Agroforest Syst
https://doi.org/10.1007/s10457-021-00596-9

# Crop productivity and tree growth in intercropped agroforestry systems in semi-arid and sub-humid regions of Ethiopia

**Shiferaw Tadesse · Wondwossen Gebretsadik · Catherine Muthuri · Abayneh Derero · Kiros Hadgu · Hadia Said · Aynalem Dilla**

Received: 18 May 2020 / Accepted: 2 January 2021


**Abstract** Agroforestry has been practiced traditionally by smallholder farmers in tropical countries, including Ethiopia. However, scientific information on tree-crop interactions isn't widely available. Long-term agroforestry field experiments were conducted, in sub-humid and semi-arid regions of Ethiopia, to explore the impacts of intercropping on crop yield and tree growth. The treatments in the sub-humid areas were; tree alone (*Cordia*, *Grevillea, Croton,* and *Acacia abyssinica),* (2) crop alone, *teff* (*Eragrostis tef*), *maize* (*Zea mays)* and *finger millet* (*Eleusine coracana),* (3) tree + crop, (4) mix of four tree species and (5) mix of tree species + crops. The treatments in the semi-arid area included (1) tree + crop (*teff* with *Faidherbia*, *Moringa*, *Acacia nilotica and Cordia,* (2) crop alone, and (3) mix of trees + crops. The species choice was determined by suitability to local contexts and from farmer prioritisation participatory design workshops. Crop yield, tree height, and diameter were measured from each treatment. Crop yields under tree + crop treatments were not significantly different (α = 0.05) from crop yield in the sole crop treatments (in both areas), except crop yields under *Acacia abyssinia*, which had the lowest crop yields compared to the rest of the treatments in the sub-humid areas. In the semi-arid area, teff yield under *Faidherbia* in 2019, has increased by 64%, compared to the yield in 2017. The best growth performance was attained by *Grevillea* and *Cordia* in the sub-humid areas, whereas *Acacia nilotica* performed well in the semi-arid areas. These results suggest that the selection of appropriate tree and crop species can enhances crop and tree production in agroforestry systems of Ethiopia.

**Keywords** Crop yield · Long-term trial · Tree species mix · intercropping · Tree performance

S. Tadesse
Oromia Agricultural Research Institute, Bako Research Center, Bako, Ethiopia

W. Gebretsadik · A. Derero
Ethiopian Environment and Forest Research Centre, Addis Ababa, Ethiopia

C. Muthuri · K. Hadgu · H. Said
World Agroforestry Centre, Addis Ababa, Ethiopia

A. Dilla (✉)
Centre for Environmental Science, College of Natural Sciences, Addis Ababa, Ethiopia
e-mail: amdilla@utas.edu.au; aynalem.mamo@aau.edu.et

## Introduction

The challenge of food security is more urgent and more complex than ever; because of the growing population, urbanization, climate change, and the decrease of agricultural resources (Horlings and Marsden 2011). Agriculture must address

Published online: 16 February 2021

simultaneously several intertwined challenges, including ensuring food security for an increasing global population, reducing the environmental impact of agriculture, and increasing climate change adaptation and mitigation (Beddington 2011). One important reason for food insecurity in the developing countries, including Ethiopia, is yield instability in the current monoculture cropping system (Lithourgidis et al. 2011). Intercropping is a cultivation practice that can contribute to ecological and sustainable intensification in crop production (Jensen et al. 2020).

Tree-based intercropping (TBI) provide various ecosystem services—ES that include nutrient mineralization, water quality, soil quality, pollination, biological control, air quality, windbreak, timber provisioning, agriculture provisioning and climate regulation (Alam et al. 2014). A structured literature review on the roles of trees across a spectrum of ecosystem services (ESs) in Sub-Saharan Africa concluded that the effects of trees were mainly positive but decline in crop production was noted as a key trade-off (Kuyah et al. 2016). In Ethiopia Trees on farms are a widespread feature across a large part of the landscapes with an important role in enhancing the resilience of smallholder livelihoods through the provision of ES (Iiyama et al. 2017). The study revealed two major tree adoption strategies: farmer managed natural regeneration (FMNR) of trees to meet subsistence needs as well as contributing to other ecosystem services; and, high value agroforestry (HVAF) involving planted trees used largely to produce fruits, timber and fodder. Nevertheless when trees are grown in association with crops competition for resources like water, light, nutrients can occur and therefore characterisation of component interactions in agroforestry systems is crucial in determining the extent of competition and complementarity between trees and crops (Muthuri et al. 2005). Consequently, appropriate management is needed to minimize tree-crop trade-offs Ong and Kho 2015) and should not only deal with the tree component of the system but also include, depending on contexts agronomic practices such as early planting and the variety used among others (Sida et al. 2018b). In addition, the choice of species presents a major challenge (Muthuri et al. 2005) hence the need to match species to specific contexts.

The Ethiopian agricultural landscape harbours diverse tree species: native trees and exotics, planted and naturally regenerated, in different agroforestry systems and different agroecologies. Agroforestry systems are complex and the dynamics of tree crop interactions change as the trees matures yet there are limited studies involving trees from young to matures ones. Consequently, two long-term trials (LTT) were initiated to fill the knowledge gap and study these interactions as trees mature and appropriate management options are implemented.

The overarching aim of the long-term monitoring trials was to study the performance of different tree species and combinations and their impact on crop productivity with a view of building a strong database that can be used to generalize predictions of impacts of tree species and management on crop productivity. The study investigated the performance of different tree species and species mixes and their effect on crop production in agroforestry systems from the long-term trials established in the sub-humid and semi-arid of Oromia Ethiopia. The findings from the LTTs were supposed to complement efforts of ongoing participatory on-farm trials involving similar tree species across a range of contexts in in the same region.

## Materials and methods

### Study site description

Two long term trials were established in semi-arid and humid areas of Oromia to capture different contexts and accommodate a range of species. The LTT experiment for the sub-humid region was conducted at Bako Agricultural Research Center (BARC). The site is situated in the western Ethiopia at an altitude of 1650 m a.s.l; and geographical location 9°6′N and 37°9′E. Annual mean minimum and maximum air temperatures of the area ranges between 13.5 and 29.7 °C. and average annual rainfall of 1237 mm with maximum precipitation occurring from May to August. The type of soil is reddish-brown and classified as Nitisol, which is slightly acidic with pH of 5.54, total nitrogen 0.17%, organic carbon 3.12% and C: N ratio 18. The site was left fallow for about 15 years due to low soil fertility, low crop productivity and high wild animal damage to crops, mainly maize.

The LLT for semi-arid region (Melkassa) was carried out at Bishola, near Melkassa Agricultural Research Centre, which is 115 km southeast of Addis

Ababa at the geographical location 8°24′N & 39°2′E at an altitude of 1550 m. a.s.l. The area is characterized as a semiarid area and it is part of the central rift valley of Ethiopia. Mean annual rainfall varies between 512 and 1345 mm. The mean annual temperature is 21.2 °C with a mean minimum temperature of 14 °C and a mean maximum temperature of 28.4 °C. Soils in this region are of diverse type, generally low in organic matter, poor fertility, infiltration, and water holding capacity and hence drought-prone contributing to periodic crop moisture deficit. The type of soil is classified as Andosols with pH of 7.2, total nitrogen 0.3%, organic carbon 0.04% and available Phosphorous 1.5 mg/kg soil (Esayas et al. 2005).

## Field experiment description: Bako, sub-humid area

The Bako LLT was established in August 2013. Land preparation involved clearing of bushes manually and then herbicide (Glyphosate) application at the rate of 3 kg $ha^{-1}$. This was followed ploughing by oxen twice after which manual land preparation using shovel, spade and rack was done. Then the experiment was set up as a randomized complete block design (RCBD) consisting of five treatments replicated three times. Four tree species were planted in this trial which included *Cordia africana*, *Grevillea robusta*, *Croton macrostachyus,* and *Acacia abyssinica.* The treatments were (1) tree alone in monoculture (*cordia, grevillea*, *croton,* and *acacia),* (2) Tree alone in the four mixed species (3) crop alone (4) monoculture tree + crop, and (5) mix of tree species + crops. In the tree + crop treatments, *teff* (*Eragrostis tef), maize* (*Zea mays)* and *finger millet* (*Eleusine coracana)* were intercropped with the trees. A plot area of 40 m × 10 m (400 $m^2$) was allocated for tree + maize, tree + finger millet, tree + teff, and sole tree and sole crop treatments. Trees were planted at a spacing of 5 m × 5 m between and 5 m x 5 m within rows. A total of 16 trees were planted on each plot in August 2013 in planting pits having depth and width of 50 cm. Lower branches (25%) expected causing shade on crops were pruned while leaves and degradable twigs were incorporated into respective plots in the tree + crop integrated cropping during 2016, 2017, 2018 and 2019 growing seasons.

In the tree-crop treatments, crops were planted between 2 rows of trees in each plot. Maize, finger millet and teff were sown between the first and third weeks of June, July and August respectively during all cropping seasons. Maize was planted at a spacing of 75 cm between rows and 30 cm between plants, finger millet was planted at a spacing of 40 cm between rows drilled at the seed rate of 20 kg $ha^{-1}$, and teff was planted at 20 cm spacing between rows drilled at 15 kg $ha^{-1}$. The same plot area was also planted with a sole crop for comparison purposes (Fig. 1).

## Field experiment description: Melkassa, semi-arid region

Melkassa LTT trial was established on July 21, 2013; the site was a farmland traditionally used for production of teff prior to trial establishment. The experiment was set-up as a randomized complete block design with four replications. The treatments included (1) tree + crop, (2) mix of trees + crop and (3) crop alone. The tree species included *Faidherbia albida, Moringa stenopetala, Acacia nilotica and Cordia africana*. A plot area of 35 m × 35 m was allocated for each monoculture tree species intercropped with cereal, a mix of tree species intercropped with cereal and a sole crop plot. Trees were planted at a spacing of 5 m × 5 m between and 5 m × 5 m within rows,

**Fig. 1** Teff intercropping at Bako LTT

with 64 trees per plot planted in 8 rows. Spacing between plots was 6 m and spacing between block was 7 m. Hence, the net experimental area was 240 × 161 m = 38,640 $m^2$ or 3.9 ha. *Eragrostis tef (teff)* was intercropped with the trees in 2017 and 2019 (Fig. 2). Teff was sown in the third week of July during the 2017 and 2019 cropping seasons. The seed was manually broadcasted at 30 kg/ha between tree rows. Land preparation was tractor plough followed by a pair of oxen plough.

## Measurements and data collection

### *Tree growth*

Tree diameter at 1.3 m (DBH cm) and height (m) in both sites were measured using similar methods. Tree DBH was measured using diameter measuring caliper and tree height was measured using a hypsometer. Measurements, reported in this manuscript, were done at 5th year after planting in 2017 and 6th year after planting in 2018.

### *Crop yield and biomass*

*Bako LLT*—Data on biomass and crop yield was collected from four quadrants of 2 m × 2 m (4$m^2$), i.e., a total area of 16 $m^2$ under the canopies of selected trees were considered for crop yield data collection. A similar plot area but randomly sampled plot was also considered for crop data collection in crop alone plots.

Teff harvesting was done at maturity, between the first and the second weeks of November and finger millet and maize were harvested by late November during all cropping seasons. The biomass of each crop was cut above ground when crops reached full physiological maturity. Grain yields were separated from the straw through threshing (*teff and finger millet*) and shelling (maize). Measurements were determined using sensitive balance graduated to 1 gm and corrected to 12.5% moisture content, the standard for cereals.

*Melkassa LLT*—Data on biomass and crop yield was collected from 4-$m^2$ plots, located randomly under each experimental tree. Teff total above-ground biomass and grain yield were determined by manual harvesting of all the plants from the plots, harvesting was done at physiological maturity, between the first and the third weeks of November during the 2017 and 2019 cropping season.

### *Tree biomass estimation*

Species-specific allometric equations, though ideal for biomass estimations, were not available for all tree species in the study area. Therefore, the following allometric equation developed by Brown (1997) for tropical moist forest was used to estimate total above-ground biomass of trees.

$$\text{TAGB} = 42.69 - 12.8(\text{DBH}) + 1.242\left(\text{DBH}^2\right)$$

where TAGB is total above-ground biomass in kg/tree and DBH is diameter at breast height in cm. The equation of Brown (1997) was used as it was constructed from the data collected by several authors from different tropical countries and at different times. The equation is also recommended by the UNFCCC (2006).

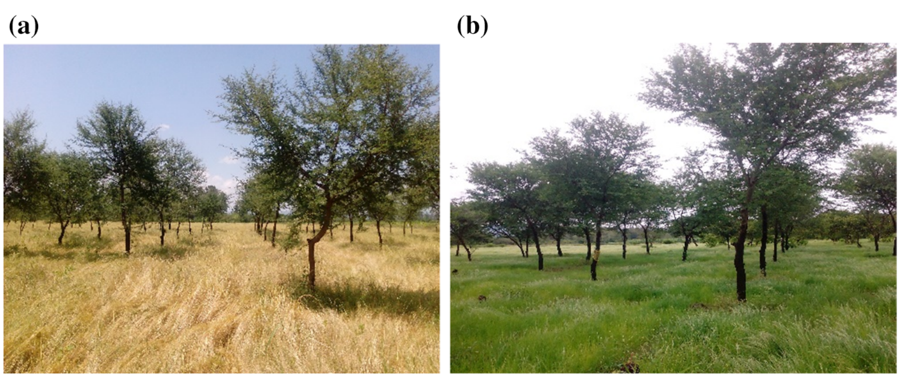

Fig. 2 Teff under *A. nilotica* in 2017 (a) and 2019 (b) at Melkassa LTT

### Data analysis

Data were analysed by analysis of variance (ANOVA), using SPSS software. Significant differences (at $P < 0.050$) between treatment means were determined by the Tukey multiple range test. Data from each year were analysed separately.

## Results

### Crop yield and biomass

Maize and finger millet yield under tree + crop treatments at Bako (sub-humid area) were not significantly different ($\alpha = 0.05$) from crop yield in the sole crop treatments, except crop yields under *Acacia abyssinica* in 2017 (Table 1, data presented for 2017 and 2019). Teff yield was significantly greater under tree + crop treatments than the sole crop treatments in 2017 (Table 1). Crop yields (teff, finger millet, and maize) under *Acacia abyssinica* were significantly lower than crop yields under the rest of tree + crop, tree mix, and sole crop conditions (Table 1 and Fig. 3). On the other hand, tree + crop treatments produced significantly greater biomass than the sole crop and sole tree conditions (Table 2).

Crop yield and biomass under tree + crop treatments at Melkassa (semi-arid area) were not significantly ($\alpha = 0.05$) different from crop yield in the sole crop treatments in 2017 (Fig. 4, data presented for teff yield and biomass in 2017 & 2019). In 2019, all tree-based treatments revealed a significantly higher teff yield compared to the yield under sole crop plots. Teff yield and biomass in 2019 was also significantly higher ($\alpha = 0.05$) than the yield and biomass in 2017, under all tree + crop treatment (Fig. 4). The highest teff yield was obtained under *F. albida* trees in 2019 (Fig. 4).

### Tree growth

In the sub-humid site, *Grevillea robusta* and *Cordia africana* had the highest growth rates in terms of diameter and height than the remaining tree species, while *Croton macrostachyus* had the lowest growth rate than the rest of tree species (Table 3).

Analysis of tree growth data in the semi-arid site indicated that *Acacia nilotica* had the highest growth ($\alpha = 0.05$) in terms of height and DBH compared to the remaining tree species (Table 4). *Faidherbia albida* showed the least growth in height and DBH.

## Discussion

Intercropping plays an important role in subsistence food production, especially in situations of limited water resources (Kebebew et al. 2014; Tsubo et al. 2005). The current study demonstrated that crop yields (maize and finger millet) under intercropping systems, in the sub-humid areas (Bako), were comparable to crop yields under sole crop conditions, whereas teff yield under tree + crop treatments was significantly greater than the yield in the sole crop treatments in 2017. This can be attributed to complementary interactions that occur when trees increase resource use by understory plants (Tanga et al. 2014) and/or when deep-rooted trees use resources which are far below the reach of crop roots. For example, a study in *maize/Grevillea* intercropping systems in Kenya (Huxley et al. 1994) indicated that there was a possible root niche differentiation for below-ground resource capture by plants, i.e., part of the soil profile to 1.3 m was shared with the maize roots, but *Grevillea* rooted further down to at least 2 m. The current study also indicated that significantly greater biomass production was found under tree + crop plots compared to sole crop and sole tree plots. This suggests that intercropping of trees and crops can be employed to increase the resource use by the whole system (Schroth 1998). The result also indicates that agroforestry trees would add to product diversification on a parcel of crop land without causing significant crop yield reduction as compared to monocropping on the same unit of land.

Trees on croplands can also enhance soil fertility, which in turn can increase crop productivity. Studies in Ethiopia reported that intercropping of *C. macrostachyus* and *F. albida* trees with maize improve soil fertility and maize yield (Manjur et al. 2014). Similarly, a study on farmers' agricultural fields at Bako, western Ethiopia, demonstrated that *C. africana* trees enhance soil fertility in the agricultural landscape of the area (Yadessa et al. 2009). This corresponds with results from a similar on-station LLT trial in Kenya where maize yield grown under *C. africana* and mixed-species including *F. albida* were higher than the control (Njoroge et al. 2019). Earlier studies at the

**Table 1** Tests of ANOVA for treatment effects on crop yield for 2017 and 2019 growing seasons, in the sub-humid region

| Crop type | Treatment | Crop yield (2017) | | | Crop yield (2019) | | |
|---|---|---|---|---|---|---|---|
| | | Std. Error | t value | Pr(>\|t\|) | Std. Error | t value | Pr(>\|t\|) |
| *Maize* | *Mix of trees- Sole* | 93.16 | 0.62 | 0.99 | 150.89 | 1.77 | 0.49 |
| | *Grevillea- Sole* | 93.16 | − 2.16 | 0.27 | 150.89 | − 0.66 | 0.99 |
| | *Cordia- Sole* | 93.16 | 1.55 | 0.63 | 150.89 | 2.38 | 0.18 |
| | *Croton- Sole* | 93.16 | 1.46 | 0.69 | 150.89 | 2.59 | 0.11 |
| | *Acacia-Sole* | 93.16 | − 3.69 | 0.01** | 150.89 | 2.59 | 0.11 |
| | *Acacia- Mix of tees* | 71.45 | − 3.69 | 0.01** | 106.69 | − 6.17 | 0.00*** |
| | *Acacia- Grevillea* | 71.45 | − 3.06 | 1.01** | 106.69 | − 6.74 | 0.00** |
| | *Acacia- Cordia* | 71.45 | − 4.89 | 0.00*** | 106.69 | − 7.03 | 0.00*** |
| | *Acacia- Croton* | 71.45 | − 4.78 | 0.00*** | 106.69 | − 7.97 | 0.00*** |
| *Teff* | *Mix of trees- Sole* | 49.46 | 4.28 | 0.00*** | 44.40 | 2.60 | 0.11 |
| | *Grevillea- Sole* | 49.46 | 3.70 | 0.01* | 44.40 | 0.63 | 0.99 |
| | *Cordia- Sole* | 49.46 | 3.42 | 0.01* | 44.40 | − 2.28 | 0.21 |
| | *Croton- Sole* | 49.46 | 3.98 | 0.00** | 44.40 | 2.28 | 0.21 |
| | *Acacia-Sole* | 49.46 | − 0.07 | 1.00 | 44.40 | − 2.96 | 0.05* |
| | *Acacia-Mix of tees* | 34.97 | − 5.96 | 0.00*** | 31.39 | − 7.87 | 0.01*** |
| | *Acacia- Grevillea* | 34.97 | − 3.72 | 0.01** | 31.39 | − 5.08 | 0.00*** |
| | *Acacia- Cordia* | 34.97 | − 4.74 | 0.00*** | 31.39 | − 7.406 | 0.00*** |
| | *Acacia- Croton* | 34.97 | − 5.53 | 0.00*** | 31.39 | − 8.50 | 0.01*** |
| *Finger millet* | *Mix of trees- Sole* | 77.49 | 1.22 | 0.82 | 104.55 | 0.52 | 0.99 |
| | *Grevillea- Sole* | 77.49 | 2.59 | 0.11 | 104.55 | 0.08 | − 1.00 |
| | *Cordia- Sole* | 77.49 | 1.37 | 0.74 | 104.55 | 1.91 | − 0.40 |
| | *Croton- Sole* | 77.49 | 1.82 | 0.46 | 104.55 | 0.39 | − 0.10 |
| | *Acacia-Sole* | 77.49 | − 4.20 | 0.00** | 104.55 | − 2.85 | 0.06 |
| | *Acacia- Mix of tees* | 54.79 | − 7.67 | 0.00*** | 77.93 | − 3.90 | 0.05* |
| | *Acacia- Grevillea* | 54.79 | − 9.62 | 0.00*** | 77.93 | − 3.70 | 0.01** |
| | *Acacia- Cordia* | 54.79 | − 7.88 | 0.00*** | 77.93 | − 6.73 | 0.00*** |
| | *Acacia- Croton* | 54.79 | − 8.51 | 0.00*** | 77.93 | − 4.56 | 0.00*** |

same site reported complementary, neutral and competitive effect on resource use and consequently maize yields in *A. acuminata, Paulownia fortunei and Grevillea robusta* respectively (Muthuri et al. 2005), thus species differences played a key role in the observed differences. Lack of yield benefit in the intercropping treatments of the current study can be attributed to the age of trees (about 5 years), i.e., the benefits associated with trees may take decades to develop (Dilla et al. 2019; Poschen 1986). In addition, Njoroge et al. 2019 reported significant variation in soil heterogeneity as important source of variation in crop yields rainfall variability and variation notwithstanding.

In the sub-humid areas, crop yields (teff, finger millet, and maize) under *A. abyssinica* were significantly lower than crop yields under the rest of tree-crop, tree mix, and sole crop treatments, in 2017. This could indicate that *A. abyssinica* competes with the crops, for limited resources such as light, water, and nutrients (Jose et al. 2000). Unlike most *acacias, Acacia abyssinica* has umbrella shaped canopy and highly ramifying root structure that could make it highly competitive to resources. Several studies showed that intercepted solar radiation by understory crops is lower compared to crops grown in open areas (Bayala et al. 2014). For example, a study on the effect of *A. nilotica* on crop yield, in a traditional

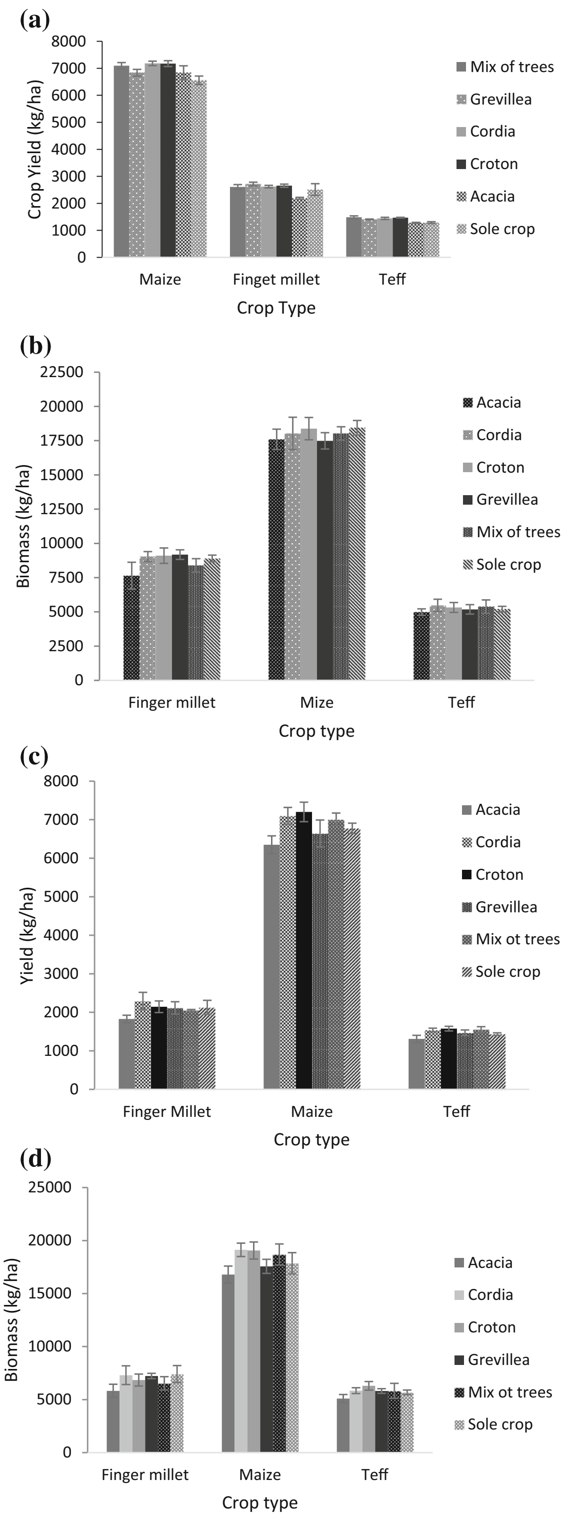


**Fig. 3** Crop yield in 2017 (**a**) and 2019 (**c**) and biomass in 2017 (**b**) and 2019 (**d**) under variable intercropping conditions at Bako LTT

agroforestry system in sub-humid regions of Chhattisgarh state, showed that gram crop yield was reduced by 38% under *A. nilotica* canopies compared to the sole crop condition (Bargali et al. 2004). Above- and below-ground competition in agroforestry systems can be minimized by crown pruning (Semwal et al. 2002). A recent study in the semiarid areas of Ethiopia reported that canopy pruning resulted in increased photosynthetically active radiation (PAR) transmitted under *F. albida* trees, thereby increasing crop yield under the trees (Dilla et al. 2019). An on-farm study in the semi-arid and sub-humid area of Ethiopia, also reported that maize yield was lower under mature canopies of *Cordia africana, Croton macrostachyus,* and *Acacia tortilis* compared to the respective crop alone fields (Sida et al. 2018b). They concluded that on farm trees are not only maintained for their compatibility for crops but also because of their direct utilization values such as firewood, timber and fencing material, and their income generation values (Sida et al. 2018b). Thus, it is necessary to improve knowledge of how on-farm tree species affect crop productivity and designing appropriate tree management strategies such as crown pruning, to minimize above- ground competition, and fertilization to overcome below-ground competition (García-Barrios and Ong 2004).

In the semi-arid area (Melkassa), the study showed that there was no significant difference in teff yield and biomass under all treatment conditions in 2017. However, all tree-based treatments revealed a significantly higher teff yield in 2019 as compared to sole crop conditions. This result indicates that the positive impacts of agroforestry trees could be increased as the trees mature. For instance, the yield under *F. albida*, in 2019, has increased by 64%, compared to the yield in 2017. Nevertheless, excessive crown pruning and pollarding of *Faidherbia* crown which is widely practiced in the area was found to reduce wheat yield (Assefa 2020), the reduced water uptake notwithstanding. This therefore means that there is need for optimised tree management / pruning to maximise resource use, crop productivity as well as provide the much needed tree products like firewood and fencing materials. Results from a baseline survey of the current study site indicated that the site was deficit in soil nutrients such as carbon and nitrogen, which can limit crop yield. Thus, the increased teff yield under nitrogen-fixing leguminous tree i.e. *F. albida,* could

**Table 2** Mean biomass production under tree + crop, sole tree and sole crop treatments in 2017, at Bako

| Treatment | Biomass | | |
|---|---|---|---|
| | Tree + crop | Sole crop | Sole tree |
| *Acacia + maize* | 22,374 a | 1844 b | 3924 c |
| *Acacia + finger millet* | 12,724 a | 8897 b | 3924 c |
| *Acacia + teff* | 9661 a | 5204 b | 3924 c |
| *Cordia + maize* | 22,009 a | 18,441 b | *6048 c* |
| *Cordia + finger millet* | 12,975 a | 8897 b | *6048 c* |
| *Cordia + teff* | 9360 a | 5204 b | *6048 c* |
| *Croton + maize* | *14,787 a* | 1844 b | 4500 c |
| *Croton + finger millet* | *22,981 a* | 8897 b | 4500 c |
| *Croton + teff* | *11,320 a* | 5204 b | 4500 b |
| *Grevillea + maize* | *21,728 a* | 1844 b | 4998 c |
| *Grevillea + finger millet* | *13,261 a* | 8897 b | 4998 c |
| *Grevillea + teff* | *9373 a* | 5204 b | 4998 b |

Different letters in the same row (same tree species) indicate significant difference at $p < 0.05$

imply that soil fertility has been improved under these trees. A study in northern Ethiopia, also revealed that soil organic matter, total N and available P were greater under *F. albida* tree canopies than outside canopies (Hadgu et al. 2009). Comparable results were also reported in other studies (Kho et al. 2001; Umar et al. 2013; Rhoades 1995).

In the sub-humid area, the best performance in terms of tree diameter and height growth was attained by *G. robusta* and *C. africana* indicating the suitability of the area for the survival and growth of these tree species. *Cordia africana* trees are usually retained by the smallholder farmers in arable fields, coffee farms, grazing lands, homesteads, or on field margins for various reasons including timber, fodder, firewood, and soil amelioration (Yadessa et al. 2009). The current study also showed that the height and diameter growth of *C. macrostachyus* and *A. abyssinica* were lowest compared to the rest of tree species.

*Acacia nilotica* had the highest DBH and height compared to the rest of tree species in the semi-arid areas, which indicates the suitability of the area (climate and soil type) to the growth of this tree species. Our study indicated that *F. albida* had the least DBH and height growth compared to the rest of the tree species. Njoroge et al. (2019) reported significant growth of *C. africana* and *F. albida* in mixed stand and Cambisols compared to monoculture and in Vertisols which pointed out to some synergistic effects in mixed species treatments over monocultures and the impact of variation in soils on tree performance. *Faidherbia albida* is one of the main tree species in the semi-arid regions of Ethiopia. Findings from on-farm participatory trials in the same sites revealed that growth differences of the six shared species common to both agroecologies could be attributed to significant effects of species and niche (Derero et al. 2020). In addition, population of the tree species is declining due to various factors including high mortality of seedlings; caused by exposure of the seedlings to excessive heat and free grazing (Sida et al. 2018a). Their findings indicated that appropriate tree management and policy are required to enhance the growth and survival of the trees. A study on farmland tree species diversity in semi-arid region of Ethiopia also suggested that planned intervention is needed for enhancing the establishment of trees through managing natural regeneration and/or planting, and for handling the issue of aftermath grazing during dry seasons, which leads to unsustainable browsing (Endale et al. 2017). Besides increasing tree through a farmer-led approach that couples understanding of species and planting niche preferences with appropriate seedling supply and management was proposed as a means to increase the diversity of trees in farmed landscapes (Derero et al. 2020).

## Conclusion

The current study concluded that there is great potential for tree-based intercropping systems in both

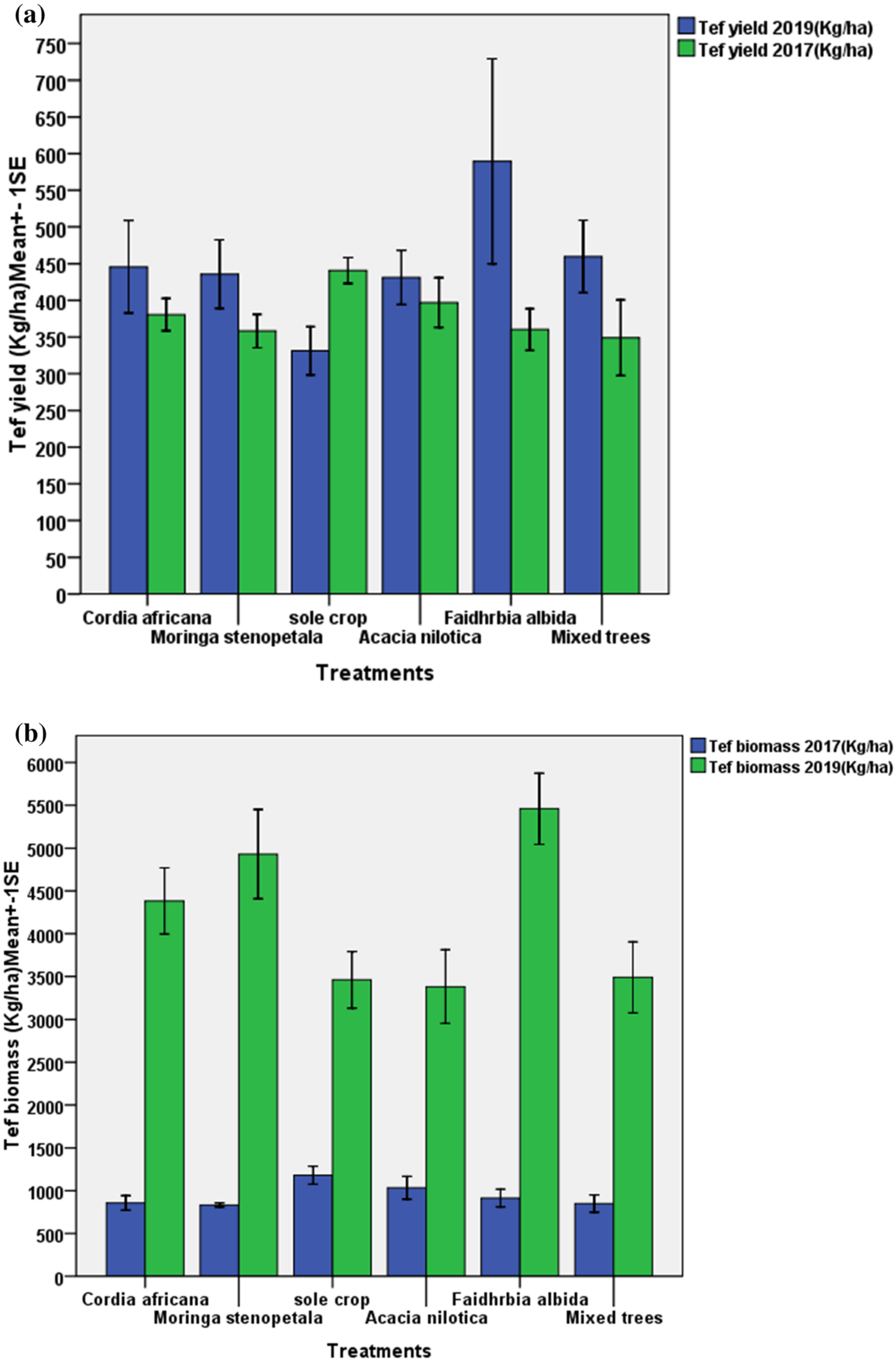


**Fig. 4** Teff biomass (**a**) and yield (**b**) in 2017 and 2019 under variable intercropping conditions at Melkassa LTT

sub-humid and semi-arid regions of Ethiopia, which could have positive impacts on crop productivity. The finding from both sub-humid and semi-arid sites suggest that proper matching of trees with the right crops and sites should be in place to enhance the adoption and scaling up of agroforestry practices. We recommend that further research in the long-term trials should consider plot-level tree density changes over the years because of seedling mortality, replanting, and thinning. Further studies should also explore the

**Table 3** Tree height and DBH with different intercropping condition at Bako, 2017 and 2018

| Tree type | Treatment | Tree Height (cm) (2017) | | DBH (cm) (2017) | | Tree Height (cm) (2018) | | DBH (cm) (2018) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SE (+) | Mean | SE (+) | Mean | SE (+) | Mean | SE (+) |
| *G. robusta* | Grevillea /maize | 397 | 30.34 | 6.00 | 0.47 | 546 | 33.15 | 8.00 | 0.63 |
| | Grevillea /finger millet | 368 | 32.33 | 5.78 | 0.38 | 562 | 22.41 | 10.06 | 1.00 |
| | Grevillea /teff | 234 | 25.84 | 4.37 | 0.58 | 360 | 35.20 | 5.36 | 0.89 |
| | Mix of trees + crops | 229 | 38.67 | 4.17 | 0.42 | 338 | 53.23 | 4.84 | 0.88 |
| | Mix of trees | 118 | 61.59 | 1.70 | 1.25 | 191 | 120.20 | 3.90 | 0.10 |
| *C. africana* | Cordia/maize | 294 | 21.51 | 5.60 | 0.50 | 352 | 26.27 | 5.77 | 0.67 |
| | Cordia/finger millet | 272 | 34.05 | 4.83 | 0.68 | 286 | 21.63 | 4.68 | 0.78 |
| | Cordia/teff | 320 | 33.91 | 5.08 | 0.47 | 390 | 29.09 | 6.74 | 0.78 |
| | Mix of trees + crops | 337 | 28.16 | 5.66 | 0.82 | 401 | 29.82 | 8.59 | 0.74 |
| | Mix of trees | 168 | 33.60 | 4.50 | 0.40 | 269 | 9.00 | 3.77 | 0.77 |
| *C. macrostachyus* | Croton/maize | 225 | 34.49 | 3.95 | 0.18 | 314 | 23.09 | 3.79 | 0.40 |
| | Croton/finger millet | 229 | 29.44 | 3.25 | 0.44 | 304 | 22.46 | 3.74 | 0.50 |
| | Croton/teff | 186 | 1.60 | 3.09 | 0.22 | 257 | 16.29 | 3.43 | 0.27 |
| | Mix of trees + crops | 213 | 37.62 | 3.70 | 0.36 | 321 | 28.78 | 4.10 | 0.04 |
| | Mix of trees | 137 | 30.33 | 0.97 | 0.13 | 181 | 10.67 | 1.37 | 0.03 |
| *A. abyssinica* | Acacia/maize | 219 | 17.37 | 3.81 | 0.53 | 282 | 22.80 | 4.19 | 0.67 |
| | Acacia/finger millet | 175 | 14.46 | 3.60 | 0.61 | 289 | 15.50 | 3.93 | 0.59 |
| | Acacia/teff | 206 | 19.31 | 3.89 | 0.35 | 290 | 19.99 | 3.98 | 0.43 |
| | Mix of trees + crop | 224 | 25.52 | 3.16 | 0.59 | 255 | 15.58 | 4.19 | 0.64 |
| | Mix of trees | 207 | 89.74 | 1.60 | 0.21 | 298 | 73.39 | 6.00 | 2.21 |

**Table 4** Tree height and DBH in the semi-arid areas (Melkass) in 2018

| Tree species | Tree H (m) | | DBH (cm) | | CD (cm) | |
|---|---|---|---|---|---|---|
| | Mean | SE (+) | Mean | SE (+) | Mean | SE (+) |
| *Acacia nilotica* | 5.39 | 1.52 | 12.31 | 0.59 | 15.51 | 1.66 |
| *Cordia africana* | 3.17 | 0.98 | 7.30 | 0.22 | 10.33 | 0.73 |
| *Faidherbia albida* | 3.13 | 0.30 | 5.43 | 0.29 | 8.01 | 0.38 |
| *Moringa Stenopetala* | 3.43 | 5.29 | 10.71 | 0.98 | 16.36 | 5.89 |

potential of these agroforestry systems to provide ecosystem services, including carbon sequestration and degraded land restoration. Besides LLTs should be used as demonstration and co-learning sites where farmers can benefit as well as share experiences from their on-farms tree crop systems so as to enhance the focus of the studies within the trials to well align to farmer's needs.

**Acknowledgement** This research was conducted as part of the Trees-for-Food-Security project, under the auspices of the CGIAR research program on Forests, Trees, and Agroforestry. The project was funded by the Australian Centre for International Agricultural Research (ACIAR).

## References

Alam M, Olivier A, Paquette A, Dupras J, Revéret J-P, Messier C (2014) A general framework for the quantification and valuation of ecosystem services of tree-based intercropping systems. Agrofor Syst 88:679–691

Assefa A (2020) Ecophysiology of *Faidherbia albida*; effect of pruning on tree water relations, cambium dynamics and understorey wheat productivity in Ejerssa Joro. Addis Ababa University, Addis Ababa

Bargali S, Singh S, Pandya K (2004) Effects of *Acacia nilotica* on gram crop in a traditional agroforestry. Int J Ecol Environ Sci 30:363–368

Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo S (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr Opin Environ Sustain 6:28–34

Beddington JR (2011) The future of food and farming: Challenges and choices for global sustainability. Final project report of the UK government foresight global food and farming futures. Government Office for Science

Brown S (1997) Estimating biomass and biomass change of tropical forests: a primer. Food Agric Org 134:10–12

Derero A, Coe R, Muthuri C, Hadgu KM, Sinclair F (2020) Farmer-led approaches to increasing tree diversity in fields and farmed landscapes in Ethiopia. Agroforest Syst. https://doi.org/10.1007/s10457-020-00520-2020

Dilla AM, Smethurst PJ, Barry K, Parsons D, Denboba MA (2019) Tree pruning, zone and fertiliser interactions determine maize productivity in the *Faidherbia albida* (Delile) A. Chev parkland agroforestry system of Ethiopia. Agrofor Syst 93:1897–1907

Endale Y, Derero A, Argaw M, Muthuri C (2017) Farmland tree species diversity and spatial distribution pattern in semi-arid East Shewa, Ethiopia. For Trees Livelihoods 26:199–214

Esayas A, Tafesse D, Ali A, Belay G (2005) Soils of Melkassa Research Center and its testing sites. Ethiopian Agricultural Research Organization, National Soil Research Center, Addis Ababa

García-Barrios L, Ong C (2004) Ecological interactions, management lessons and design tools in tropical agroforestry systems. In: Nair PKR, Rao MR, Buck LE (eds) New vistas in agroforestry. Springer, Berlin, pp 221–236

Hadgu KM, Kooistra L, Rossing WA, van Bruggen AH (2009) Assessing the effect of *Faidherbia albida* based land use systems on barley yield at field and regional scale in the highlands of Tigray, Northern Ethiopia. Food Secur 1:337–350

Horlings LG, Marsden TK (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world.' Global Environ Change 21:441–452

Huxley P, Pinney A, Akunda E, Muraya P (1994) A tree/crop interface orientation experiment with a *Grevillea robusta* hedgerow and maize. Agrofor Syst 26:23–45

Iiyama M, Derero A, Kelemu K, Muthuri C, Kinuthia R, Ayenkulu E, Kiptot E, Hadgu K, Mowo J, Sinclair FL (2017a) Understanding patterns of tree adoption on farms in semiarid and sub-humid Ethiopia. Agrofor Syst 91:271–293

Jensen ES, Carlsson G, Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev 40:5

Jose S, Gillespie A, Seifert J, Biehle D (2000) Defining competition vectors in a temperate alley cropping system in the midwestern USA: 2. Competition for water. Agrofor Syst 48:41–59

Kebebew S, Belete K, Tana T (2014) Productivity evaluation of maize-soybean intercropping system under rainfed condition at Bench-Maji Zone, Ethiopia. Eur Res 79:1301–1309

Kho R, Yacouba B, Yayé M, Katkoré B, Moussa A, Iktam A, Mayaki A (2001) Separating the effects of trees on crops: the case of *Faidherbia albida* and millet in Niger. Agrofor Syst 52:219–238

Kuyah S, Öborn I, Jonsson M, Dahlin AS, Barrios E, Muthuri C, Malmer A, Nyaga J, Magaju C, Namirembe S, Nyberg Y (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. Int J Biodivers Sci , Ecosyst Serv Manag. https://doi.org/10.1080/21513732.2016.1214178

Lithourgidis A, Dordas C, Damalas CA, Vlachostergios D (2011) Annual intercrops: an alternative pathway for sustainable agriculture. Aust J Crop Sci 5:396

Manjur B, Abebe T, Abdulkadir A (2014) Effects of scattered F. albida (Del) and C. macrostachyus (Lam) tree species on key soil physicochemical properties and grain yield of Maize (Zea Mays): a case study at umbulo Wacho watershed, southern Ethiopia Wudpecker. J Agric Res 3:63–73

Muthuri CW, Ong CK, Black CR, Ngumi VW, Mati BM (2005) Tree and crop productivity in *Grevillea, Alnus* and *Paulownia* -based agroforestry systems in Kenya. For Ecol Manag (FEM) 212:23–39. https://doi.org/10.1016/j.foreco.2005.02.059,2005

Njoroge J, Muthuri C, Kuyah S, Nyaga J, Sinclair F (2019) Rainfall variability, soil heterogeneity and role of trees in influencing maize productivity- the case from an on-station agroforestry experiment in semi-arid Kenya. For Trees Livelihoods. https://doi.org/10.1080/14728028.2019.1685410

Ong C, Kho R (2015) A framework for quantifying the various effects of tree-crop interactions. Tree–crop interactions, 2nd edn. Agroforestry in a changing climate CAB International, Wallingford, pp 1–23

Poschen P (1986) An evaluation of the Acacia albida-based agroforestry practices in the Hararghe highlands of Eastern Ethiopia. Agrofor Syst 4:129–143

Rhoades C (1995) Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (*synAcacia albida*) in central Malawi. Agrofor Syst 29:133–145

Schroth G (1998) A review of belowground interactions in agroforestry, focussing on mechanisms and management options. Agrofor Syst 43:5–34

Semwal R, Maikhuri R, Rao K, Singh K, Saxena K (2002) Crop productivity under differently lopped canopies of multipurpose trees in Central Himalaya. India Agrofor Syst 56:57–63

Sida TS, Baudron F, Deme DA, Tolera M, Giller KE (2018a) Excessive pruning and limited regeneration: are *Faidherbia albida* parklands heading for extinction in the Central Rift Valley of Ethiopia? Land Degrad Dev 29:1623–1633

Sida TS, Baudron F, Hadgu K, Derero A, Giller KE (2018b) Crop vs. tree: can agronomic management reduce trade-offs in tree-crop interactions? Agr Ecosyst Environ 260:36–46

Tanga AA, Erenso TF, Lemma B (2014) Effects of three tree species on microclimate and soil amelioration in the

Central Rift Valley of Ethiopia. J Soil Sci Environ Manag 5:62–71

Tsubo M, Walker S, Ogindo H (2005) A simulation model of cereal–legume intercropping systems for semi-arid regions: I. Model development. Field Crops Res 93:10–22

Umar BB, Aune JB, Lungu OI (2013) Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia. Afr J Agric Res 8:173–183

UNFCCC (2006) Revised simplified baseline and monitoring methodologies for selected smallscale afforestation and reforestation project activities under the clean development mechanism. CDM–Executive Board AR-AMS0001/ Version 04. United Framework Convention on Climate Change, Executive Board, Report of 28th meeting, Annex 2006 Dec 18

Yadessa A, Itanna F, Olsson M (2009) Scattered trees as modifiers of agricultural landscapes: the role of waddeessa (*Cordia africana* Lam.) trees in Bako area, Oromia, Ethiopia. Afr J Ecol 47:78–83