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Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia

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ABSTRACT

Faidherbia albida parklands cover a large area of the Sudano-Sahelian zone of Africa, a region that suffers from soil fertility decline, food insecurity and climate change. The parklands deliver multiple benefits, including fuelwood, soil nutrient replenishment, moisture conservation, and improved crop yield underneath the canopy. Its microclimate modification may provide an affordable climate adaptation strategy which needs to be explored. We carried out an on-farm experiment for three consecutive seasons in the Ethiopian Central Rift Valley with treatments of *Faidherbia* trees with bare soil underneath, wheat grown beneath *Faidherbia* and wheat grown in open fields. We tested the sensitivity of wheat yield to tree-mediated variables of photosynthetically active radiation (PAR), air temperature and soil nitrogen, using APSIM-wheat model. Results showed that soil moisture in the sub-soil was the least for wheat with tree, intermediate for sole tree and the highest for open field. Presence of trees resulted in 35–55% larger available N close to tree crowns compared with sole wheat. Trees significantly reduced PAR reaching the canopy of wheat growing underneath to optimum levels. Midday air temperature was about 6 °C less under the trees than in the open fields. LAI, number of grains spike^{-1}, plant height, total aboveground biomass and wheat grain yield were all significantly higher ($P < 0.001$) for wheat associated with *F. albida* compared with sole wheat. Model-based sensitivity analysis showed that under moderate to high rates of N, wheat yield responded positively to a decrease in temperature caused by *F. albida* shade. Thus, *F. albida* trees increase soil mineral N, wheat water use efficiency and reduce heat stress, increasing yield significantly. With heat and moisture stress likely to be more prevalent in the face of climate change, *F. albida*, with its impact on microclimate modification, maybe a starting point to design more resilient and climate-smart farming systems.

1. Introduction

Faidherbia albida (Del. A. Chev) trees are common features of the Sudano-Sahelian region of sub-Saharan Africa, forming 'parklands' (Bayala et al., 2014). 'Parklands', where scattered mature trees occur as an integral part of crop and livestock production landscapes, are one of the oldest agroforestry systems in Africa. They generate numerous provisioning and regulating ecosystem services (Sinare and Gordon, 2015), valuable assets in the economy of local communities (Mokgolodi et al., 2011) and socio-cultural values (Wahl and Bland, 2013). *Faidherbia* trees improve soil fertility through ecological process of nitrogen fixation (Giller, 2001), nutrient recycling (Sileshi, 2016) and accumulated soil organic matter (Gelaw et al., 2015). They improve water availability through different ecological processes such as hydraulic redistribution and improve water use efficiency of understorey crops (Bayala et al., 2015). Agroforestry has been suggested as an option to adapt to climate change (Matocha et al., 2012), which poses a serious threat to food security in smallholder agriculture (Mbow et al., 2014). According to a study from the Sahel, the parklands buffer climate risk and sustain agricultural production (Bayala et al., 2014), magnifying their importance under expected future climate change (Kassie et al., 2014). Despite these positive effects, trees in parkland systems also compete with crops for scarce resources (Bayala et al., 2015). Thus, research into management practices that maximize facilitation and minimize competition is needed. In the Central Rift Valley of Ethiopia, *Faidherbia* is the most common tree species, whereas wheat is the second most important crop after *teff* [*Eragrostis tef (Zucc.)* Trotter]. The current study focuses on unravelling the effects of interactions between

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Faidherbia and wheat. Frequent droughts and sparse use of fertilizer and improved seeds in the area cause extremely small crop yields (Van Halsema et al., 2011). Wheat yields average 1.4 t/ha, far below the yields of close to 5 t/ha reported from experimental stations (Abate et al., 2015). As crop yields are expected to fall further due to expected climate variability and change in the region (Kassie et al., 2014), these parkland systems could provide sustainable and affordable coping strategies for smallholder farmers with limited access to inputs (Lin, 2007).

F. albida is well known for its positive impacts on the productivity of the crop beneath its crowns (Mokgolodi et al., 2011). A unique 'reverse phenology' − i.e., shedding leaves during the crop growing season, which permits penetration of enough radiation for the understorey crops, has been understood to be one of the main reasons for the 'albida effect'. Although most of the 'albida effect' has been attributed to improved water and nutrient availability (Mokgolodi et al., 2011; Sileshi, 2016), Kho et al. (2001) hinted that the lower temperature under the canopy of *F. albida* could play an important role.

While the importance of such microclimate modification has been acknowledged, it has seldom been studied, especially under farmers' conditions. Similarly, detailed studies focusing on physiological responses of understorey crops are scarce. Microclimate modification by parkland trees was reported to benefit understorey herbaceous plants in savannah ecosystems (Ludwig et al., 2004), but can be outweighed with below-ground competition for annual crops (Kho et al., 2001; Van Noordwijk et al., 2015). Although trees reduce the quantity of incident radiation, which is directly related to dry matter accumulation in annual crops (Black and Ong, 2000), tree shades could buffer understorey crops against the predicted heat stress in the face of climate change. Thus, this study aims to quantify the impact of *F. albida* on the resources available to wheat (nutrients and water), on the microenvironment of wheat (temperature and radiation), and their impacts on the development and productivity of understorey wheat.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the Central Rift Valley of Ethiopia (8°30′33″ N and 39°04′16″ E) at an elevation of 1665 m above sea level and has a flat topography. The climate is semi-arid with a potential evapotranspiration of 1305 mm yr^{-1} and an average annual rainfall of 700 mm yr^{-1} over the last decade (RSO, 2003). The rainy season generally starts in June and ends in September. The long term average mean minimum daily temperature is 24.2 °C and the mean maximum daily temperature is 31 °C. However, the maximum daily temperature often exceeds 35 °C during the cropping season (Van Halsema et al., 2011). Andosol is the dominant soil type, according to FAO soil taxonomy (RSO, 2003). Except for strong phosphate fixation, andosols are generally fertile with good nutrient content, aggregate stability and high porosity (Matus et al., 2014).

The natural vegetation in the area is classified as woodland and savannah, where *Acacia* species are commonly incorporated into the rain-fed farming system, forming 'parkland' agroforestry. *F. albida* is the main agroforestry species in fields where teff [*Eragrostis tef* (Zucc.) Trotter] is the most important crop, while wheat (*Triticum aestivum* L. *var aestivum*) is the second most important. The density (mean ± sd) of *F. albida* on the selected farms was 5.6 ± 1.3 trees ha^{-1}. The other dominant tree species in the area are: *Acacia tortilis*, *Acacia etbaica* and *Balanites aegyptiaca*, respectively (Iiyama et al., 2017). Wheat is generally planted early July and harvested late in October. In the study area, the 'reverse phenology' of *F. albida* is generally not observed. Heavy and frequent pruning of the trees towards the end of dry season (for fencing, charcoal and firewood production) apparently 'forces' the regeneration of green canopies during the crop growth period.

2.2. Experimental design and plot management

Tree-crop interaction was explored for wheat growing under crowns of scattered on-farm *F. albida,* replicated in three farms (Fig. 1). Two mature *F. albida* trees per farm were selected for an on-farm experiment. Selected pairs of trees were located in a single field within a farm and had approximately similar crown structures and pruning history (Table 1). For each tree, plots measuring 10 × 10 m were established with trees at the centre. Within the same field, another plot of the same size was established in an open field, at least 70 m away from any tree. This made a total of three plots per farm. Wheat was grown under the crown of one of the trees and in the open filed. The plot under the crown of the other tree remained bare. Treatments were designated as: 'tree with wheat' – for wheat grown under the canopy of *F. albida,* 'sole wheat' – for wheat grown in the open, and 'sole tree' – for *F. albida* without wheat. The experiment was replicated on three contrasting farms, creating a total of nine plots, and repeated for three seasons. Both trees and plots were managed following farmers' typical practices. Wheat variety 'Ude', which is well-adapted to semi-arid conditions, was used. Plots were fertilized with 64 kg ha^{-1} N (split applied 50% at sowing and the remaining side dressed at tillering) and 30 kg ha^{-1} P broadcast at sowing. Seed was drilled at a spacing of 20 cm between rows at the rate of 150 kg ha^{-1}. All plots were kept weed free. The experiment was conducted over three seasons from 2013 to 2015. Seasons 2013 (1001 mm yr^{-1}) and 2014 (727 mm yr^{-1}) had good rainfall, while 2015 was an El Niño season with 578 mm yr^{-1}, below the long-term average of 700 mm yr^{-1} for the area.

2.3. Soil sampling and analysis

Soil was sampled from all plots at depths of 0–10 cm, 10–20 cm and 20–40 cm at wheat grain filling stage, in 2014. For each depth and treatments, the samples were composited from three cores, oven-dried for 48 h at 60 °C and sieved to 2 mm. The composite bulk samples were analysed for $pH_{(water)}$, organic C (Walkley-Black), total N (micro Kjeldahl), P (Olsen), exchangeable K (Ammonium acetate method), and texture (hydrometric method) following procedures described in (Van Reeuwijk, 2008). Separate soil samples were collected using auger cores of known volume for bulk density determination. These samples were oven-dried at 105 °C for 24 h and weighed to determine bulk density. Soil nutrient contents were adjusted for bulk density during final mean comparison among treatments. Soil samples were also collected in the same manner at the end of dry season (May 2015) and available Nitrogen (NO_3-N) was analysed using a fast nitrate test method (Reflectoquant®, EM Science) following a procedure outlined in (Schmidhalter, 2005), where $CaCl_2$ was used as extracting agent.

2.4. Climatic, microclimatic and soil water data

Soil moisture was measured using Delta-T© moisture probes (Delta-T-Devices, 2013) at depths of 10, 20, 30, 40, 60 and 100 cm within pre-installed access tubes. The access tubes were installed at three distances from the tree trunk: under the tree crown (at 0.7 m and 6.2 m from the tree trunk) and outside the canopy i.e. in the sole wheat treatment (minimum of 70 m from the trunk of any surrounding tree). Soil moisture was measured twice a week during the cropping season (July–October) and twice a month during off-season (October–June). Tinytag© temperature loggers (Gemini-Instruments, 2013) from Gemini© instruments were installed at a height of 60 cm above-ground (approximately at the height where floral initiation and anthesis is expected for the wheat variety used), 0.7 m away from the trunk in the TW treatment and in the centre of the plot for the W treatment. Temperatures were recorded every 30 min starting from two weeks after wheat emergence (July) to harvesting (October) for all seasons (2013–2015). Photosynthetically active radiation (PAR) sensors from SunScan© Canopy Analysis System (Webb et al., 2013) were used to