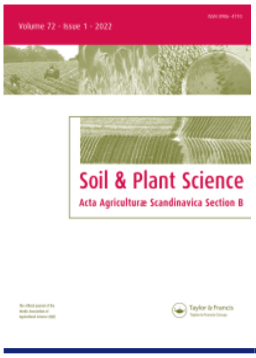

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Comparative study on the effects of *Acacia albida* on yield and yield components of different cereal crops in Southern Ethiopia

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ABSTRACT
We studied the effects of *Acacia albida* on the growth and yield of wheat, maize, and teff with increasing distance from trees in Ethiopia in the 2014/2015 cropping season. The treatments comprised four radial distances of 1.5m, 3.5m, 5.5m, and 12.5m as a control away from the tree with three replications. Results showed that higher wheat yields were recorded at 5.5m and 3.5m than at 12.5m, with yield increments of 11 and 12%, respectively compared to 12.5m. The highest maize yield was obtained from 3.5m, with a yield advantage of 12.3% compared to 12.5m. Teff yield increased with increasing distance from the tree trunk. Wheat and maize yield gains near the canopies may be associated with higher organic matter and soil nutrients, while their yield reduction with decreasing distance from the tree may be associated with the shading effect of tree canopies. Wheat was the most compatible crop when integrated with *A. albida* under shade conditions followed by maize, while teff was highly susceptible to shading effect. We suggest that integrating *A. albida* with the right crops and appropriate tree management could enhance crop yield. Lopping is required before sowing teff and maize with *A. albida* to minimize shading effects

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Compatibility; Ethiopia; intercropping; parkland agroforestry; tree–crop interaction

Introduction

In developing countries like Ethiopia, smallholder farmers contribute more than 90% of agricultural production (Agidew and Singh 2018). At the same time, soil degradation due to soil nutrient depletion is currently impacting agricultural production and food security in Ethiopia (Haileslassie et al. 2005; Tesfahunegn 2013; Agegnehu and Amede 2017). Soil erosion and the associated decline in soil fertility and organic matter depletion are developing into major constraints to agricultural production in Ethiopia. More importantly, the pressure with increasing rural population decreased the per-capita landholding, leading to a reduced or abandoning of fallow periods by farmers and continuous cultivation with little or no added fertilisers (Haileslassie et al. 2005; Agegnehu and Amede, 2017), which further contributed to soil degradation through loss of soil organic content and nutrients (Zeleke et al. 2010; Tesfahunegn 2013).

Green agriculture which is defined as agriculture that integrates trees with annual food crops is important to mitigate the continuous loss of soil nutrients and the corresponding decline in crop productivity (CRGE 2010; Garrity et al. 2010; Hadgue et al. 2011) and this requires exploiting underutilised existing scattered trees on farms. Scattered trees on farms play a vital role in nutrient cycling and conserving moisture and thereby improved crop yield provided the right trees are integrated with appropriate crops and tree management (e.g. Saka et al. 1994; Yadessa et al. 2009; Hadgu 2009; Kassa et al. 2010). Trees on farmland can also improve the fertility status of the upper soil horizons by taking up nutrients that occur deep in the soil profile and deposit them on the surface soil layers where they are available for crops (Rochelau et al. 1988; Nair 1993; Abebe and Bekere 2002). On-farm trees may also contribute to the fertility of the soil in their vicinity by trapping wind-blown dust, and depositing bird dropping and cow-dung manure under their canopies (Gindaba et al. 2005). Nitrogen fixation by farm trees can also add nitrogen to the surface soil with their nitrogen-rich leaf litter (Cuevas and Lugo 1998). Trees in croplands bring about microclimate changes under their canopies by reducing soil and air temperature, irradiance, and wind speed (Shiferaw et al. 2014; 2018). These changes will have direct influence on soil water evaporation and humidity, which in turn may significantly affect crop growth, depending on the climate. In addition to their environmental benefits, trees in crop land also provide multiple socioeconomic benefits, such as

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fodder, fuel wood, fencing and shade (Adamu and Garba 2009).

Scattered or dispersed trees in croplands, often known as 'parklands', are a widespread traditional practice in the semi-arid tropics (Zomer et al., 2009)., Agroforestry is the most dominant practice in the semi-arid and sub-humid areas of Ethiopia, covering a large tract of agricultural landscapes (Gebrehiwot 2004; Hadgue et al. 2011). The best-known systems are those involving Acacia albida (*Faidherbia albida*), prevalent throughout sub-Saharan Africa (Garrity et al., 2010).

Retaining and intercropping of *A. albida* with annual food crop systems is an indigenous agroforestry system that is commonly practiced in different regions of the country, habitats, soil types and agro-ecologies (Poschen 1986; Kamara and Haque 1992; Haile et al. 2014). *A. albida* is a well-known parkland agroforestry tree species which has been growing with agricultural crops such as wheat, sorghum, maize, barely and teff in Ethiopia (Poschen 1986; Jiru 1998). *A. albida* is an indigenous nitrogen-fixing tree with a peculiar reverse phenology, i.e. it drops its leaf during the growing period and retains it during the dry period (Kamara and Haque 1992; Williams et al. 1998; Kho et al. 2001).

Studies in Ethiopia have shown that *A. albida* tree improves soil properties mainly nitrogen and organic carbon and thus crop yield under tree canopy (Kamara and Haque 1992; Yadessa et al. 2009; Haile et al. 2014; Manjur et al. 2014). Moreover, studies in other parts of Sub-Saharan Africa (Saka et al. 1994; Kho et al. 2001; Adamu 2012; Bridget et al. 2013) also showed improvement in soil fertility and crop yield under its canopies compared to far from tree trunk. However, the effects of *A. albida* on crop yield and yield components varied due to differences in tree management, crop types, soil conditions and age and size of trees (Saka et al. 1994). For instance, Poschen (1986) reported significantly higher grain gain of 76% for maize but lower grain gain of 36% for sorghum under the canopy compared to far from canopy in Eastern Ethiopia. Similarly, Jiru (1998) reported significantly higher grain gain of 101% for sorghum followed by maize (67%), wheat (39.79%) and a slight increment of 12% for teff crops under trees than open area (15 m) in central Ethiopia.

In the study area, many farmers grow different types of cereal crops such as maize, wheat, teff, sorghum and, barely beneath the canopies of *A. albida* for resource conservation and poverty alleviation. However, the effect of existing on-farm *A. albida* trees on crop yield in the areas where cereal crops (e.g. wheat, maize and teff) are commonly intercropped with it has not been adequately investigated and differences in compatibility among cereal crops with respect to the distance from *A. albida* trunk have not been well considered. Such information is required for designing productive agroforestry system and management of tree canopies. Therefore, as a contribution to this research gap (1) the interaction of *A. albida* with wheat, maize and teff on farmers' fields were analysed by measuring yield and yield components with increasing distance from tree trunks and (2) compatible and incompatible crops were identified that were integrated with *A. albida* under shaded condition.

Materials and methods

Description of the study area

The study was conducted at Meskan district of southern Ethiopia. The geographic location of the study site is between 8°15′0.7″ – 38°33′50.9″ E and 8°1′ 58.8″ – – 8° 16′ 29.6″ N in Gurage Zone of Southern Ethiopia (Figure 1). The study was undertaken during 2014/2015 cropping season.

The dominant soil types of the district include eutric Cambisols, chromic Luvisols, chromic Vertisols, eutric Fluvisols, Leptosols and pellic Vertisols (FAO 2015). The soil at the experimental sites is classified as pellic Vertisol based on FAO classification. The slope of the specific study site which was estimated from Digital Elevation Model (DEM) ranged between 5% and 8%. The study area is characterised by bimodal rainfall, which receives rain from March to September, with the biggest rains being in July and August (Figure 2). During the experimental period of 2014/2015 cropping season, the study sites received the biggest rainfall in the month of August followed by September. However, based on long-term meteorological data, the average mean annual rainfall was 1056 mm and mean monthly maximum and minimum temperatures were 26.01°C and 9.58°C, respectively.

The study site, namely Ile was selected purposefully based on the existence of extensive practice of traditional cereal food crops and *A. albida* intercropping (Figure 1). The altitude of the experimental site ranged between 1870 and 1900 m asl. At the study site, the dominant annual crops associated with *Acacia albida* were maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), *teff* (*Eragrostis tef* (Zucc.) Trotter), sorghum (*Sorghum bicolor* L.) and barely (*Hordeum vulgare L.*). The effects of *A. albida* on the first three crops with increasing distance from *Acacia albida* tree trunk were tested. The test crops were selected based on their coverage and contribution to food security in the country. The selected test crops are those that are widely grown in

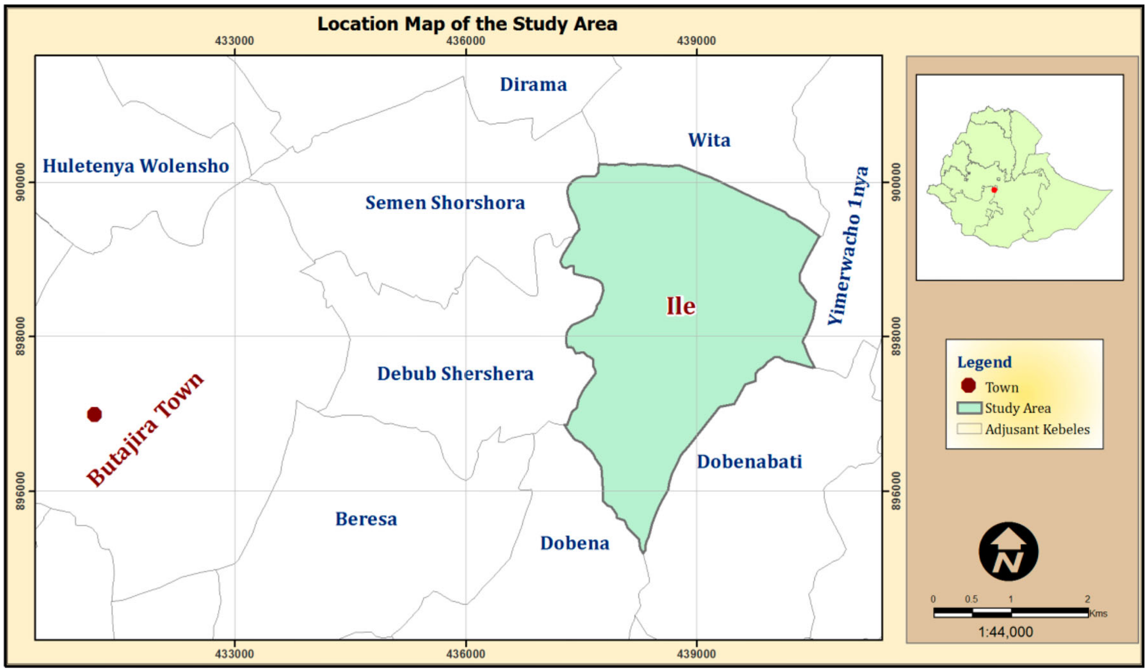

Figure 1. Base map of the study area.

the study area in combination with *A. albida*. Besides, the selected crops vary in their photosynthetic pathway where teff and maize are categorised as C4 crops, whereas wheat is categorised as a C3 crop. Hence, different responses were expected as the test crops have a contrasting resource use efficiency.

Experimental design and data collection

Three independent experiments were conducted using randomised complete block design (RCBD) to evaluate the performance of the three cereal crops (wheat, maize and teff) grown beneath the *A. albida* under shaded conditions and each replicated three times. The experiments were conducted under on-farm condition using the existing scattered *A. albida* on farmers' fields. Tree–crop combination of three experiment were *A. albida* + wheat, *A.albida* + maize and *A. albida* + teff and totally nine mature trees were considered for the experiments. The experimental plots were contiguous and had similar soil type (Vertisol), rainfall, temperature, topography and crop husbandry.

The selected trees had relatively similar age, diameter (38–40 cm), height (9–10 m), canopy (3–4 m). Each experiment comprised of four treatments (distance) from the tree trunk, including 1.5, 3.5, 5.5 and 12.5 m (control). The effects of *A. albida* on each test crop were evaluated by measuring their yield and yield components at four points along radial distances namely, 1.5, 3.5, 5.5 and 12.5 m (control) from the tree trunk. To minimise the variation between experimental plots as results of cereal-legume rotations and applied fertilisers, the agronomic history of the experimental plots was checked with farm owners. Hence, plots that were consistently cropped with cereals for at least five years were considered as experimental units. Nine of the selected trees were those that did not receive or experience pollarding or lopping for at least 2–3 years to investigate the performance of the test crops under shaded conditions. In addition, semi-structured interviews, visual observations and informal discussions were held with owners of the experimental plots to capture additional information such as their perception on the effects of *A. albida* trees on the crops, incidence of insect pests and diseases, date of germination and physiological maturity of crops.

Some selected soil physicochemical characteristics (0–15 cm, $N = 9$) of the experimental sites with increasing distance from tree trunks are shown in Table 1. Significantly higher soil organic carbon (SOC%), and total nitrogen concentrations (TN%) were obtained from under and near tree canopies than far from tree canopies (Table 1). Despite statistically non-significant, numerically higher available Bray phosphorus concentration and moisture content were also recorded from the soil under the canopy than the soil far from tree canopies (Table 1).

For data collection, a compass and a tape metre were used to measure the directions of the transect lines and distances along the transect lines, respectively. As

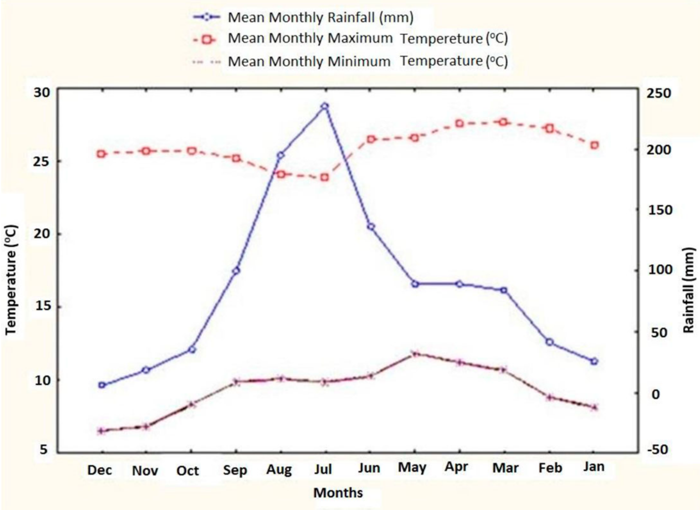

Figure 2. Climatic condition of the study area (Source: NMSA 2015).

illustrated in Figure 3, the data were collected from four compass directions (east, west, south and north) and averaged for analysis. Threshing was done manually to separate the grain from the straw and grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) were determined for each quadrant after harvesting. Yield and dry biomass of the samples were determined using a total harvesting method. A wooden frame of 1 × 1 m dimension was used for sample harvesting along the demarcated lines at 1.5, 3.5 and 5.5 and 12.5 m (control) far from the tree trunk.

Yield gain/oss of wheat, maize and teff due to the presence of *A. albida* was computed using the following equation:

$$\text{Yield gain/loss} = (\text{YUIT} - \text{YOIT})/(\text{YUIT}) * 100 \qquad (1)$$

where YUIT yield under the influence of tree, YOIT yield outside the influence of tree.

Planting dates were on 20 April 2014 for maize, 24 June 2014 for wheat and 15 July 2014 for *teff*. Weeding was carried out using hoe for maize crop while for wheat and teff a combination of herbicide (2.4D) and hand weeding were used. All plots received uniformly 38 kg N ha^{-1} and 20 kg P ha^{-1} in the form of urea and diammonium phosphate (DAP).

Data on other agronomic parameters such as total plant height, spike length, number of tillers m^{-2} and per plant, ear length and number of stem m^{-2} were collected at physiological maturity prior to harvesting using five randomly selected plants from three points i.e. two from the edge and three from the centre of each plot in four directions at 1.5, 3.5 m, 5.5 and 12.5 m. The average measurements were used for statistical analysis. In addition, other yield component data, such as thousand or hundred grain weights were measured for wheat and maize, respectively.

Statistical analysis.

The data of crop yields and yield components in response to the distances from the tree trunks were subjected to GLM test procedure of one-way-ANOVA using the SPSS statistical software version 20.0 for windows (SPSS Inc., Chicago, U.S.A.) (SPSS Inc 2006). The treatment means that showed significant differences by F-test were separated by Tukey's honestly significant

Table 1. Mean ± standard error of some selected soil physical and chemical proprieties with increasing distance from the base of *A. albida* in the study area.

	Distance from the base of *A. albida* tree (m)				
Property	1.5 m	3.5 m	5.5 m	12.5 m	Significance level
OC (%)	2.74 ± 0.08^{a}	2.62 ± 0.07^{ab}	2.44 ± 0.09^{b}	2.35 ± 0.04^{b}	*
TN (%)	0.21 ± 0.02^{a}	0.19 ± 0.01^{ab}	0.18 ± 0.00^{b}	0.17 ± 0.00^{b}	**
P (mg kg^{-1})	17.10 ± 2.02	16.10 ± 0.66	14.81 ± 0.88	15.16 ± 0.11	ns
C/N ratio	13.49 ± 0.83	13.72 ± 0.4	13.95 ± 0.40	14.23±0.24	ns
pH	6.18 ± 0.06	6.15 ± 0.09	6.11 ± 0.07	6.12 ± 0.07	ns
MC (%)	29.53 ± 1.01	28.75 ± 1.13	28.35 ± 1.45	28.32 ± 1.49	ns
BD (g cm^{-3})	1.12 ± 0.04	1.13 ± 0.03	1.14 ± 0.06	1.15 ± 0.02	ns

Note: *, **Significant at $p < 0.05$ and $p < 0.01$, respectively; ns: not significant. MC: Moisture content, BD: Bulk density. Source Haile et al. (2014).

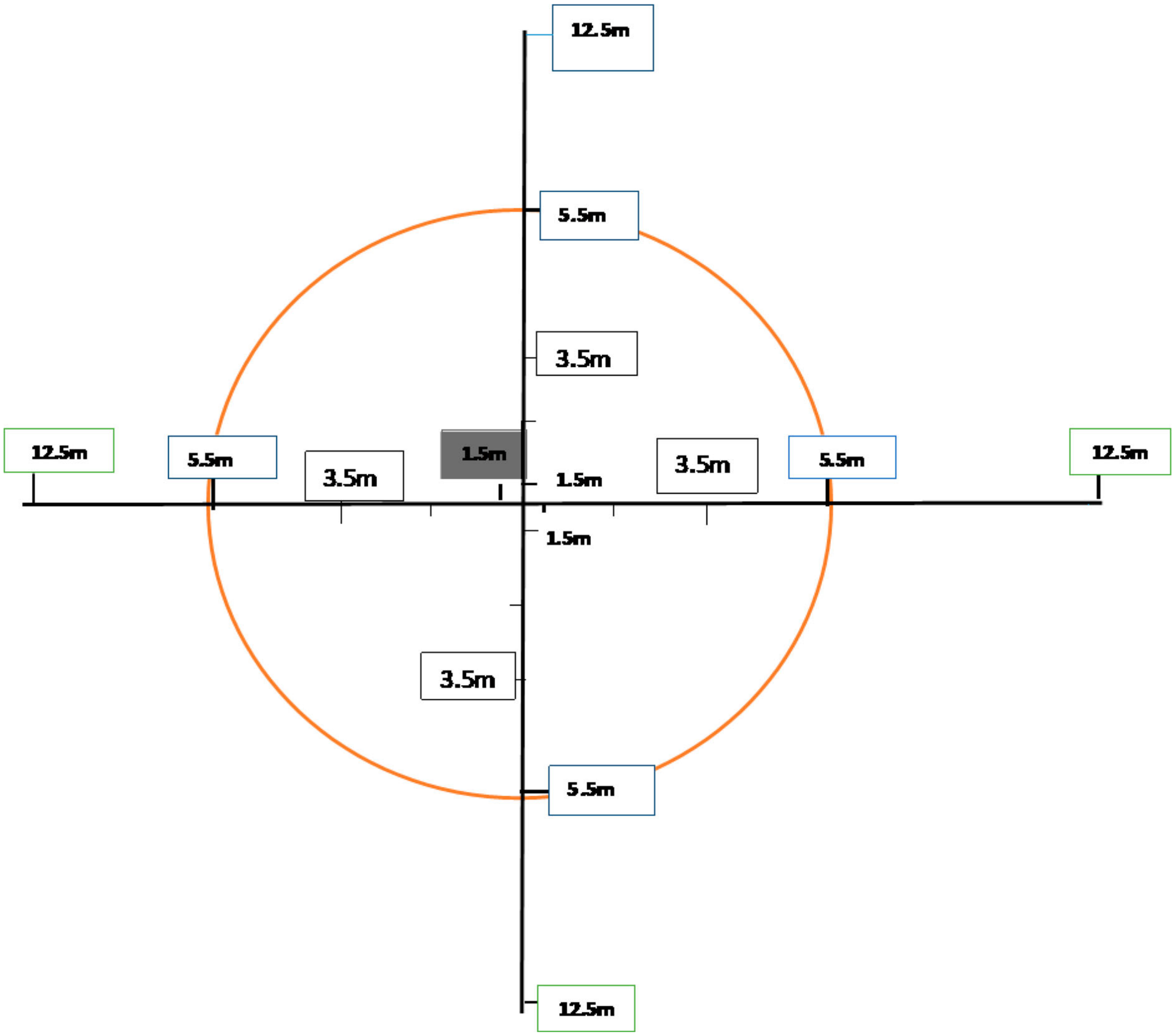

Figure 3. Schematic illustration of sampling points and direction used for data collection (1) The centre of the circle represents a single *A. albida* tree; (2) The circle represents the area covered by the canopy of the tree; (3) The area covered by the canopy is divided into four radial transects (fully labelled here); (4) four plots (1 × 1 m each) were established on each radial transect at distances of 1.5 m, 3.5 m, 5.5 m and at 12.5 m away from tree trunk in all directions and a total of 16 plots were considered in single tree. (5) The four plots located at a similar distance on each of the four radial transects were considered as a single treatment, e.g. the plots at a distance of 1.5 m on each of the four radial transects.

difference test (Tukey-HSD test) and significance was declared at $p < 0.05$ significant levels, which is the most widely used multiple comparison procedure (Zar 1996).

Results

Yield and yield components of wheat

Yield of wheat showed statistically significant ($p < 0.05$) difference with the presence of *A. albida*. Higher wheat grain yields of 4430 kg ha^{-1} and 4415 kg ha^{-1} were measured at 5.5 m and 3.5 m, respectively, than the yields of 3975 kg ha^{-1} recorded in the open area at 12.5 m (control) and 4020 kg ha^{-1} at 1.5 m (Table 2). Results showed that wheat yield increased with decreasing distance from tree trunks except the observed slight inconsistency at 1.5 m. In addition, significantly higher total biomass of 19,500 kg ha^{-1} and 18,800 kg ha^{-1} were measured at 5.5 m and 3.5 m, respectively than 17,500 kg/at 12.5 m far from the tree trunk (Table 2).

Higher 1000 seed weights of 42.32 ± 1.64 g at 1.5 m and 41.96 ± 0.78 g at 3.5 m, and 39.57 ± 0.88 g at 5.5 m were recorded from the radial distances of 1.5 m, 3.5 m and 5.5 m than the seed weight of 36.41 ± 0.29 g recorded at 12.5 m. Wheat yield showed a decreasing trend with increasing distance from the tree trunk. Wheat grain yield was higher by 11.1% at 3.5 m and

Table 2. Yield and yield component of wheat along increasing radial distances from the tree trunk.

Measured parameter	Radial distance from study tree (m)				Significance level
	1.5	3.5	5.5	12.5	
1000 seed weight	42.32 ± 1.64^{a}	41.96 ± 0.78^{ab}	39.57 ± 0.88^{ab}	36.41 ± 0.29^{b}	**
Wheat grain yield (kg ha^{-1})	4020 ± 190^{b}	4415 ± 270^{a}	4430 ± 530^{a}	3975 ± 610^{b}	*
Biomass (kg ha^{-1})	18,200 ± 400	18,800 ± 500	19,500 ± 800	17,500 ± 110	*
Height in cm	88.70 ± 2.2	87.42 ± 1.25	85.64 ± 4.86	86.24 ± 2.94	ns
Number of tillers/m^2	362.00 ± 41.65	349.15 ± 52.85	360.34 ± 37.67	359.00 ± 13	ns
Spike length (cm)	7.06 ± 0.06	7.09 ± 0.59	7.07 ± 0.27	7.29 ± 0.49	ns
Number of tillers /plants	4.33 ± 1.86	2.67 ± 0.33	3.00 ± 0.00	3.33 ± 0.67	ns
Yield gain (%)	1.10%	11.07%	11.45%		

Note: *, **Significant at $p < 0.05$ and $p < 0.01$, respectively; ns: not significant. Means followed by the same letter in a row are not significantly different at $p < 0.05$.

11.5% at 5.5 m compared to the yield achieved from 12.5 m away from the tree trunk. However, only a slight increment of 1.1% wheat grain yield was obtained at 1.5 m, which is close to the tree trunk (Table 2). Moreover, plant height and number of tillers per m^2 were relatively higher under and near the edge of the tree canopies than far from the tree trunk and decreased subsequently with increasing distance from the tree trunk except for the spike length that was higher at 12.5 m (Table 2).

Yield and yield components of maize

Results showed that grain yield and biomass of maize were significantly different ($p < 0.05$) due to differences in radial distance. The highest maize grain yield of 6595 kg ha^{-1} was measured at 3.5 m, followed by 5875 kg ha^{-1} at 12.5 m far from the canopy. In contrast, the lowest and expected maize grain yield of 3725 kg ha^{-1} was measured at 1.5 m, close to the tree trunk.

Maize ear length was significantly ($p < 0.05$) affected due to the presence of *A. albida*. The highest ear length of 17.42 cm was measured at 3.5 m, followed by 15.92 cm at 5.5 m and the lowest earl length of 13.36 cm was measured at 1.5 m. Similarly, higher stem number of 5.67 ± 0.34 was found at (3.5 m) from tree base. The observed higher ear length and higher number of stems per m^2 may have contributed to the higher maize grain yield at 3.5 m (Table 3). Despite the inconsistency, maize yield showed a decreasing trend with increasing distance from the tree trunk. Maize grain yield resulted in an increment of 12.26% at 3.5 m, but the expected yield loss of 36.6% was measured at 1.5 m compared to the control (12.5 m). Similarly, significantly higher maize total biomass of 35,500 kg ha^{-1} was found at 3.5 m than the total biomass harvested at 12.5 m. However, the lowest maize total biomass of 16,800 kg ha^{-1} was measured at 1.5 m. In contrast to the observed low maize yield beneath the canopies, a higher 100- maize grain weight of 31 g was measured under the canopies (1.5 m) than far from the canopies (12.5 m).

Yield and yield components of teff

Unlike the previous two test crops, teff grain yield decreased with a decreasing distance from the tree trunk (Table 4). The highest teff grain yield of 2000 kg ha^{-1} was measured at 12.5 m, followed by 1750 kg ha^{-1} at 5.5 m. In contrast, the lowest teff grain yield of 1300 kg ha^{-1} was measured close to tree trunk at 1.5 m. Similarly, *A. albida* had a significant ($p < 0.05$) adverse effect on teff total biomass. The significantly highest total teff biomass of 12,000 kg ha^{-1} was measured at 12.5 m far from the tree trunk, while the lowest total biomass of 6200 kg ha^{-1} was measured at 1.5 m, close to the tree trunk. Teff grain yield was reduced by 35% at 1.5 m, 20% at 3.5 m, 12.5% at 5.5 m compared to the control (12.5 m) (Table 4). Other

Table 3. Effect of radial distance on yield and yield components of maize.

Measured parameters	Radial distance from study tree (m)				Significance level
	1.5	3.5	5.5	12.5	
Biomass (kg ha^{-1})	$16{,}800 \pm 260^{a}$	$35{,}500 \pm 440^{b}$	$28{,}800 \pm 870^{ab}$	$31{,}000 \pm 550^{b}$	**
Grain yield (kg ha^{-1})	3725 ± 225^{a}	6595 ± 125^{b}	5790 ± 93^{b}	5875 ± 765^{b}	**
Ear length (cm)	13.36 ± 0.03^{a}	17.42 ± 0.25^{b}	15.92 ± 1.00^{ab}	15.85 ± 0820^{ab}	*
100 seed weight (g)	31.51 ± 6.08	30.08 ± 2.56	30.77 ± 0.91	30.98 ± 0.71	ns
Stem number/m^2	4 ± 0.33^{a}	5.67 ± 0.34^{b}	5.34 ± 0.34^{ab}	5 ± 0.00^{ab}	ns
Total height (m)	2.44 ± 0.14	2.55 ± 0.16	2.44 ± 0.08	2.36 ± 0.07	ns
Yield gain/loss (%)	−36.6%	+12.26%	−1.5%		

Note: *, **Significant at $p < 0.05$ and $p < 0.01$, respectively; ns: not significant. Means followed by the same letter in a row are not significantly different at $p < 0.05$.

growth parameters such as total plant height, number of tillers per m^2, number of tillers per plant and spike length also showed an increasing trend with increasing distance from the tree trunk (Table 4).

Further observation from this study is that the reverse phenology of *A. albida*, i.e. dropping of leaf during cropping period, seemed not true in the situation of the study area. We observed that the tree maintains its leaf during the entire cropping season (Figure 3). In addition, the germination of teff was lower under the canopy than far from the canopy. Low incidence of fungal diseases was also observed on wheat and teff under the canopy than far from canopies. The observed low incidence of fungal diseases may be explained by microclimate modification such as the presence of good moisture and the cooling effects of trees, but the observed low germination of teff may be associated with light depression. Moreover, crops grown under the canopy mature late compared to crops grown far from the tree canopy, suggesting the presence of higher organic carbon and moisture content close to the tree trunk than far from trees.

Discussion

The results of the study demonstrated that *A. albida* had facilitative interaction effect on wheat and maize yields, but it had competitive effects on teff. At harvest, the wheat crop had longer spikes, more tillers/m^2, taller plants height, higher grain and straw yields under the canopy than far from it. Our findings were more similar to the finding of Shiferaw et al. (2014) who found higher leaf area index, longer wheat spike length, more grains per spike, higher grain yield (23.5% higher) and straw yield under the tree canopy than far from it. Wheat yield gain was increased by 11.07% at 3.5 m, 11.45% at 5.5 m compared to the control (12.5 m). Results reported in this study complement and support the findings of other researchers in Ethiopia (Jiru 1998; Degu 2010; Shiferaw et al. 2014). For instance, Jiru (1998) found higher wheat yield of 40% under a canopy as compared to outside the canopy (15 m) in central Ethiopia. Shiferaw et al. (2014) also found higher wheat yield of 23% under a tree canopy than in an open area in the Rift Valley of Ethiopia. A similar study by Degu (2010) also showed higher wheat grain gain of 244.11% at 0.5 m, 206.38% at 1 m, 182.13% at 2 m and 100% at 10 m from the tree trunk than the control in Southern Ethiopia. Hadgu (2009) also reported higher barley yield gain of 49% in northern Ethiopia compared to the control.

The observed higher yield of wheat at 1.5 m and near the edge of the canopies at 3.5 m and 5.5 m may be associated with the availability of higher soil organic matter and nutrients, such as nitrogen and available phosphorus and soil water contents in the vicinity of trees (Table 1). Obviously, higher soil organic carbon and total nitrogen were observed under the canopy compared with open plots due to leaf litter fall, nutrient cycling and nitrogen fixation by the leguminous tree species. Other external inputs like bird droppings, livestock manure and urine during dry period could also be contributing factors to improvement in soil fertility. Moreover, the other possible cause for wheat yield improvement may be due to the compatibility of the wheat crop with shading effects and associated efficient resources use, such as light, moisture and nutrients. Another study by Shiferaw (2018) measured 35–55% more nitrogen and 6°C lower temperature under the canopy compared with nearby open fields, and hence improved wheat growth and yield.

Our results also revealed that the *A. albida* tree had facilitation effects on maize growth and yield, which was reflected by the observed taller plant height, more stems per m^2, ear length and ear number per plant, higher grain yield and total biomass at the edge of the tree canopy (3.5 m) than the open area due to increasing resources available to the crop (water, nutrient), and the buffering effect of trees against extreme temperatures (cooling effects) and fungal diseases. The results of the present study showed that maize yield increment of 12.3% was measured at the edge of the canopy (3.5 m) compared to the expected maize yield loss of 36.6% at 1.5 m as it became closer to the trunk (Table 3). This may be due to the shading effect, which indicates the

Table 4. Effect of radial distance on yield and yield components of teff.

	Radial distance from study tree (m)				
Measured parameters	1.5	3.5	5.5	12.5	Significance level
Teff grain yield (kg ha^{-1})	1300 ± 200^{c}	1600 ± 100^{b}	1750 ± 50^{b}	2000 ± 100	**
Biomass kg ha^{-1}	6200 ± 40^{b}	8600 ± 120^{ab}	9500 ± 80^{ab}	$12{,}000 \pm 80^{a}$	**
Plant height (cm)	104.96 ± 1.64^{c}	106.91 ± 2.91^{b}	111.54 ± 1.89^{a}	113.29 ± 2.67^{a}	*
Number of tillers/m^2	$135.5.2 \pm 34.5^{c}$	175 ± 79.12^{b}	174.09 ± 59.58^{b}	269.5 ± 97.3^{a}	**
Spike length (cm)	39.23 ± 0.56	40.81 ± 0.04	41.4 ± 3.9	43.97 ± 0.87	ns
Number of tillers /plant	5.17 ± 0.48	6.67 ± 1.26	6.67 ± 0.95	7.67 ± 1.31	ns
Yield loss	35%	20%	12.5%		

Note: *, **Significant at $p < 0.05$ and $p < 0.01$, respectively; ns: not significant. Means followed by the same letter in a row are not significantly different at $p <$ 0.05.

Figure 4. Growth and yield of maize as affected by the shading effects of *A. albida* tree in western direction.

need for the removal of lateral branches through lopping or pollarding prior to sowing of maize for minimising the shading effects.

Our results agree well with the finding of Saka et al. (1994) who found 100% more grain gain of maize beneath the tree trunk than the open area in Malawi. Other researchers also found 76% higher maize yield under the canopies of *A. albida* than far from the tree trunk in eastern Ethiopia (Poschen 1986) and 67% grain gain of maize under lopped *A. albida* tree compared to 15 m away from tree trunk in central Ethiopia (Jiru 1998). Similarly, Manjur et al. (2014) reported maize grain yield increment of 11.5% at 3.5 m compared to yield recorded at 25 m far away from *A. albida* tree trunk in Southern Ethiopia but contradicts with the finding of the same author who found 17.5% maize yield increment at 1.5 m. The observed maize yield reduction close to tree trunk is more similar to the finding of Shiferaw (2018) who found maize yield loss of 59%, 42% and 26% under the canopies of *Cordia africana, Croton macrostachyus* and *Acacia tortilis,* respectively, compared with the corresponding open field yields in the Rift valley of Ethiopia. The observed significant yield reduction of maize grain yield and biomass beneath the canopy (1.5 m) may be associated with shading effect of trees. Other possible causes for maize yield reduction could be competition of trees for resources (light/radiation, space, nutrient and water) against the maize crop (Shiferaw 2018; Figure 4). This result agrees well with the finding of Saka et al. (1994) who noted lower maize yield beneath the tree canopy than far from the canopy in Malawi. Ghosh et al. (2004) also reported negative impacts of trees on available resources including nutrients, light, temperature and space. Hence, maize production beneath the canopies of trees could be enhanced by minimising the shading effects of trees through appropriate tree management such as removal of lower branches by lopping and/or pollarding (Figure 5). For instance, from pollarded *A. albida,* Musema et al. (2019) observed an increasing trend of maize yield with decreasing distance from tree trunk with a order of 32.06% at 1.5 m, 30.18% at 3.5 m and 16.92% at 5.5 m compared to the control (25 m).

The observed higher yield of maize near the canopies was further supported by Hailu et al. (2000) who found better growth and maize biomass beneath the canopies than far from the canopies of different tree species (*Millettia ferruginea)* in Southern Ethiopia. Abebe et al. (2001) also reported lower maize yield under the canopy of different tree species (e.g. *Cordia africana)* than far from the canopy in western Oromia. The authors claim that as shading is a contributing factor to yield reduction and lopping of lateral branch is recommended specifically in eastern direction to lessen the adverse effect of trees on crop production. However, in the study area, the impacts of shading on crop growth and yield appeared to be more pronounced in the western direction than in other directions (Figure 3), hence it is recommended to remove lateral branches in this direction to enhance the yield of maize close to the tree trunk.

In contrast to maize and wheat, teff crop showed a decreasing trend in grain yield with decreasing distance from the tree trunk. At harvest, the teff crop had shorter spikes length, reduced height, lesser number of tillers per m^2 and tillers per plants, lower grain and biomass yield under the tree canopy than far from the canopies (Table 4). Our findings were similar to that involving a different tree species (*Vitellaria paradoxa*) where the lowest sorghum plant height, biomass and yield were measured closer to the tree base than the open area. Teff grain yield loss was higher by 35% close to the

Figure 5. Inconsistency of the leafing phenology of *A. albida*.

tree trunk at 1.5 m, 20% at 3.5 m, 12.5% at 5.5 m compared to the control (12.5 m). This is consistent with the findings of previous studies (Jiru 1998; Kessler 1992; Boffa et al. 2000) who reported poor response of small grain C4 crops like teff when grown beneath tree canopies because of their low resource use efficiency such as light trapping, nutrient mining and water absorption. The observed grain loss of teff under and near the canopies could indicate the susceptibility of teff to shading effects of tree canopies. In the present study, shading had adverse effects on teff yield due to the reduction of soil temperature and light, but it had a slight effect on wheat, which had also a negative effect on maize yield close to the tree trunk (1.5 m). Shiferaw et al. (2014) noted the beneficial effects temperature reduction for wheat growth and yield beneath the canopies of *A. albida* in the Rift Valley of Ethiopia. However, such microclimate modification did not benefit the growth and yield of small grains such as teff, implying that light interference could outweigh the benefit of reduced temperatures.

In the study area, *A. albida* exceptionally deviated from its natural reverse phenology. It appeared that the mature of *A. albida* tree retains its leaves during cropping seasons (Figure 6) and this could be due to the frequent pollarding of the tree by farm owners for tree products. Such changes in the trend of *A. albida* leafing phenology may have increased competition between the trees and teff for radiation to the detriment of the teff since teff is planted in late cropping period in the middle of August. The results of the experiment also suggested that the influence of *A. albida* on crop yield

Figure 6. Lopping of *A. albida* improve the productivity of maize in the study area.

and yield components may be crop-dependent. This may be attributed to the difference in photosynthetic pathway of the three crops, and thus differences in the complementarity of the three cereal crops, especially in their shade tolerance. Abebe et al. (2001) reported a significantly higher maize yield reduction under the tree trunk than far from the tree trunk due to the presence of unlopped *Cordia africana* trees in Ethiopia. Our finding is in accordance with the findings of Roupsard et al. (1999) who found a significant effect of shade on crop yields, while Kho et al. (2001) noted only a slight effect of canopy shade on grain yield. ICRAF (1993) also reported the yield reduction of cereal crops as a consequence of light depression.

On the other hand, the observed grain gain, specifically for wheat under and near the edge (3.5 and 5.5 m) of canopies and maize at the edge (3.5 m) of the canopies may be associated with the observed higher soil organic carbon (SOC%) and total nitrogen (TN%) under the canopies than far from canopies (Table 1). Another study by Hadgu (2009) indicated a positive correlation between growth resources (moisture content) and barley yield in northern Ethiopia. The presence of *A. albida* could also improve microclimate such as air and soil temperature and this could affect crop growth (Shiferaw et al. 2014). In addition to the improvement in nutrient availability and microclimate, variation in resource use efficiency among the test crops are also contributing factors to the growth and yield of crops. Crops can be categorised into different types based on their level of shade tolerance, resource use efficiency such as light trapping, nutrient mining and water absorption and crop size (large and small). For instance, C3 crops such as wheat and barley and large C4 crops like maize may have better resources use efficiency than small C4 crops such as teff. Similarly, Jiru (1998) noted the direct correlation between yield increase with crop size, where the yields of large crops such as sorghum and maize could be better enhanced than small crops such as wheat and teff when they were intercropped with *A. albida*. Hence, the observed positive interaction of wheat and maize and negative interaction of *teff* with *A. albida* may be associated with their variation in this aspect.

The results of this study further suggest that the planting of teff and maize in combination with A. *albida* may require lopping of lateral branches prior to sowing to minimise shading effects, whereas intercropping of wheat requires no lopping management. Tree management such as lopping or pollarding of *A. albida* canopy could enhance the yield of cereal crops by minimising competition for light. According to Jiru (1998), higher grain yield gain of 101%, 67%, 40% and 12% were observed for sorghum, maize, wheat and teff, respectively, when they were intercropped with lopped *A. albida* in central Ethiopia. Our results also agree well with the findings of Krampen et al. (2015) who found the negative impacts of *A. albida* on teff when it is grown under shaded conditions in mojor area of central Ethiopia. The low response of teff in the current study and in the earlier studies imply the incompatibility of intercropping of teff with *A. albida*.

The results of our experiment are also in concordance with the perception of farmers who claimed yield gains for crops like wheat and barley, but they perceived that *A. albida* reduced maize and teff yield unless the canopy is lopped. This is consistent with similar findings (Kessler 1992; Boffa et al. 2000) who reported poor response of C4 crops when grown beneath the tree canopies. In many drylands of Africa, traditional farmers remove canopies of *A. albida* trees for utilising branches for fuel wood and fencing, but such kind of heavy pollarding may change their typical leafing patterns, which normally involves leaf dropping during the rainy seasons (NFT 1995). Likewise, in the study area, farmers frequently pollard/lop *A. albida*, where such kind of heavy pruning may lead to longer leaf retention periods which hinders the rotational resource use mainly light (Figure 5) For instance, during field data collection we observed lower germination status and stunted growth of teff plants under the canopies compared to open area. Thus, the presumed benefits of reverse phenology of *A. albida* might not be realised for crops like teff which is commonly planted in late rainy seasons (August). Thus, good agronomic practices, such as early planting, improved weed management and fine seedbed preparation could also mitigate the adverse effects of shading on teff crops (Shiferaw et al. 2018). As the reverse leafing phenology of *A. albida* is changing, the competition for light is becoming a major factor adversely affecting crop yield. Hence, in addition to identifying a compatible crop that better fits with *A. albida*, designing appropriate tree management is crucial for improving teff productivity.

This study highlights the importance of tree management, such as lopping or pollarding of tree canopy particularly for integrating teff with *A. albida* if farmers' priority is crop production over tree products (such as fuel, fencing, shading and fodder). The results of this study provide more alternatives on how farmers will enhance the productivity of cereals through either intercropping the tree with or without pollarding based on their desires as most farmers in the study area own two or more fragmented parcels of crop fields. If farm owners' priority is productivity or intensification, they can integrate either teff or maize with lopped and/or pollarded *A. albida* but if farm owners prefer to diversify farm products or if they are labour constrained for pollarding or lopping, they may integrate wheat without lopping *A. albida*.

Wheat + *A. albida* combination may be the first alternative crop suitable for cultivation without pollarding the canopies of *Acacia albida*. The second alternative potential crop for cultivation under *Acacia albida* may be maize, but it seems that the crop needs the removal of lower branches (4 m) through lopping to enhance yield close to the tree trunk (1.5 m) (Poschen 1986). Based on the results of this study, the combination of teff with *A. albida* is competitive due to the observed remarkable yield reduction under, near and at intermediate distance from tree canopy compared to the control. The negative effects of *A. albida* observed in this study are likely due to differences in climate between studies, changes in leafing phenology due to the typical management practice of pollarding, or from the crop species studied. The benefits of *A. albida* may not be seen in more moderate climates, where high temperature is not a limitation for crop growth and survival, or where farmer's management alters leafing patterns and decreases litter accumulation under trees. However, it is too early to draw a conclusion that teff + *A. albida* is incompatible land use as the finding was based only on one-season yield data. Hence, further experiments need to be conducted to understand the effects of pollarding intensity and cycles on yield and yield components of teff productivity in the future. The observed contrasting yield gain/loss among the three cereal crops indicated the existence of differential tree–crop interaction. From the overall results of the study, the comparability of the three crop species was arranged according to increasing yield and yield components as wheat > maize > teff.

The observed increment in the yields of wheat and maize under and edge of the canopies may be associated with the improvement of soil fertility and microclimate while the yield reduction in teff may be associated with shading effects. Thus, farmers should select the right tree–crop combination and/or systematically reduce the canopy of the trees to enhance cereal yield. In general, from the three experiments, we observed a contrasting yield gain/loss of the three crops due to the presence of *A. albida* which clearly reflected the existence of differential tree–crop interaction. In other words, the generalisation of soil improvement due to agroforestry trees is not necessarily reflected in crop yields unless the right crops are combined with *A. albida* tree or appropriate tree management is applied. Therefore, planting of teff and maize in combination with *A. albida* may require lopping of lower branches prior to sowing to minimise shading effects, whereas inter-cropping of wheat does not require lopping management. Thus, farmers should be advised to combine wheat without lopping tree branches or maize and teff by properly trimming lower branches to improve their productivity while supplying tree products.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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