from a semi-arid agroecoregion. The semi-arid site – Meki – is located in the Central Rift Valley of Ethiopia, while the two sub-humid sites – in Bako – are located in the western part of the country. All study sites are similarly characterised by mixed crop-livestock farming systems, with substantial on-farm tree cover as a dominant feature. Trees are scattered within crop fields, retained during selective clearing of the original vegetation (Tolera et al., 2008).

2.2. *Sampling and data collection*

2.2.1. *Sampling and yield estimation*

We purposively selected three indigenous on-farm tree species, which were the most dominant in each of the sites. *Cordia africana* (Cordia) and *Croton macrostachyus* (Croton) were the most dominant species in Bako, whereas *Acacia tortilis* (Acacia) was the most dominant in Meki. To simplify reporting, we used genus names (given in the parenthesis) when referring to these species in the rest of the paper. For each species, we randomly selected 45 farmers who managed trees on maize fields, creating a combined sample of 135 farms. We purposefully selected one field from every farm for data collection using the criteria: (1) the tree species of interest was grown within maize fields, (2) the selected tree was located in maize field isolated from other on-farm trees by at least 40 m, and (3) open field and under canopy plots had similar landform and cropping history. In addition, individual trees for a particular species were selected to be as similar as possible. We measured tree heights and canopy diameters (East-West and North-South) for the sampled trees. We fixed the DBH, canopy radius and height of the selected trees to be within 10% of the size of the first randomly selected tree, in order to maintain reasonable similarity between selected trees.

We established three sampling plots, each 4 m^2 in size, for each of the 135 farms (Fig. 1). One plot was established for maize in the open field, which was at least 40 m away from the nearest tree, and two plots, from which a single average yield was computed to account for under canopy heterogeneity, were established at a distance of 2 m from the tree trunk (referred to as under tree canopy maize). We collected maize yield and yield components from all plots. Maize samples were oven-dried for 48 h at 60 °C to determine total dry biomass and grain yields.

2.2.2. *Soil moisture and solar radiation*

For all plots described in the previous section, we measured topsoil moisture content three times between silking and physiological maturity using ML3 ThetaProbe© moisture sensors (Delta-T-Devices, 2013). For each measurement time, we sampled soil moisture from five points, randomly selected within the plots (Fig. 1a), and used the mean value from these five points for analysis. Similarly, for each measurement time, we measured photosynthetically active radiation (PAR) above maize canopies using sensors from SunScan© Canopy Analysis System (Webb et al., 2013). All PAR measurements were conducted at midday on cloudless days over maize canopies of sampled plots. We made this measurement simultaneously over the canopy of maize under and away from tree canopy, using a Beam Fraction Sensor (BFS) that was wirelessly connected to the main scanner (Fig. 1b). We used the mean of these three measurements for analysis.

2.2.3. *Household survey*

Each household whose field was selected for data collection was surveyed for socio-economic characterization (Appendix A). Farm-level information such as land holding, family size, livestock holdings and total number of trees on the farms were recorded. The agronomic management of the selected fields such as: land preparation, planting date, fertilization rate, variety used, weeding, and cultivation were recorded, using open-ended questions implemented from the start of seedbed preparation to harvesting. In addition, we used a questionnaire to explore the main rationale of maintaining selected scattered on-farm tree species. First, we appraised this rationale, using semi-structured interviews with key informants and focus group discussions. We identify the 10 most frequently mentioned values of each tree species and quantified the values on a Likert scale with five levels (Gliem and Gliem, 2003). We also quantified the direct economic benefits from trees in the form of charcoal, timber, fencing material and firewood from this survey, using open-ended questions.

Table 1
Summary of the general characteristics of the study areas.

Site features	Meki	Bako 1	Bako 2
Region	Central Rift Valley of Ethiopia	Western Ethiopia	Western Ethiopia
Geographic location	38.866° E and 8.181° N	37.098° E and 9.126° N	37.067° E and 9.088° N
Agroecology	Semi-arid	Sub-humid	Sub-humid
Mean annual rainfall	731 mm	1266.5 mm	1283.4 mm
Mean annual maximum T°	28.4C°	29.8C°	30.5C°
Mean annual minimum T°	13.6C°	13.4C°	13.6C°
Annual mean T°	21C°	21.6C°	22.1C°
Dominant soil type	Andosols	Nitisols	Nitisols
Elevation m.a.s.l.	1500–1650 m	1700–2000 m	1500–1727 m
Dominant on-farm tree species	*Acacia tortilis, Faidherbia albida*, other *Acacia* spp.	*Croton macrostachyus, Ficus* spp.	*Cordia africana, Ficus* spp.
Tree species studied	*Acacia tortilis*	*Croton macrostachyus*	*Cordia africana*
Major crops	Maize, *teff*, beans, wheat, sorghum	Maize, *teff*, sorghum, *Nug*	Maize, *teff*, sorghum, *Nug*
Number of fields surveyed	45	45	45
Farm area (ha/household ± sd)	4.1 ± 0.9	1.7 ± 2.1	2.3 ± 1.5

2.3. Statistical analysis

2.3.1. Farmers' rationale to maintain on-farm trees

To explore farmers' rationale of planting and maintaining on-farm trees beyond crop productivity, we used a generalized linear model (GLM). We used the on-farm density and total number of trees as proxies for the importance that farmers attach to the utilities of on-farm trees. Thus, we examined the influence of the perceived values on the density and total number of trees. In the GLM, we treated density and total number of on-farm trees as dependent variables. The perceived values (in Likert Scale) of each species were modelled as independent variables. We used log-transformed values of on-farm tree density to satisfy the parametric assumption (Eq. (1)). An additional model where the absolute number of trees was used as a dependent variable was fitted using a Poisson distribution (which is appropriate for count data). The variable 'land size' was added as a factor in both models.

$$(1)\,\boldsymbol{Y_{ijklmnpqrs} = \alpha + \varphi LS + \beta TM_i + \mu CC_j + \partial SF_k + \gamma CY_l + \delta FD_m + \eta CV_n + \rho FW_p + \tau FN_q + \lambda SH_r + \pi SM_s + R}$$

Where, $Y_{ijklmnpqrs}$ is the log-transformed on-farm tree density or the number of on-farm trees, LS is the land size, TM_i is the i^{th} value for timber production, CC_j is the j^{th} value for charcoal production, SF_k is the k^{th} value for soil fertility improvement/maintenance, CY_l is the l^{th} value in improving yield, FD_m *is* the m^{th} value as source of animal fodder, CV_n is the n^{th} value as cultural utility, FW_p is the p^{th} value as source of firewood, FN_q is the q^{th} value as source of fencing material, SH_r is the r^{th} value as animal/human shade and SM_s is the s^{th} value as soil moisture improvement/maintenance, while α, φ, β, μ, ∂, γ, δ, η, ρ, τ, λ and π represent regression coefficients and R is the residual of the model. We fitted the models for each tree species separately, as the rationale of maintaining each of them could be species-specific. Detailed description of the variables assessed, their units and assessment methods were presented in Table 2.

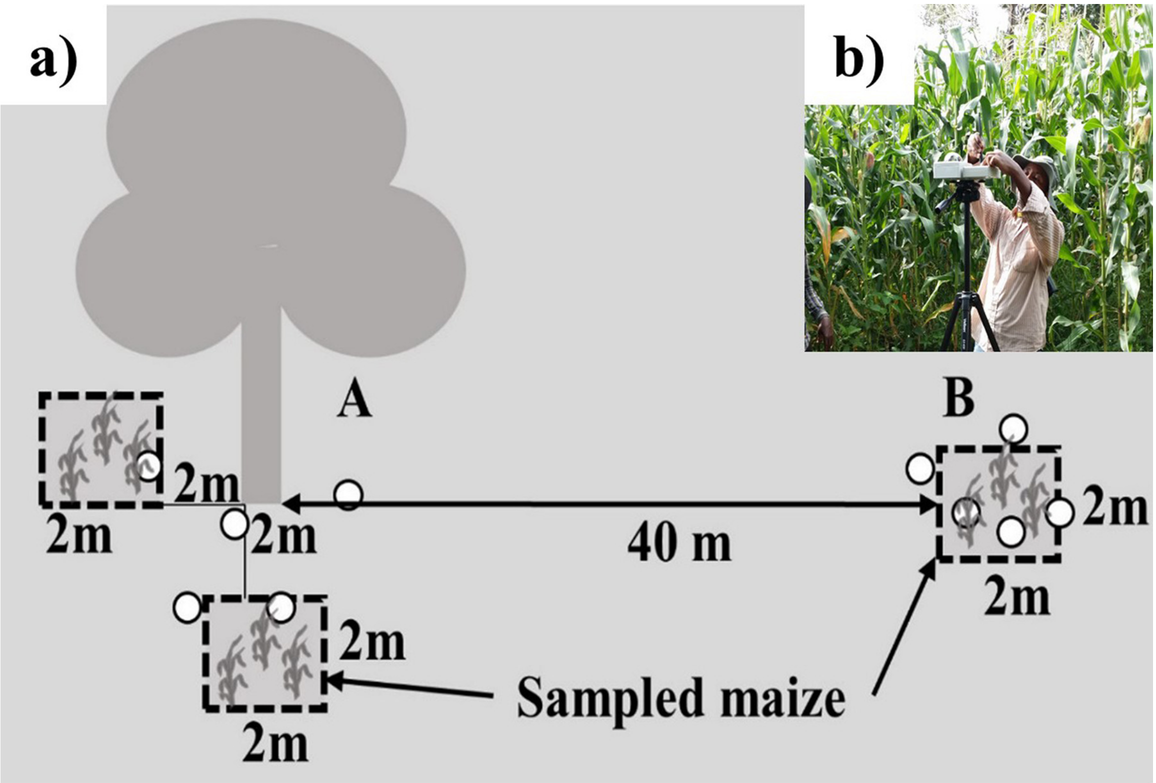

Fig. 1. A sketch of measurement set up within the field (a) and wireless beam fraction (BFS) sensor setting in open field for PAR measurement (b). Broken lines and white dots indicate maize yield and moisture measurement locations, respectively, under tree canopy (A) and in the open field (B).

Table 2
Summary of major variables assessed, their units, methods of assessment and sample size.

Variables	Unit	Method	N
Measuredvariables			
Grain yield	kg ha^{-1}	Direct measurement	270
PAR	μmolm^{-2}s^{-1}	Direct measurement	270
Soil moisture	%V	Direct measurement	270
Land size	ha	GPS measurement	135
Number of trees	No. ha^{-1}	GPS & Survey	135
Tree canopy diameter	m	Direct measurement	135
Perceived values of trees			
Soil fertility maintenance	Likert scale	Survey	135
Maize yield improvement	Likert scale	Survey	135
Human and animal shade	Likert scale	Survey	135
Timber production	Likert scale	Survey	135
Cultural value	Likert scale	Survey	135
Firewood production	Likert scale	Survey	135
Fencing material	Likert scale	Survey	135
Charcoal production	Likert scale	Survey	135
Soil moisture improvement	Likert scale	Survey	135
Inputs and management practices			
Rate of urea	kg ha^{-1}	Survey & measurement	270
Rate of DAP	kg ha^{-1}	Survey & measurement	270
Rate of organic fertilizer	kg ha^{-1}	Survey & measurement	270
Date of planting	Calendar date	Survey & observation	270
Crop variety	Variety name	Survey & observation	270
No. herbicide application	No.	Survey & measurement	270
No ploughing	No.	Survey & measurement	270
No. weeding	No.	Survey & measurement	270
Farm-level benefits			
Direct values of tree products	ETB/farm	Shadow price	135
Sale of maize	ETB/farm	Shadow price	135
Farm-level- trade-offs			
Yield loss because of trees	ETB/farm	Calculation	135

2.3.2. Impact of agronomic practices on maize yield

We used GLM to assess the impact of different agronomic practices on the variability of maize yield (Eq. (2)).

$$(2)\,Y_{ijkl} = \alpha + \partial TR_{k(i)} + \gamma UR + \delta DAP + \theta OF + \rho DP + \varphi CV_l + \lambda HF + \Psi NC + \mu NP + \pi WF + \omega SP_j{:}TR_{k(i)} + \chi SPj{:}UR + \vartheta SP_j{:}DAP + \Lambda SP_j{:}DP + \eta SP_j{:}CV_l + \tau SP_j{:}HF + \text{ʒ} SP_j{:}WF + R$$

Where, $Y_{ijkl,}$ is square-root-transformed maize yield, SP_j is the j^{th} tree species, $TR_{k(i)}$ is the k^{th} treatment (i.e. presence or absence of a tree) nested within the i^{th} farm, UR is the rate of urea fertilizer, DAP *is* the rate of DAP fertilizer, OF is the rate of organic amendment, DP is the date of maize planting, CV_l is the l^{th} type of maize variety, HF is the frequency of herbicide application, NC is the frequency of cultivation, NP is the number of ploughing for seedbed preparation and WF *is* the x^{th} frequency of hand weeding, while $\alpha, \beta, \partial, \gamma, \delta, \theta, \rho, \varphi, \lambda, \Psi, \mu, \pi, \omega, \vartheta, \Lambda, \eta, \tau, \chi$ and ʒ are coefficients of main and interaction effects, and R is the residual of the model. Because under canopy and open field samples within a single farm were significantly correlated ($r = 0.23, P < 0.01$), the effect 'treatment' was analysed nested within the factor 'farm'. Tree species (which overlaps with location) and the vector of variables of agronomic practices were modelled as independent variables. Although the model was applied to square-root-transformed values of grain yield to satisfy the normality assumption during mean comparison, reference to the mean in the discussion section is made to the back-transformed least squared mean (i.e. the mean that was adjusted for other factors). We used the probability level of 0.05 to test the significance of each effect in the model, unless otherwise stated. Interactions and main effects that had small explanatory power, i.e., variables with *F*-values of less than 0.1, were removed.

2.3.3. Partial trade-off analysis

To make a partial economic analysis, we first computed the total area of the farm covered by tree canopies (Table 2). To calculate this area, we computed the mean canopy diameter from North-South and East-West canopy extensions of the sample trees. We extrapolated this area for the total number of trees on the farm to get the total area of the farm under the influence of tree canopies. We calculated the reduction in maize yield under canopies for this area and computed total yield penalty as a result of the presence of trees. We made the assumptions: (1) that all trees within a farm have approximately similar mean canopy diameter and (2) that maize under the other tree canopies would be

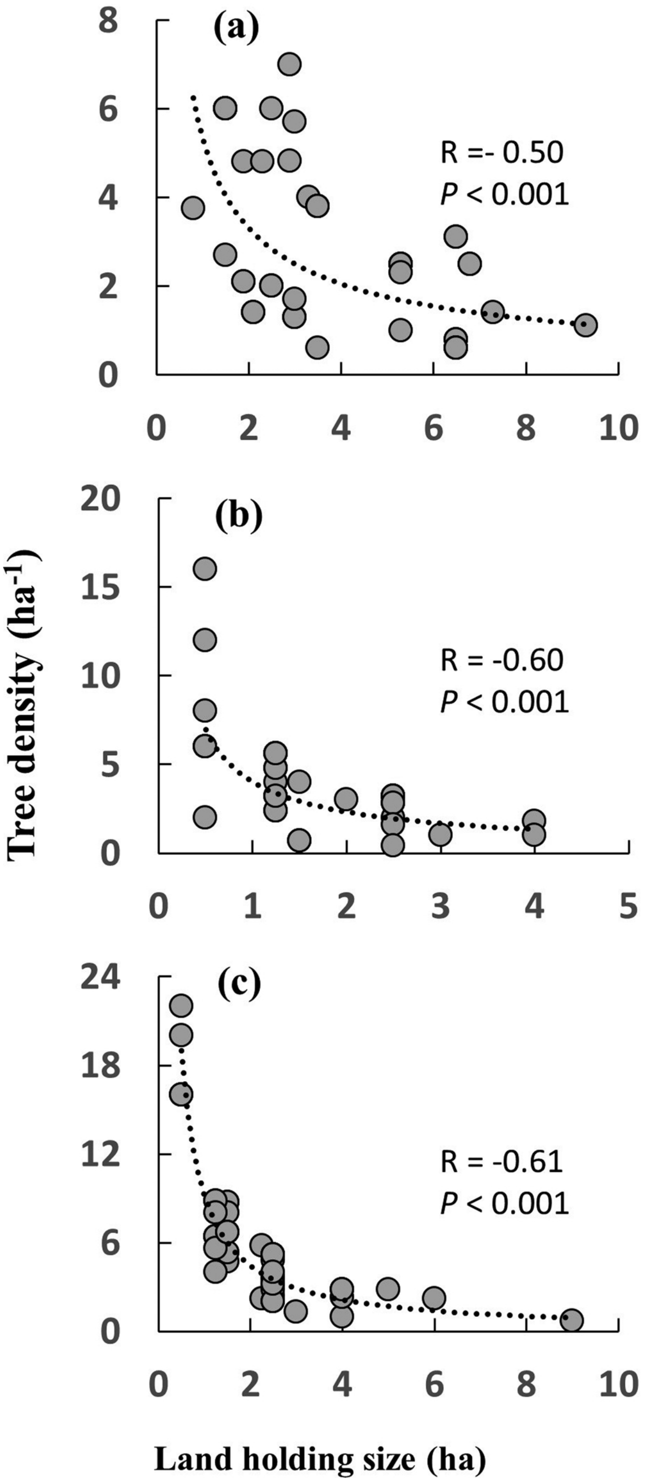

Fig. 2. Relationship between households land holding size and the density for three on-farm tree species: *Cordia africana* (a), *Croton macrostachyus* (b) and *Acacia tortilis* (c).

Table 3
Summary of the result of a regression model showing the variation in on-farm density and number (ha^{-1}) of*Cordia africana* (Cordia) as a result of its perceived utilization values. Probabilities with significant effects ($P < 0.05$) are indicated in bold.

Explanatory variables	Dependent variables			
	Tree density (No.ha^{-1})		Tree count (No. farm $^{-1}$)	
	Coefficients	*P* values	Coefficients	*P* values
(Intercept)	0.25	0.581	0.40	0.430
Land size	−0.23	< **0.001**	0.04	0.422
Maize yield improvement	−0.07	0.128	−0.02	0.724
Timber production	0.18	< **0.01**	0.05	0.373
Firewood production	0.04	0.384	−0.02	0.578
Fencing material	0.18	< **0.05**	0.24	< **0.05**
Soil fertility maintenance	0.07	0.095	0.01	0.816
Human and animal shade	0.09	0.398	0.14	0.216
Charcoal production	−0.01	0.851	0.02	0.723

Table 4
Summary of the result of a regression model showing the variation in on-farm density and number (ha^{-1}) of *Croton macrostachyus*(Croton) as a result of its perceived utilization values. Probabilities with significant effects ($P < 0.05$) are indicated in bold.

Explanatory variables	Dependent variables			
	Tree density (No.ha^{-1})		Tree count (No. farm $^{-1}$)	
	Coefficients	*P* values	Coefficients	*P* values
(Intercept)	1.13	< **0.05**	−0.28	0.759
Land size	−0.06	0.524	0.55	< **0.001**
Maize yield improvement	0.02	0.676	0.02	0.750
Timber production	0.01	0.890	−0.07	0.363
Firewood production	0.29	< **0.01**	0.33	< **0.01**
Fencing material	0.13	0.139	0.10	0.411
Soil fertility maintenance	−0.02	0.668	0.01	0.820
Human and animal shade	0.02	0.695	0.07	0.626
Charcoal production	−0.05	0.289	0.03	0.671

affected in a similar manner to our samples. As the economic benefits per tree depended on the frequency of pruning and site-specific local prices (Appendix B), we quantified these values for each farm separately. We estimated the amount of each harvestable products from each tree, using the questionnaire. We used current market values of the corresponding products to monetize them. We used local units and local market prices of these products (Appendix B) to calculate the total farm-level income from each tree species. In cases where the economic benefits were expected to occur in the future, we calculated Net Present Values (NPV) using the current interest rate of Oromia International Bank, which was 4.5%. Farm gate maize prices were used to estimate losses in maize yield associated with trees (Appendix B). Because of the difficulty of measuring all aspects of ecosystem services of trees and their contributions to livelihoods, this study was limited to a trade-off analysis based solely on monetary valuations. We plotted total farm-level income from tree products against total farm-level loss of income resulting from the impact of trees on maize yield (i.e., the opportunity cost associated with trees, which was used in the rest of the text).

3. Results

3.1. Rationale for maintaining on-farm trees and its relation to land size

Although densities of on-farm trees could be higher when other tree species are considered, the current densities of Cordia (*Cordia africana*), Croton (*Croton macrostachyus*) and Acacia (*Acacia tortilis*) were 4.6, 3.7 and 2.6 trees ha^{-1}, respectively (Fig. 2). However, on-farm tree densities varied from farm to farm with the perceived utilities of each tree species (Tables 3–5). The density of Cordia was significantly higher on farms where farmers rated its direct use as timber and fencing material to be highly important ($P < 0.05$). Its density was 18% higher on farms where farmers rated it to be highly important as a source of timber (Table 3). On farms where this species was perceived to be highly important as a source of fencing material, the density and total number of on-farm Cordia trees, respectively, were 18% and 24% higher, compared with farmers who rated it less for these utilities. From the coefficients in Table 4, the density of Croton trees was 29% higher ($P < 0.01$) and the total number of Croton trees was 33% larger on farms where farmers perceived it as an important source of firewood. From Table 5, the density of Acacia was significantly higher ($P < 0.01$) on farms where it was valued for shade provision (21% higher), firewood (12% higher) and charcoal production (14% higher). Only the perceived importance in shade provision was significantly related to the total number of on-farm Acacia trees.

In addition to their utilities, incorporation of trees into crop fields appeared to be dictated by land size (Fig. 2 and Tables 3–5). Farmers whose land holding was within the first quartile of the sampled farms had significantly ($P < 0.01$) higher density of Cordia, Croton and Acacia trees on-farm compared with farmers whose land size was within the fourth quartile for all tree species studied. Mean land size for the first quartile of farmers was 0.96 ha in the Cordia-dominated site (Bako). Mean on-farm density of Cordia for farmers in this category of land size was 11.9 trees ha^{-1}. By contrast, mean land size for the fourth quartile of farmers was 4.9 ha in the Cordia-dominated site, while farmers in this land size category owned only about two trees ha^{-1}. Similarly, farmers who were within the first quartile for their land size (mean of 0.5 ha) were in the fourth quartile for on-farm density of Croton (mean of 8 trees ha^{-1}). The trend remained similar for the Acacia-dominated site (Meki), where farmers who were in the first quartile for their land size (mean of 1.7 ha) were within the fourth quartile for their on-farm density of Acacia (mean of 3.8 trees ha^{-1}).

3.2. Consequences of on-farm trees on crop performance

Our results indicated that trees had generally a negative effect on

Table 5
Summary of the result of a regression model showing the variation in on-farm density and number (ha^{-1}) of *Acacia tortilis* (Acacia) as a result of its perceived utilization values. Probabilities with significant effects ($P < 0.05$) are indicated in bold.

Explanatory variables	Dependent variables			
	Tree density (No.ha^{-1})		Tree count (No. farm $^{-1}$)	
	Coefficients	*P* values	Coefficients	*P* values
(Intercept)	−0.68	< **0.05**	−0.30	0.571
Land size	−0.09	< **0.001**	0.11	< **0.01**
Animal fodder	−0.06	0.297	−0.10	0.281
Firewood production	0.12	< **0.05**	0.06	0.417
Fencing material	0.12	< **0.05**	0.08	0.428
Soil fertility maintenance	−0.01	0.732	0.02	0.623
Human and animal shade	0.21	< **0.01**	0.33	< **0.01**
Cultural value	−0.03	0.178	−0.03	0.383
Soil moisture improvement	−0.03	0.245	−0.02	0.617
Charcoal production	0.14	< **0.01**	0.11	0.126

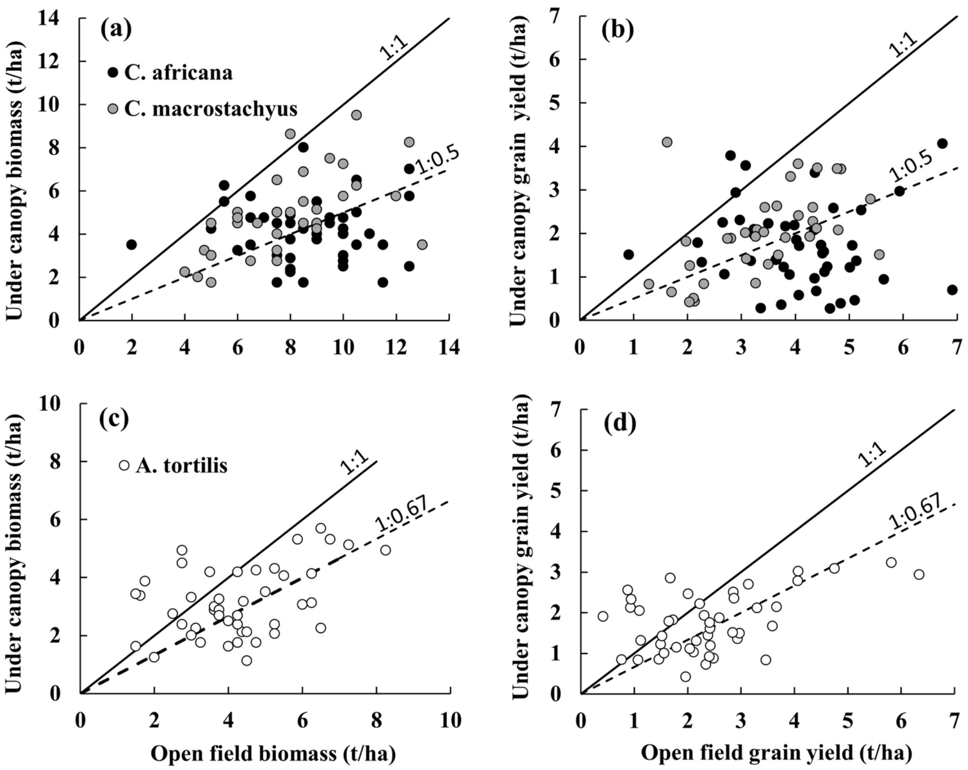

Fig. 3. Comparison of total aboveground biomass (a) and maize grain yield (b) between open field and under canopy for *Cordia africana, Croton macrostachyus*, and total aboveground maize biomass (c) and maize grain yield (d) between open field and under canopy for *Acacia tortilis*. Solid lines represent the 1:1 relationship, while broken lines represent fitted values for maize yield in the open fields and under tree canopies.

total aboveground biomass and grain yields, both in sub-humid and semi-arid agroecologies (Fig. 3). As indicated in Table 6, grain yield was significantly higher ($P < 0.01$) in the open field (average grain yield of 3289 kg ha^{-1}) than under tree canopies (average grain yield of 1795 kg ha^{-1}), regardless of the tree species. However, the model output in Table 6 showed that the interaction between tree species and treatment (i.e., presence or absence of trees) was highly significant ($P < 0.01$), highlighting species-specific or climate dependent effects of trees. For example, the reduction in mean grain yield was the highest for Cordia: 1683 kg ha^{-1} and 4063 kg ha^{-1} under and away from tree canopy, respectively, which was a 78.9% reduction. The second most important reduction in grain yield was for Croton with mean grain yield of 1683 kg ha^{-1}and 3415 kg ha^{-1} under and away from tree canopy, respectively, which corresponded to a 41.6% reduction. The presence of Acacia resulted in a mean grain yield reduction of 27.5% (i.e., an average grain yield of 1752 kg ha^{-1} under its canopy compared with an average grain yield of 2418 kg ha^{-1} in open fields).

3.3. *Impact of agronomic management practices on tree-crop interaction*

From Table 6, there was a highly significant interaction effect between treatment and date of maize planting ($P < 0.01$). Planting dates, which ranged from April 23 to June 21 in the study area, were categorized into: early planting dates (earlier than the 3rd of May), medium planting dates (3rd to 11th of May) and late planting dates (later than May 11th) for analysis. Late planting date resulted in the highest yield penalty (62% reduction) from the presence of the tree (least squared mean grain yield of 3811 kg ha^{-1} and 1436 kg ha^{-1} for open field and under canopy, respectively). Planting earlier than the 3rd of May, resulted in a 46% yield reduction associated with the presence of trees (least squared mean grain yield of 3611 kg ha^{-1} and 1942 kg ha^{-1} for open field and under canopy grain yields, respectively). A yield reduction of 26% due to the presence of trees was observed for the planting window of 3rd-10th of May. However, this window of planting resulted in the lowest mean grain yield of all the planting periods for open field (least squared mean of 2668 kg ha^{-1}).

The model in Table 6 also showed that there was a significant interaction effect ($P < 0.05$) between treatment and application rate of urea. At low rate of urea (0–50 kg ha^{-1} urea), both under canopy (least squared mean 1765 kg ha^{-1}) and open field (least squared mean of 2809 kg ha^{-1}) grain yields were low. In this case, tree presence reduced yields by 37%, which was still significant ($P < 0.01$). For medium rate of urea (50–125 kg ha^{-1} urea), grain yield in the open field increased to 3990 kg ha^{-1}, while under canopy grain yield remained almost similar

Table 6

Summary of the results of a GLM model explaining the variability of maize grain yield as a result of agronomic management for maize grown in open conditions and under shades of different tree species (*Acacia tortilis, Croton macrostachyus*, and *Cordia africana*). Treatment = presence or absence of trees, No. ploughing = number of ploughing for seedbed preparation, No. cultivation = number of maize cultivation, No. weeding = number of hand weeding operations, No. herbicide application = number of application of herbicide, and DAP = diammonium phosphate fertilizer. Probabilities of significant effects ($P < 0.05$) are indicated in bold.

Effects	DF	F-Value	*P*-value
Intercept	127	15.1	< **0.001**
Tree species	2	0.3	0.614
Treatment (tree or no tree)	1	253.7	< **0.001**
Crop variety	8	3.1	< **0.01**
Date of planting	2	2.5	0.088
No. ploughing	1	9.5	< **0.01**
Rate of DAP	1	1.7	0.194
Rate of organic fertilizer	1	0.4	0.524
No. weeding	1	9.3	< **0.01**
No. herbicide application	1	18.1	< **0.001**
No. cultivation	1	0.8	0.381
Tree Species: Treatment	2	39.2	< **0.001**
Treatment: Rate of Urea	2	4.7	< **0.05**
Treatment: No. cultivation	1	11.2	< **0.01**
Treatment: Rate of DAP	1	3.0	0.084
Treatment: Date of planting	2	5.3	< **0.01**
Treatment: Crop variety	8	2.0	< **0.05**
Treatment: No. ploughing	1	23.0	< **0.001**
Treatment: Herbicide	1	5.0	< **0.05**

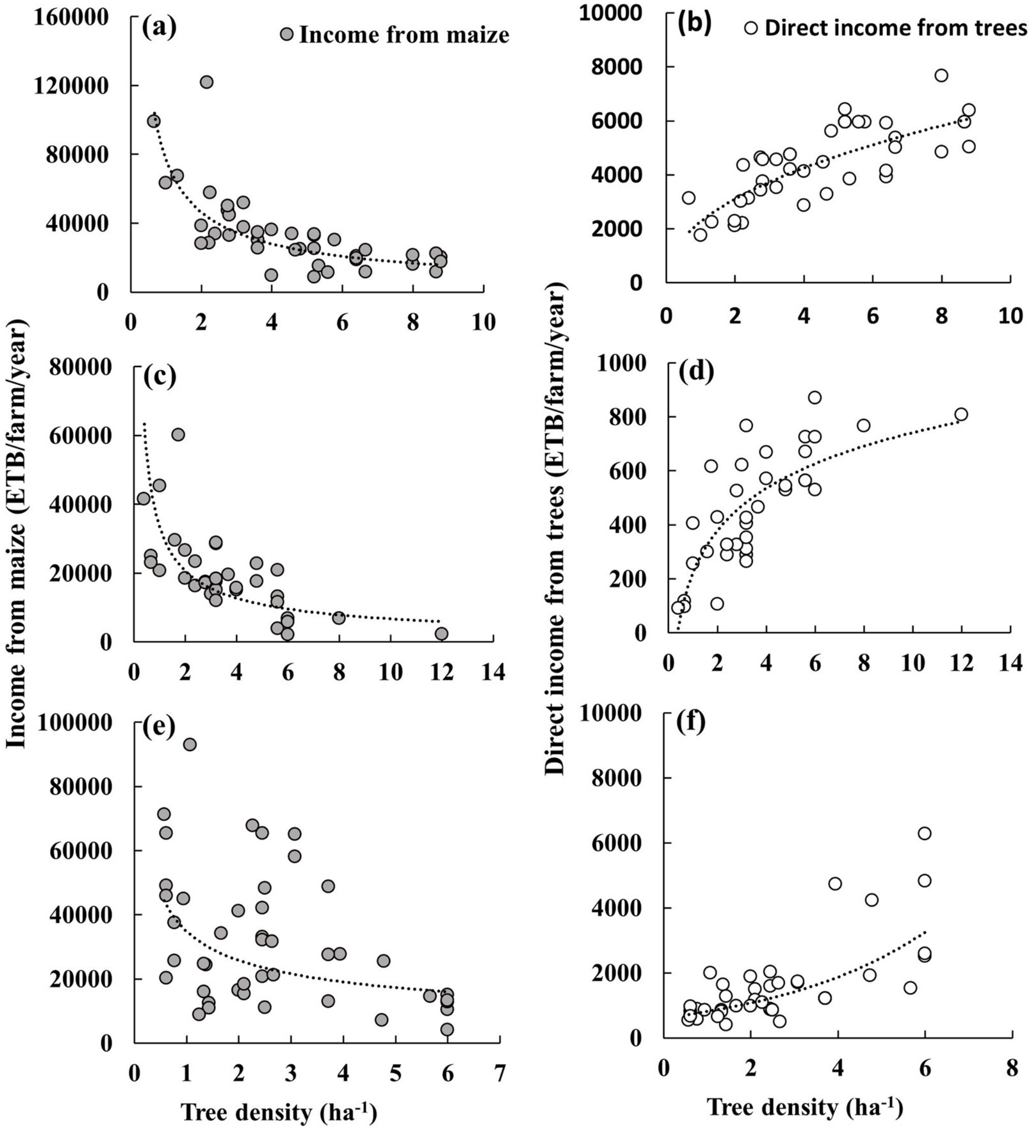

Fig. 4. Relationship between total annual farm income from maize and on-farm tree density (a, c, e) and Net Present Values of annual direct income from tree products (b, d, f) for *Cordia africana* (a–b), *Croton macrostachyus* (c-d) and *Acacia tortilis* (e-f). Broken lines represent fitted curves. ETB = Ethiopian Birr (20ETB = 1USD, 2016).

to the under canopy yield with low rate of urea (1785 kg ha^{-1}). This corresponded to 55% reduction in maize grain yield under tree canopy compared with open field conditions. At higher rates of urea (125–200 kg ha^{-1} urea), under canopy grain yield (least squared mean of 3440 kg ha^{-1}) was only 20% lower compared with open field grain yield (least squared mean of 4341 kg ha^{-1}). From this result, there is an indication that maize grown under the canopy only responded to the highest rates of urea application. This analysis did not include Acacia.

From the model results, the type of maize variety had a highly significant interaction effect with the presence or absence of trees ($P < 0.001$). High-yielding hybrid varieties such as BH-661 (76.7% grain yield reduction), BH-660 (74.1% grain yield reduction), BH-540 (69.5% grain yield reduction) and BH-543 (62.3% grain yield reduction) appeared to be the varieties most severely affected by the presence of tree. By contrast, varieties such as 'Shone' (29.5% grain yield reduction), 'Militia' (14.4% grain yield reduction) and 'Limmu' (1.7% higher grain yield under the canopies) appeared to be affected less severely by the presence of tree (or to benefit from it in the case of Limmu).

Agronomic practices with a potential to suppress competition from weed and tree roots such as tillage frequency, herbicide application, maize cultivation and weeding frequency interacted positively with the presence of trees ($P < 0.05$), increasing maize grain yield under tree canopy.

3.4. Partial economic trade-off analysis for on-farm trees

3.4.1. Income from annual crops vs. tree products

Annual farm-level income from maize decreased with an increase in tree density for all species (Fig. 4a, c and e). On the other hand, the discounted direct annual income from trees increased with tree density, although the magnitude varied with tree species (Fig. 4b, d and f). Direct income from Cordia was the highest (Fig. 4a) followed by Acacia (Fig. 4e). Croton generated the lowest direct annual income from tree products (Fig. 4c). As the proportion of income from trees increased, the income obtained from maize tended to decrease (Fig. 5), with the trade-off curve concaving towards the origin.

3.4.2. Relationship between direct income from trees and tree-related opportunity cost

For Cordia (Fig. 6a) and Croton (Fig. 6b), direct income from tree products was exponentially correlated to the opportunity cost

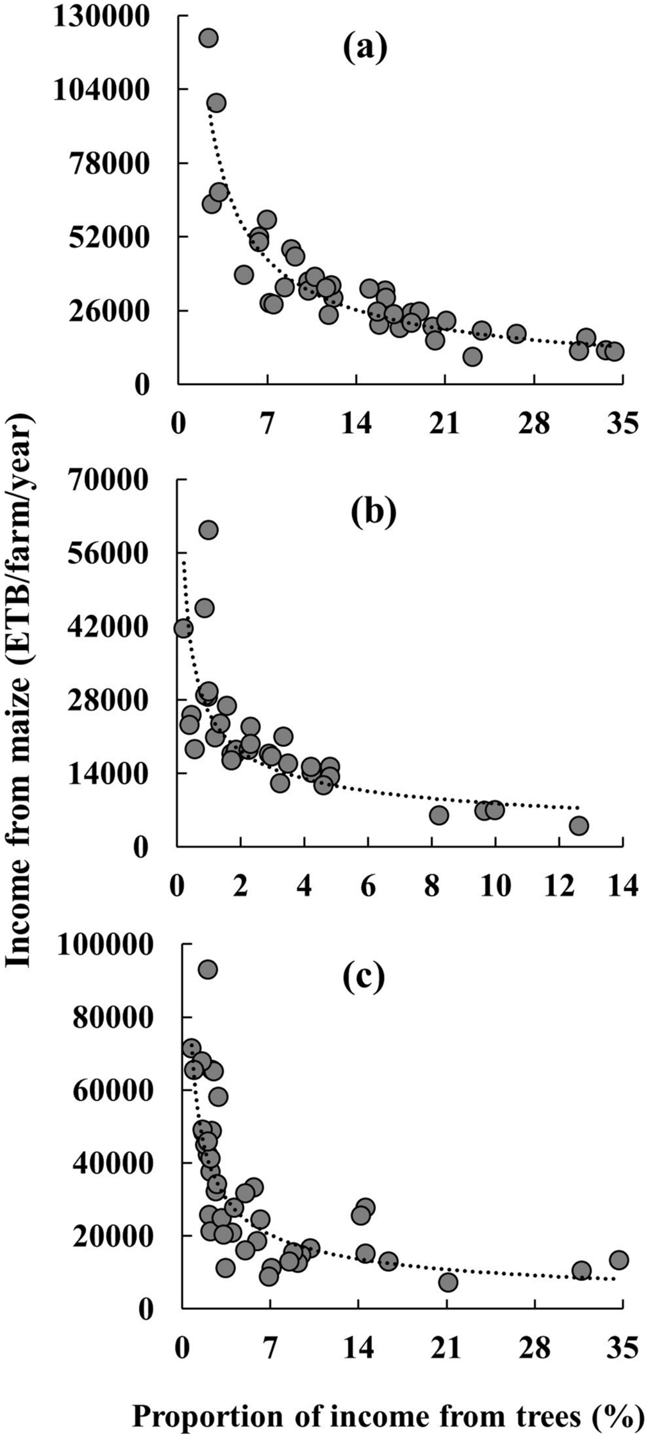

Fig. 5. Relationship between proportional income from trees (as a percentage of combined income from maize and from trees) and income from maize for *Cordia africana* (a), *Croton macrostachyus* (b), and *Acacia tortilis* (c) based farming systems. The dotted lines represent the fitted curves. ETB = Ethiopian Birr (20ETB = 1USD, 2016).

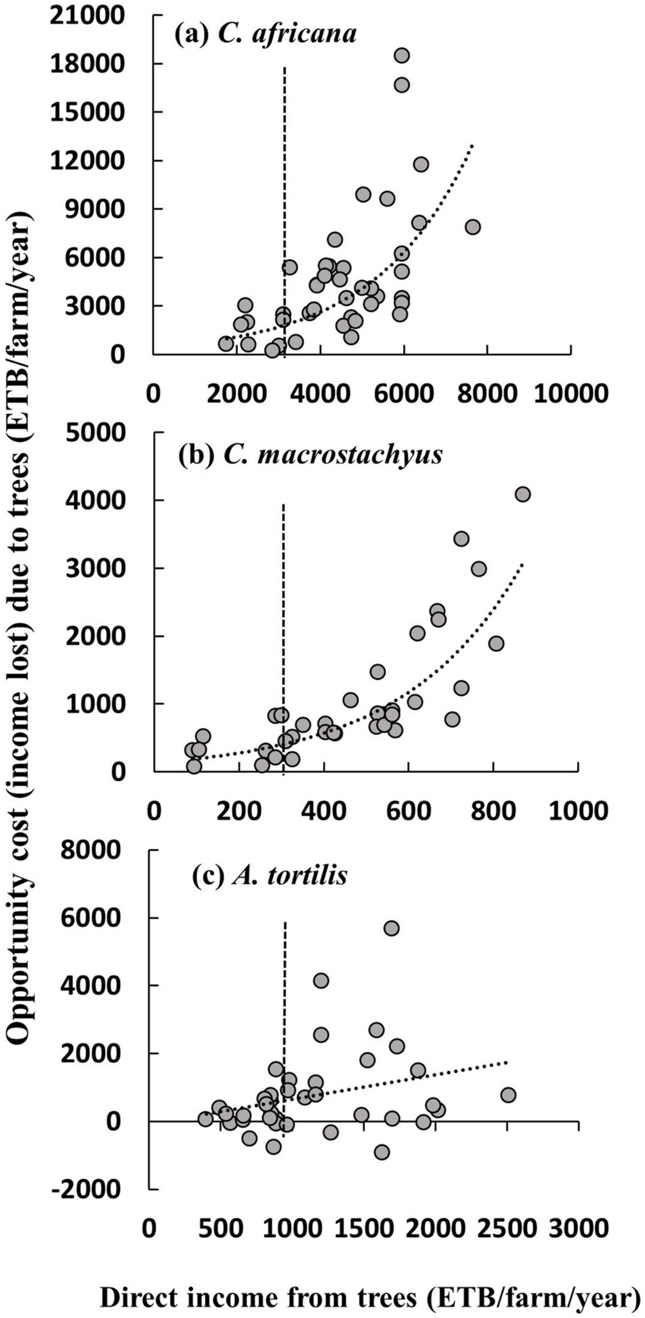

Fig. 6. Relationship between direct income from trees and tree-related opportunity cost for the tree species *Cordia africana* (a), *Croton macrostachyus* (b), and *Acacia tortilis* (c). The vertical broken line represents the level of direct income derived from trees at no significant opportunity cost as a result of trees. The dotted line represents the fitted curves. ETB = an Ethiopian currency (20ETB = 1USD, 2015).

associated with trees (i.e., as a result of yield losses caused by trees). The relationship between direct income from trees and associated opportunity cost appeared to be linear for Acacia (Fig. 6c). On average, close to 3000 ETB (~130 USD) year^{-1} farm^{-1} from Cordia, 1000 (~45 USD) ETB year^{-1} farm^{-1} from Acacia and 300 (~13 USD) ETB year^{-1} farm^{-1} from Croton can be obtained without causing significant trade-off with maize yield at farm-level. Any combination beyond the vertical line for income earned from trees was dominated by negative trade-offs (Fig. 6). The densities of trees at which the trade-offs started to increase exponentially were about 3 trees ha^{-1} for Croton and Acacia. Such a tipping point for Cordia clearly did not depend on its on-farm density.

4. Discussions

4.1. On-farm trees are maintained for direct income and utilization values in spite of associated crop yield penalty

A key result of the current study was that on-farm trees reduced maize yield (Fig. 3). Because the current study was conducted during an average season, the magnitudes of the trade-offs could vary during wetter or drier years. For example, Miller and Pallardy (2001) showed that tree-crop trade-offs intensified during relatively dry seasons because of severe competition for soil moisture. By contrast, Gerjets et al. (2017) demonstrated that the positive effects of tree strips on crop growth were more pronounced in crops facing drought stress. Thus, the net effect of trade-offs could be balanced out over the long term. Regardless of the prevailing trade-offs, farmers still maintained trees on their farms in part because of their income generating values (Tables 3–5). A previous work on tailoring agroforestry technologies to the diversity of smallholder agriculture reported that compatibility with crops was one of the criteria used to select tree species incorporated in the farms (Bucagu et al., 2013). The current result, however, suggested that on-farm trees are not solely maintained because of their compatibility with annual crops. We found they were generally kept for their direct utilization values such as timber, firewood, charcoal and fencing material. However, it is important to underline that most of these utilities are not substitutable through local market mechanisms. Previous studies on the income generation values of trees (e.g., Alavalapati et al., 2004; Gustad et al., 2004) focused on tree products that can be traded beyond local levels as they are used as industrial inputs. Our results, in addition, hinted that locally traded tree products such as fencing material and firewood may motivate smallholder farmers to practice mixed tree-crop systems. Den Biggelaar and Gold (1996) similarly reported that integration of trees into farms was highly dependent on the capacity of trees to offer multiple utilities rather than on their direct economic contribution. In addition to their contribution in income generation, on-farm trees reduce labour drudgery on women and girls by providing onsite source of fuelwood (Leakey, 2012; Zimmerer et al., 2015).

The prominence of trade-offs depended on the tree species (Fig. 5). Most of these differences could be related to the nature of the trees, prices for tree products and the biophysical environment. For example, the trade-offs appeared to be less severe for Acacia compared with Cordia and Croton. Acacia is a valuable charcoal source, which has permanent market demand and high price. This market could be extended to big cities beyond the local demand. Similarly, Cordia is a valuable timber species, although farmers need to wait long time to harvest good quality timber. By contrast, tree products from Croton (i.e., firewood production) are used locally (for consumption at home and sold at local markets). Similarly, the value by which income from maize declined for every additional tree per hectare varied with tree species. For example, increase in the density of Cordia from 0.67 trees ha^{-1} (the lowest density) to about 3 trees ha^{-1} was associated with a decrease in the income from maize from 98,943 ETB to 32,898 ETB. This change was about 28,715 ETB decrease for every additional tree/ha. By contrast, the rate was only 10,586 ETB for every additional increase in the density of Croton. This difference was due to the higher negative effect on maize of Cordia compared with Croton (Fig. 2).

4.2. On-farm trees are maintained for farm-level income stability rather than immediate field level income

Although tree-induced trade-offs were pervasive in the systems under study, on-farm trees still dominate smallholder agricultural landscapes. The trend remained the same even under situations where tree-based utilities apparently led to inferior returns in cash equivalents compared with returns from sole annual crops. This could suggest that the main objectives of poor rural households, especially under remote locations where markets are imperfect, may not necessarily follow economic rationale and optimization behaviour (Klapwijk et al., 2014). Under the current study setting, where smallholders are constrained by various institutional and environmental factors (Stahl, 1990; Gebreselassie, 2006), these trees could provide a buffering mechanism against volatility in grain prices, which is a common characteristic of many countries in SSA (Minot, 2014). Furthermore, on-farm trees provide households with an income 'safety net' and are used as relatively stable source of household income when annual crops fail (Cadisch et al., 2004). Although small compared with income from annual crops, income from on-farm trees could provide a diversified income option. Such rationale, whereby smallholders managed risk through the practice of economies of scope (i.e., preference of small but low risk incomes over higher, but more risky incomes) rather than economies of scale that could be achieved through specialization, were also reported elsewhere (Chavas and Di Falco, 2012). On the other hand, the rationale to maintain trees in most agro-ecosystems depends on the entire bundle of ecosystem services they provide (Lescourret et al., 2015) and the contribution they make to other aspects of livelihoods (Chen et al., 2013), rather than income generation alone. For example, Chen et al. (2013) found that availability of firewood source nearby residence areas optimized the household energy demand and saved labour for other productive activities. Furthermore, van den Berg (2010) and Angelsen et al. (2014) pointed at the fact that the income from tree products, albeit small, was critical to smallholders to cover expenses such as school fee for their children.

Interestingly, farmers with smaller land holdings tended to manage higher tree densities and were subjected to stronger trade-offs from tree-crop interactions. This indicated that land-constrained farmers tended to adopt practices that reflect an income stabilization hypothesis (van den Berg, 2010). Bryceson (2002) also reported results that were consistent with our findings. Another study on farmers' risk aversion behaviour reported that less resource-endowed households produced more perennial crops for income diversification compared with better-off households (Alexander and Moran, 2013). A recent study from the same region also reported that smallholders generally tend to integrate trees on their farms to meet variable farm conditions, needs and asset profiles (Iiyama et al., 2017). As per capita agricultural land is becoming ever smaller in SSA (Garrity et al., 2017), tree-based systems could be the focus of an alternative pathway for sustainable intensification of smallholder farming systems in the region (Tilman et al., 2002; Ehui and Pender, 2005).

Tree-based systems could be preferred for income diversification and other ecosystem services such as regulating and amenity values, regardless of their significant trade-off with the production of food crops. Given the challenge of food security in SSA (Devereux and Maxwell, 2001), our results suggested that 'adapting' agronomic practices (Shiferaw et al., 2009) could minimize trade-offs arising from tree-crop interactions. Although on-farm trees are currently maintained for their non-yield values, combining 'good agronomic practices' with trees may help to harness their potential contribution to the sustainable intensification of smallholder farming systems in SSA (Garrity et al., 2017).

4.3. The impact of on-farm trees on maize yield is affected by agronomic practices

Our results clearly indicate that the impact of on-farm trees on maize yield was extremely variable from farm to farm and between tree species (Fig. 3). Results presented in Table 6 highlighted that much of the yield variability can be explained by differences in crop management. Although results from one season data may not be conclusive enough, the current finding highlighted the possibility of reducing trade-offs from tree-crop interactions through the application of particular agronomic practices. For example, change in rate of urea from low (0–50 kg ha^{-1} urea) to medium (50–125 kg ha^{-1} urea) under tree canopies did not result in yield gain (only a marginal increase in maize grain yield of 1%). Change in rates of urea from medium to high (125–200 kg ha^{-1}) was accompanied by a 93% increase in under canopy maize grain yield. On the other hand, change in rates of urea from low to medium was accompanied by a 42% increase in maize grain yield for open field. For maize in the open field, change in the rate of urea from medium to high was, however, accompanied by only a marginal increase of about 10% in maize grain yield. A similar trend, where under canopy maize responded to only higher rates of fertilization, was observed for phosphorus fertilizer. The stronger response of maize grain yield to mineral fertilizer under tree canopies is most likely related to greater soil organic matter and availability of other nutrients (Vanlauwe et al., 2015). Large differences in efficiency of response to fertilizers across small distances within farms have often been observed in SSA (*cf.* Tittonell and Giller, 2013) and must be taken into account when allocating scarce nutrient resources.

However, results could be different for tree-crop systems that involve nitrogen fixing species such as *Faidherbia albida* (Jamnadass et al., 2013). Our analysis for the impact of urea did not include Acacia, a nitrogen fixing species, as most farmers we sampled in Meki did not apply urea to maize.

Hybrid maize varieties that are normally high-yielding under conventional open field conditions performed the worst when grown under the canopies of on-farm trees. Our results generally indicated that good agronomy was more important than the presence or absence of trees on crop productivity, similar to a finding from semiarid Zimbabwe (Baudron et al., 2012), where farm-level crop management practices outweighed the effect of conservation agriculture (CA) practices. While tree management has been usually recommended in managing trade-offs in tree-crop interactions (Boffa, 2000; Bertomeu et al., 2011), the current results indicated that crop management (agronomic practices) can significantly minimize the negative impacts of trees on crops. For example, repeated tillage and weed management tended to minimize the negative impact of trees on crops, underlining the importance of agronomic practices that minimize competition between trees and crops for belowground resources.

4.4. Segregate or integrate trees into crop fields?

One of the intensely debated issues in agricultural production systems has been whether it is possible to meet the growing demand for agricultural products without compromising other ecosystem services. Whether to integrate or segregate trees and crops has been contested hotly (Fischer et al., 2008; Phalan et al., 2011; van Noordwijk et al., 2012; Ekroos et al., 2016). The general negative impact of on-farm trees on maize grain yield from the current study may point towards a recommendation to ‘segregate’ (Lefroy and Hobbs, 1998), whereas the stable income and diverse utilities received from these trees would support the argument to ‘integrate’ (Primdahl, 1990) trees and crops. In Fig. 5, the trade-off curve between income from maize and the proportional income earned from trees concaves towards the origin. According to van Noordwijk et al. (1995), multifunctional solutions that lead to potentially efficient interactions rather display convex trade-off curves between “relative agronomic functionality”, i.e., functionalities from annual crops and “relative ecological functionality”, i.e., functionalities from on-farm trees. This implies that the current system would be better-off with segregation and simplification rather than integration (van Noordwijk et al., 2012). On the other hand, segregation may aggregate perennial trees over small area and reduce the overall benefit from trees because of intraspecific competition (Pulido et al., 2001). As hinted in Section 4.3 above, farm/crop management may modify the concave shape of the trade-off curve, stretching it towards a linear and eventually convex shape, leading to synergies between tree and crop. The findings from our study, which suggest the possibility of minimizing tree-crop trade-offs through crop management practices, could be utilized to create an integrated system of ‘eco-agricultural landscapes’, as suggested by Scherr and McNeely (2008) and Cunningham et al. (2013).

5. Conclusions

Although our analysis included only the direct tree-based economic benefits, the current results indicate that economic gains from trees were not large enough to compensate for tree-induced crop yield penalties in tree-crop mixed farming systems. Farmers still maintained trees on their farms possibly for three main reasons. First, direct benefits of trees in the form of timber, fuelwood, charcoal and fencing materials cannot be substituted through current local market mechanisms. Thus, farmers may be forced to tolerate tree-induced trade-offs, as there is currently no alternatives (e.g., from the market) to the benefits these trees provide. Second, on-farm trees offer stable and diversified sources of household income, unlike annual crops that frequently fail or undergo price fluctuations. Third, under the ever diminishing per capita land size, farmers maintain on-farm trees by integrating agronomic practices that minimize trade-offs from tree-crop interactions. As these trees were proved to enhance the overall productivity of a system through other ecosystem services, the possibility of using certain agronomic practices to minimize tree-crop trade-offs appears as an important area to explore further. The current results also underlined that crop breeding and agronomic research may need to account for the needs of smallholders, where natural within field heterogeneity is probably intensified by the presence of trees. On the other hand, a comprehensive analysis that includes the quantification of non-income values of on-farm trees (such as regulation and cultural ecosystem services) would probably lead to less pronounced trade-offs. Future research that explores optimum fertilization, tillage frequency and planting dates under tree-crop integrated systems may improve our understanding.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.03.011.

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