



AN ABSTRACT OF THE THESIS OF

Jeannette T. Krampien for the degree of Master of Science in Forest Ecosystems and Society presented on December 17, 2015.

Title: *Faidherbia albida* Water Use and Impacts on Teff Growth in a Sub-humid Environment in Mojo, Ethiopia

Abstract approved:

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Badege Bishaw

ABSTRACT

*Faidherbia albida* is a widely used tree species in sub-Saharan Africa, promoted for use in parkland agroforestry systems based on reduced competition with crops during the rainy season from its reverse leafing phenology and positive effect on soil fertility. Increases in growth and yield have been reported for crops such as maize, millet, and sorghum grown with *F. albida*. However, there have been no studies on *F. albida* and the crop *Eragrostis tef* (teff) in parklands, despite the prevalence of these agroforestry systems in Ethiopia. In the first part of this study, we used sap flow measurements to characterize water use of *F. albida* from the late-hot season to rainy season in 2014. Peak sap flow density and daily sap flow density were compared across three pollarded and three unpollarded trees to assess water use changes due to the typical management practice of pollarding by smallholder farmers. Pollarding severely reduced water use, while leaf shedding on one unpollarded tree lowered water use to levels close to that of pollarded trees. Lowest sap flow densities occurred at different times during the rainy season between pollarded and unpollarded groups of trees. In the second part of this study, we used measurements of shoot height, leaf area index,  $\delta^{13}\text{C}$ , and relative chlorophyll content of teff growing in plots associated with *F. albida* to characterize the impact of this important tree species on teff, the most widely grown crop in Ethiopia. *F. albida* negatively impacted shoot height and leaf area index of the teff in close proximity to trees, but had no effect on the teff's relative chlorophyll content. Leaf  $\delta^{13}\text{C}$ , however, decreased with distance from tree base, consistent with increased stress. Understanding tree water use and

tree-crop interactions in these systems is needed so land owners can make educated management decisions that will minimize competition and maximize productivity.

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*Faidherbia albida* Water Use and Impacts on Teff Growth in a Sub-humid  
Environment in Mojo, Ethiopia

by  
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Jeannette T. Krampien, Author

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## INTRODUCTION

### *Agroforestry*

Agroforestry is a type of land management that involves the management of trees and agricultural plants and animals as components of an integrated system. The inclusion of trees in agricultural landscapes is intended to achieve some environmental and/or economic benefit. Compared to monocultures, agroforestry systems can increase soil fertility and decrease soil erosion (Heineman *et al.*, 1997; Sepulveda & Carrillo, 2015) increase water conservation and use-efficiency (Ong *et al.*, 2006), and improve nutrient acquisition and retention in whole systems (Shepard *et al.*, 1996; Lehmann *et al.*, 1998). Economic benefits of agroforestry systems include improved crop yields (Sileshi *et al.*, 2008), diversified farm products (Thorlakson & Neufeldt, 2012), and increased income generation from carbon markets, biomass, and biofuels production (Nair *et al.*, 2009; Jose & Bardhan, 2012). Agroforestry systems can also improve small-holder farmer standard of living and can be used as an adaptation strategy to climate change (Verchot *et al.*, 2007; Thorlakson & Neufeldt, 2012; Bishaw *et al.*, 2013).

### *Parklands*

There are many types of agroforestry systems that involve spatial and/or temporal arrangements of trees and associated crops. One of these systems involves the scattered distribution of trees in agricultural fields, usually as deliberately preserved remnants of cleared forests, woodlands, or fallows (Bonkougou, 2001). These systems are also known as parklands, and can also be formed from naturally regenerated trees or propagated from seed or cuttings. These fields are typical in arid to subhumid climates, and make up a lot of the agricultural lands in sub-Saharan Africa (Kassa *et al.*, 2010). Aside from the possible tree products farmers may obtain, the trees are often left in the fields to improve soil fertility and reduce erosion, with the ultimate goal of sustaining or improving crop yields over fields without trees (Boffa, 1999)

### *Balance in agroforestry*

The incorporation of trees into fields requires balancing the facilitative and competitive interactions between the trees and crops to maximize the system's

efficiency and productivity. Trees will compete with crops for nutrients, water, and light (Govindarajon *et al.*, 1996; Lott *et al.*, 2003, 2009; Lehmann *et al.*, 1998). Aboveground portions of plants will compete for sunlight, whereas belowground, roots will compete for water and nutrients through overlapping root systems or differences in resource acquisition ability. For example, in a hedgerow intercropped system with *Leucaena leucocephala* (a particularly competitive species) and maize, Mathuva *et al.* (1998) showed that maize yields were lower due to competition for water. Facilitation between trees and crops can result from improved nutrient cycling and soil fertility (through capture of leached nutrients and leaf drop), shade effects, and increased soil water holding capacity from added organic matter (Boffa, 1999). Proper design and management of agroforestry systems that aim to maximize facilitative interactions can increase the system's overall productivity and ecosystem services.

Ong & Leakey (1999) suggested that a mix of species would result in greater ecosystem productivity through more efficient resource use, while Ong *et al.* (2006) suggested greater water productivity may be possible in agroforestry systems. More biologically diverse systems can access more resource niches than monoculture systems. This greater efficiency can come from complementary resource use, because trees and crops use different resources spatially and temporally. Trees may access deeper water and nutrients in soils, whereas crops may compete better for surface soil resources (Scroth, 1999; Lehmann *et al.*, 1998), or tree and crop resource use may vary by season (Ong *et al.*, 2006) due to differences in phenology. In an intercrop system with *Acacia saligna* and *Sorghum bicolor*, complementary resource use developed as the tree roots expanded more into the subsoil after root pruning in the intercrop system than when planted alone (Lehmann *et al.*, 1998). It was more advantageous to allow the roots of the two species to develop a spatial separation in resource use, and the result was greater water use efficiency in the system than either sole cropped trees or crops. This complementary water use was also observed in a Sahelian ecosystem in Senegal, in which the shrubs used a deeper soil profile than Pearl millet (Kizito *et al.*, 2006).

Despite the idea of complementarity, results from studies of water and nutrient use in agroforestry systems have often been contradictory. Based on crop yields compared between sole crops and crops grown under trees, some tree species and conditions are associated with depressed yields (Bazie *et al.*, 2012; Bayala *et al.*, 2002, 2003; Wajja-Masukwe *et al.*, 2008; Coulibaly *et al.*, 2013), increased yields (Sileshi *et al.*, 2008; Kho *et al.*, 2001; Coulibaly *et al.*, 2013), or similar yields (Bayala *et al.*, 2002; Noumi *et al.*, 2011; Jonsson *et al.*, 1999). Even so, patterns seem to be emerging with more research. A combination of factors, such as climate, species characteristics, and management decisions, among others, can determine whether a system is competition or facilitation dominated.

#### *Interactions in parkland agroforestry*

Competition between trees and crops in water limited areas is usually belowground for water, and agroforestry systems can experience intense competition if the plants are using the same set of resources (Ong & Leakey, 1999). Belowground interactions may change over the course of a season and over years depending on changes in precipitation frequency and intensity, which alters available soil moisture. At the onset and end of a rainy season, there is a lower soil moisture content, which can lead to more intense competition than in the midseason. In this case trees and crops are using more water than the sole crop would use (Boffa, 1999), which may induce drought-like conditions that affect crop leaf elongation, transpiration, photosynthesis and ultimately growth (Acevedo *et al.*, 1971; Tardieu *et al.*, 2000). The overall effect on crop yield may depend on availability of moisture at critical development stages (Yihun *et al.*, 2013). Generally though, there is an increase in crop yield with increasing rainfall (Coulibaly *et al.*, 2013), and many tree species are known to increase soil moisture beneath their canopies (Kizito *et al.*, 2006). This may be due to decreased radiation and temperature leading to decreased evaporation (Boffa, 1999).

Interactions between trees and crops for available soil moisture also depend on the species' rooting patterns and transpirational demand. Trees with deep roots can access water in deeper soil layers and maybe less competitive with crops as complementary resource use develops in the system over time (Kizito *et al.*, 2006,



2007; Lehman *et al.*, 1998). Trees with more shallow root systems may exert a more competitive effect on associated crops (Boffa, 1999).

Transpirational demand differs between species and depends on timing of leafing (phenology), total leaf area and size of the tree, and water use efficiency. Leaves are both the location of energy production in plants and the main avenue for water loss as water is evaporated through stomates. Water movement takes place along gradients of decreasing water potential, from soil, to plant roots, shoots, leaves, and finally the atmosphere which has the greatest water deficit (Millar *et al.*, 1971). Leaf development in trees is mostly associated with the onset of the rainy season in arid areas since water is more readily available, and therefore transpirational demand is higher during this time. Trees such as *Faidherbia albida* may be able to avoid or minimize competition with nearby plants for water by developing leaves at the end of the rainy season, and using water accessed from deeper soil layers or from ground water during the dry season (Roupsard *et al.*, 1999).

Relative to leaf area however, different species do have different water use efficiencies (Deans & Munro, 2004) and different abilities to withstand aridity and drought conditions (Gebrekirstos *et al.*, 2006). Finding tree species that capture and use water efficiently without exerting strong competitive effects on crops could be the key to designing successful agroforestry systems in dryland environments (Muthuri *et al.*, 2005; Ong *et al.*, 2006). Agroforestry systems can increase the quantity of water used over monoculture crops or trees, but this can have a negative impact on crop production; effectively designed systems can instead increase water-use efficiency, where a greater amount of biomass is produced per unit water used (Lott *et al.*, 2003; Lehmann *et al.*, 1998; Ong *et al.*, 2006).

Trees can also modify the microclimate for associated crops, which, depending on environmental conditions, can have facilitative or competitive effects on the crop. The amount of radiation and heat reaching crops is reduced beneath tree canopies, and this can result in reduced soil evaporation and evapotranspiration from the crops. In extremely dry or hot conditions this can benefit crop productivity by protecting crops from supra-optimal growing conditions (Jonsson *et al.*, 1999; Kho *et al.*, 2001). However, the reduction in light is more often associated with reduced crop

yields, as photosynthesis is severely hindered in cereal plants that are adapted to full light conditions (Coulibaly *et al.*, 2013; Baize *et al.*, 2012; Kessler, 1992). Boffa *et al.* (1999) found photosynthetically active radiation to be reduced by an average of 40% under *Vitellaria paradoxa* trees with 2.4 - 4.8 m crown radius.

Generally, agroforestry trees are known to have positive effects on soil fertility indices through root nutrient pumping in deep soil layers (Shepard *et al.*, 1996), accumulation of tree litter (Umar *et al.*, 2013), and nitrogen fixation (Brewbaker, 1987). In dry sites that may be moisture limited, the negative impact on crops from reduced light and competition for soil moisture can be negated through increased soil fertility or temperature decreases around the tree (Ludwig *et al.*, 2001).

The nature of facilitative and competitive interspecific interactions between trees and crops needs to be understood so productive and sustainable systems parklands can be designed and managed (Ong *et al.*, 2006). Despite the multitude of interactions, two main questions arise for agroforestry researchers: what species will be best suited to a particular environment, and how should those species be managed to minimize competition and maximize facilitation in the system.

### *Pruning*

Manipulation of tree water use through pruning is a management option that is known to have positive effects on crop yield. Pruning is known to have positive impacts on sorghum and millet (*Pennisetum glaucum*) yields and growth under *Parkia biglobosa* and *Vitellaria paradoxa* in West Africa due to reducing competition for light (Bayala *et al.*, 2002, 2003; Coulibaly *et al.*, 2013; Bazie *et al.*, 2012). Since leaves are removed with pruning treatments, the rate of transpiration will also be reduced, leaving more water available for crop use (Bayala *et al.*, 2002). Pruning can also modify root distribution of trees, with reductions in root density in upper soil layers, which can reduce belowground competition between fine roots of trees and crops (Bayala *et al.*, 2004). These effects can be species-specific. Bayala *et al.* (2013) found that pruning was associated with increased yield in untrenched plots (indicating competition for light) under *P. biglobosa*, while pruning caused a decrease in yield in trenched plots (indicating facilitative effect for water retention or light reduction) compared to unpruned trenched plots. It is unclear exactly how pruning may affect

soil moisture, as reduced shading can result in increased evaporation from soil and crops, but also reduce tree water use. Hydraulic lift is the movement of water from deeper to surface soil layers via plant roots; water is passively released into the surrounding soil layers as it moves out of the fine lateral roots of the plant in the upper soil layers (Richards & Caldwell, 1987; Caldwell & Richards, 1989). Hydraulic lift usually occurs at night, and can result in an increase of soil moisture (Caldwell *et al.*, 1998). There is evidence that this process can continue after pruning, but at a reduced magnitude (Kizito *et al.*, 2012). Hydraulic lift combined with tree pruning may lead to an increase in available soil moisture for crops, resulting in increased crop growth or reduced water stress.

#### *Faidherbia albida* in parklands

In many parklands, including the Great Rift valley of Ethiopia, *F. albida* is used, or preserved, as the tree component of these systems. It is adapted to arid, semi-arid, and sub-humid conditions, has fast-growing shoots, and a deep rooting system which allows it to use water from the water table (Orwa *et al.*, 2009; Roupsard *et al.*, 1999; Jama *et al.*, 1989). It also has many social or cultural uses: people can eat the seeds, animals can eat the pods and leaves, dry-season flowers can supply honey bees with nectar, the bark and other parts are used for traditional medicines, and wood is used for fencing, firewood, and small wood crafts (Mokgolodi *et al.*, 2011; Roupsard *et al.*, 1999; Orwa *et al.*, 2009). As a result, these *F. albida* trees are often pruned or pollarded (complete branch removal to the main trunk of tree, without severing the trunk) on farms, but it is unknown how pruning or pollarding alters water use or leafing phenology.

#### *Eragrostis tef* in parklands

In the same area in Ethiopia, *Eragrostis tef* (teff) is one of the most important crop species. Traditional farming systems have typically have teff, other mixed cereals (wheat, maize, barely), and livestock that graze after the rainy season. Teff is the most widely grown grain in Ethiopia and is cultivated on 2.8million hectares (or about 30% of total acreage of cereals grown; Tefera & Tefera, 2013; Mengistu, 2009). The grain is primarily used to make injera, the traditional flat bread used in Ethiopian meals, but is also used for porridge, home brews, and for export (Tefera &

Ketema, 2000). In Ethiopia it is used both as a primary crop, sown in mid-late growing season, or used as a standby crop. Since the crop is quick to grow and mature, if farmers decide that their maize or wheat field is going to fail from drought, they may still be able to plant teff and have a harvest that season (Tefera & Ketema, 2000). The national average yield is about 910 kg ha<sup>-1</sup>, though yields up to 2000 kg ha<sup>-1</sup> have been reported in optimal growing locations and conditions. The crop can also be used as a cash crop, as its grain and straw prices are higher than other cereals (Tefera & Ketema, 2000). Teff is often found in combination with *F. albida* in the semi-arid areas of the Great Rift Valley.

#### *Teff cultural practices*

Typical teff production practices in Ethiopia start with ploughing (with oxen-drawn ploughs), and occurs between April and June, after rain events soften the soil, and fields can be ploughed multiple times (average of three times in the Southeast Shewa region). Sowing occurs between June and August, and hand broadcast seeding is the most commonly used method, at about 30 kg ha<sup>-1</sup>, although this varies depending on individual farmers and expected germination rate of seed. Weeding occurs July and September, and usually happens only twice and is done by hand. Fertilizer can be used, and is recommended to increase yields, but for most farmers the profit of increased yields would not offset the increased cost of production from fertilizer purchase and application. Harvest occurs between October and December, when the lower part of the culm is cut using a sickle (by hand), and the crop is left to dry for 5 days before it is processed to get the grain. Rotation is also common, where teff is alternated with other cereals and legumes like wheat, barley, maize, and chickpea (Yadeta *et al.*, 2000; *personal observations and conversations with local farmers*).

There is also commercial production in the US and South Africa, where the crop is grown mostly for hay but there is limited grain production in the US as well (National Research Council, 1996). The grain also has promise as a health food, as it is both more nutritious than many other cereal grains and gluten free. As a forage species, the grass is quick to grow, soft and fast drying, and nutritious and palatable for livestock (National Research Council, 1996). The main drawback of this crop is

that the grain is hard to handle because of its small size (1-1.5 mm long). Wind and rain can bury the seeds after sowing, before the plant can emerge and establish, and processing (threshing, winnowing, grinding) seeds is laborious.

In the first part of this study, we used sap flow measurements to characterize water use of trees from a late-hot season to rainy season period (17 April to 17 September, 2014) and across pollarding treatments. To our knowledge, there have been no studies on the effect of pollarding on *F. albida*. Since this species has a unique reverse leafing pattern, there may be unique consequences of pollarding on the tree's regrowth and water use. Furthermore, most studies that examine water use of parkland trees, particularly *F. albida*, focus on patterns from dry seasons. However, it is during the rainy season that *F. albida* is potentially competing with surrounding crops, so it is water use during this time that is of importance to crop production.

In the second part of this study, we used measurements of  $\delta^{13}\text{C}$ , shoot height, leaf area index, and relative chlorophyll content of teff plots across distance and orientation from the base of unpollarded *F. albida* trees to gauge the impact of the associated trees on teff growth. Despite the *F. albida*-teff association being a common cropping system in parklands, there have been no studies on the effects of *F. albida* on teff growth or yield.

## REFERENCES

- Acevedo E, Hsiao TC, and Henderson DW. 1971.** Immediate and subsequent growth responses of maize leaves to changes in water status. *Plant Physiology* 48:631-636.
- Bayala J, Teklehaimanot Z, and Ouedraogo SJ. 2002.** Millet production under pruned tree crowns in a parkland system in Burkina Faso. *Agroforestry Systems* 54:203-214.
- Bayala J, Mando A, and Ouedraogo SJ. 2003.** Managing *Parkia biglobosa* and *Vitellaria paradoxa* prunings for crop production and improved soil properties in the sub-Saharan zone of Burkina Faso. *Arid Land Resource and Management* 17:283-296.
- Bayala J, Teklehaimanot, Z, and Ouedraogo SJ. 2004.** Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. *Agroforestry Systems* 60:13-26.
- Bayala J, Bazie HR, and Sanou J. 2013.** Competition and facilitation-related factors impacts on crop performance in agroforestry parkland system in Burkina Faso. *African Journal of Agriculture Research* 8:5307-5314.
- Bazie HR, Bayala J, Zombre G, Sanou J, and Ilstedt U. 2012.** Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforestry Systems* 84:377-388.
- Bishaw B, Neufeldt H, Mowo J, Abdelkadir A, Muriuki J, Dalle G, Assefa T, Guillozet K, Kassa H, Dawson IK, Luedeling E, and Mbow C. 2013.** Farmers' Strategies for Adapting to and Mitigating Climate Variability and Change through Agroforestry in Ethiopia and Kenya. Editors Davis CM, Bernart B, and Dmitriev A. *Forestry Communications Group*, Oregon State University, Corvallis, Oregon.
- Boffa JM. 1999.** Agroforestry parklands in sub-Saharan Africa, FAO Conservation Guide 34 [Internet]. Rome, Italy: Food and Agriculture Organization [cited 2013 Nov 10]. Available from <http://www.fao.org/docrep/005/x3940e/x3940e00.htm>
- Bonkougou E. 2001.** Network on agroforestry and soil conservation. Lome, Togo: Secretariat of the Convention to Combat Desertification.
- Brewbaker JL. 1987.** Significant nitrogen fixing trees in agroforestry systems. Gholz, H.I. Edition *Agroforestry: realities, possibilities and potentials* 31-45. *Martinus Nijhoff Publications* Dordrecht, 227pp.
- Caldwell MM, Dawson TE, and Richards JH. 1998.** Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia* 113:151-161.

**Caldwell MM, and Richards JH. 1989.** Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. *Oecologia* 79(1):1-5.

**Coulibaly YN, Mulia R., Sanou J, Zombre G, Bayala J, Kalinganire A, and van Noordwijk M. 2014.** Crop production under different rainfall and management conditions in agroforestry parkland systems in Burkina Faso: observations and simulation with WaNuLCAS model. *Agroforestry Systems* 88:13-28.

**Deans JD, and Munro RC. 2004.** Comparative water use by dryland trees in Parklands in Senegal. *Agroforestry Systems* 60:27-38.

**Gebrekirostos A, Demel T, Masresha F, Mitlohner R. 2006.** Adaptation of five co-occurring tree and shrub species to water stress and its implication in restoration of degraded lands. *Forest Ecology and Management* 229:259–267

**Govindarajan M, Rao MR, Mathuva MN, and Nair PKR. 1996.** Soil-water and root dynamics under hedgerow intercropping in semiarid Kenya. *Agronomy* 88:513-520.

**Heineman AM, Otieno HJO, Mengich EK, and Amadalo BA. 1997.** Growth and yield of eight agroforestry tree species in line plantings in Western Kenya and their effect on maize yields and soil properties. *Forest Ecology and Management* 91:103-135.

**Jama B, Nair PKR, and Kurira PW. 1989.** Comparative growth performance of some multipurpose trees and shrubs grown at Machakos, Kenya. *Agroforestry Systems* 9:17-27.

**Jonsson K, Ong CK, and Odongo JCW. 1999.** Influence of scattered néré and karité on microclimate, soil fertility and millet yield in Burkina Faso. *Experimental Agriculture* 35:39–53.

**Jose S, and Bardhan S. 2012.** Agroforestry for biomass production and carbon sequestration: an overview. *Agroforestry Systems* 86:105-111

**Kassa H, Gebrehiwet K, and Yamoah C. 2010.** *Balanites aegyptiaca*, a potential tree for parkland agroforestry systems with sorghum in Northern Ethiopia. *Journal of Soil Science and Environmental Management* 16:107-114.

**Kessler JJ. 1992.** The influence of karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees on sorghum production in Burkina Faso. *Agroforestry Systems* 17:97–118

**Kho RM, Yacouba B, Yaye M, Katkore B, Moussa A, Iktam A, and Mayaki A. 2001.** Separating the effects of trees on crops: the case of *Faidherbia albida* and millet in Niger. *Agroforestry Systems* 52:219-238.

**Kizito F, Dragila MI, Sene M, Brooks JR, Meinzer FC, Diedhiou I, Diouf M, Lufafa A, Dick RP, Selker J, and Cuenca R. 2012.** Hydraulic redistribution by two

semi-arid shrub species: Implications for Sahelian agro-ecosystems. *Journal of Arid Environment* 83:69-77

**Kizito F, Dragila MI, Sene M, Lufafa A, Diedhiou I, Dick RP, Selker J, Dossa E, Khouma, M, Badiane A, and Ndiaye S. 2006.** Seasonal soil water variation and root patterns between two semi-arid shrubs co-existing with pearl millet in Senegal, West Africa. *Journal of Arid Environment* 67:436-455.

**Kizito F, Sene M, Dragila MI, Lufafa A, Diedhiou I, Dossa E, Cuenca R, Selker J, Dick RP. 2007.** Soil water balance of annual crop-native shrub systems in Senegal's Peanut Basin: the missing link. *Agriculture Water Management* 90:137-148.

**Lehmann J, Peter I, Steglich C, Gebauer G, Huwe B, Zech W. 1998.** Below-ground interactions in dryland agroforestry. *Forest Ecology and Management* 111:157-169.

**Lott JE, Khan AAH, Black CR, and Ong CK. 2003.** Water use in a *Grevillea robusta*-maize overstorey agroforestry system in semi-arid Kenya. *Forest Ecology and Management* 180:45-59.

**Lott JE, Ong CK, and Black CR. 2009.** Understorey microclimate and crop performance in a *Grevillea robusta*-based agroforestry system in semi-arid Kenya. *Agriculture and Forest Meteorology* 149:1140-1151.  
doi:10.1016/j.agrformet.2009.02.002.

**Ludwig F, de Kroon, Hans, Prins HT, and Berendse F. 2001.** Effects of nutrients and shade on tree-grass interactions in an East African savanna. *Journal of Vegetation Science* 12:579-588.

**Mathuva MN, Rao MR, Smithson PC, and Coe R. 1998.** Improving maize (*Zea mays*) yield in semiarid highlands of Kenya: agroforestry or inorganic fertilizers? *Field Crops Research* 55:57-72.

**Mengistu DK. 2009.** The influence of soil water deficit imposed during various developmental phases on physiological processes of tef (*Eragrostis tef*). *Agriculture Ecosystems and Environment* 132:283-289.

**Millar AA, Jensen RE, Bauer A, and Norum EB. 1971.** Influence of atmospheric and soil environmental parameters of the diurnal fluctuations of leaf water status of barley. *Agricultural Meteorology* 8:93-105.

**Mokgolodi NC, Setshogo MP, Shi L, Liu Y, and Ma C. 2011.** Achieving food and nutritional security through agroforestry: a case of *Faidherbia albida* in sub-Saharan Africa. *Forestry Studies in China* 13: 123-131.

**Nair PKR, Kumar BM, and Nair VD. 2009.** Agroforestry as a strategy for carbon sequestration. *Plant Nutrition and Soil Science* 172: 10-23.



- Noumi Z, Abdallah F, Torre F, Michalet R, Touzard B, and Chaieb M. 2011.** Impact of *Acacia tortilis* ssp. *Raddiana* tree on wheat and barley yield in the south of Tunisia. *Acta Oecologia* 37:117-123.
- Ong CK, Black CR, and Muthuri CW. 2006.** Modifying forestry and agroforestry to increase water productivity in the semi-arid tropics. CAB Reviews: Perspectives in Agriculture, Veterinary Science, *Nutrition and Natural Resources* 1.
- Ong CK, and Leakey RRB. 1999.** Why tree-crop interactions in agroforestry appear at odds with tree-grass interactions in tropical savannahs. *Agroforestry Systems* 45:109–129.
- Orwa C, Mutua A, Kindt R, Jamnadass R, and Simons A. 2009.** Agroforestry Database: a tree reference and selection guide version 4.0 [Internet]. Nairobi, Kenya: World Agroforestry Centre; [cited 2013 Nov 8]. Available from <http://www.worldagroforestry.org/af/treedb/>
- Muthuri CW, Ong CK, Black CR, Ngumi VW, Mati BM. 2005.** Tree and crop productivity in *Grevillea*, *Alnus* and *Paulownia*-based agroforestry systems in Central Kenya. *Forest Ecology and Management* 212:23–39.
- Richards JH, and Caldwell MM. 1987.** Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentate* roots. *Oecologia* 73(4):486-489.
- Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, and Dreyer E. 1999.** Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese West Africa. *Functional Ecology* 13:460-472.
- Schroth G. 1999.** A review of belowground interactions in agroforestry, focusing on mechanisms and management options. *Agroforestry Systems* 43:5–34.
- Sepúlveda B, and Carrillo A. 2015.** Soil erosion and erosion thresholds in an agroforestry system of coffee (*Coffea arabica*) and mixed shade trees (*Inga* spp and *Musa* spp) in Northern Nicaragua. *Agriculture Ecosystems and Environment* 210:25-35
- Sheperd KD, Ohlsson E, Okalebo JR, and Ndufa JK. 1996.** Potential impact of agroforestry on soil nutrient balances at the farm scale in the East African Highlands. *Fertilizer Research* 44(2):87-99.
- Sileshi G, Akinnifesi FK, Ajayi OC, and Place F. 2008.** Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant Soil* 307:1-19.
- Tardieu F, Reymond M, Hamard P, Granier C, and Muller B. 2000.** Spatial distributions of expansion rate, cell division rate and cell size in maize leaves: a synthesis of the effects of soil water status, evaporative demand and temperature. *Journal of Experimental Botany* 51:1505-1514.

**Tefera H, and Ketema S. 2000.** Production and importance of tef in Ethiopian Agriculture. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, teff research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p3-7.

**Tefera A, and Tefera T. 2013.** Grain and feed and annual report for Ethiopia. United States Department of Agriculture, Foreign Agricultural Service. Available from [http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual\\_Addis%20Ababa\\_Ethiopia\\_5-24-2013.pdf](http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Addis%20Ababa_Ethiopia_5-24-2013.pdf)

**Thorlakson T, and Neufeldt H. 2012.** Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya. *Agriculture and Food Security* 1:15pp.

**Umar BB, Aune JB, and Lungu OI. 2013.** Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia. *African Journal of Agricultural Research* 8(2):173-183.

**Verchot LV, van Noordwijk M, Kandji S, Tomich T, Ong CK, Albrecht A, Mackensen J, Bantilan C, Anupama KV, and Palm C. 2007.** Climate change: linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change* 12:901-918.

**Wajja-Musukwe TN, Wilson J, Sprent JI, Ong CK, Deans JD, and Okorio J. 2007.** Tree growth and management in Ugandan agroforestry systems: effects of root pruning on tree growth and crop yield. *Tree Physiology* 28:233-242.

**Yadeta K, Ayele G, and Negatu W. 2000.** Farming systems research on tef: smallholders' production practices. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, teff research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p9-23.

**Yihun YM, Haile AM, Schultz B, and Erkossa T. 2013.** Crop water productivity of irrigated teff in a water stressed region. *Water Resource Management* 27: 3115-3125.

**EFFECTS OF POLLARDING ON THE COURSE OF RAINY-  
SEASON WATER USE OF *FAIDHERBIA ALBIDA* IN SUB-HUMID  
ETHIOPIA.**

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## INTRODUCTION

*Faidherbia albida* is a widely used tree species in Africa with some peculiar characteristics that may reduce competition with crops for light and water in parkland systems. Part of the reason for the presumed reduced-competition during a rainy season is the reverse leafing phenology of the species; typical leafing phenology for deciduous species consists of leaf drop during dry or cold seasons when water and light are least available, and leaf flush occurs with the onset of rains during rainy and warm seasons. Leaf drop usually occurs as an adaptation to drought conditions to prevent loss of water transportation that could negatively impact net photosynthetic rates or possibly lead to plant death (Manzoni *et al.*, 2015). However in *F. albida*, Roupsard *et al.* (1999) found that leafiness appeared to be inversely related to the distribution of rain events. Leaf drop can start about a month after rains start, with maximum defoliation generally occurring during the middle of the rainy season, and maximum foliation in mid-dry season. The physiological mechanism behind this reverse phenology is unknown, but an outcome of dropping leaves during the rainy season is that the litter can be more quickly decomposed due to higher levels of soil moisture and microbial activity than during dry seasons (Butenschoen *et al.*, 2011). This would make the nutrients more readily available and mobile to growing roots than nutrients released during periods with low soil moisture.

It is often assumed that this tree species is non-competitive with crops due to its peculiar reverse phenology. However, little is known about how water use by *F. albida* changes during the rainy season, and there have been no studies that examine the effects of pollarding, a common management practice, on water use by this species.

*Faidherbia albida* is adapted to many environmental conditions in part due to the plasticity of its rooting system and depth of water uptake. In areas with alluvial soils, trees can develop an extensive set of shallow roots, and in sandy or sandy-clays trees will develop both shallow roots and taproots that can utilize water from deep soil layers or the water table (Alexandre & Ouedraogo, 1992). This deep-rooting ability allows *F. albida* to experience only moderate drought stress during the dry season (Roupsard *et al.*, 1999). Roupsard *et al.* found that leaf drop did not occur due

to stress; the predawn leaf water potential of trees in the middle of the dry season was -0.5 MPa, and after the rains resumed, leaf drop occurred even though the predawn potential recovered to -0.3 MPa. They also found that *Faidherbia albida* maintained a stable midday leaf water potential during the dry season (between -2.0 to -2.7 MPa), by accessing water from the water table. Tree daily water use (daily cumulative sap flow, kg) was drastically reduced (by 87%) during this leaf shedding in the rainy season, with maximum daily sap flow actually occurring near the end of the rainy season. Dry season daily sap flow was reduced by 25-38%, likely due to reduced stomatal conductance.

In addition to reduced rainy season water use, light interception is also reduced with leaf drop, allowing crops underneath to receive nutrients from decomposing *F. albida* leaves with minimal competition with the tree for light and water (Roupsard *et al.*, 1999; Orwa *et al.*, 2009). Thus, *Faidherbia albida* is also widely known for its positive effect on crop yields through increased soil fertility under the tree crown (Poschen, 1986; Subrahmanyam & Bheemaiah, 2003) and from its nitrogen fixing ability (Brebaker, 1987; Dupye & Dreyfus, 1992; Campa *et al.*, 2013). Generally, organic matter and available nitrogen, phosphorous, and potassium, are higher under *F. albida* canopies than outside, and soil temperatures can be lower (Kamara & Haque, 1992; Vandenbeldt & Williams, 1992). In Niger, Kho *et al.* (2001) reported a 36% higher millet production under the canopy compared to open field associated with a higher N and P availability, with negligible negative effects of light and water competition. Similarly, Vandenbeldt & Williams (1992) found that millet growth was positively related to duration of shade created by trees and the resulting reduced soil temperature.

The increase in soil fertility under the trees is mostly attributed to accumulation of organic matter from leaf litter. However, this effect may not be evenly distributed under the canopy, as Kamara & Haque (1992) found greater organic matter content under the west side of the tree due to prevailing winds. The authors also found an east-west shadow effect, where soil temperatures on the east side of the tree under canopy were always lower than the west side when compared to outside the canopy. They indicated that these temperature differences could also lead

to differential rates of litter decomposition on different sides of the tree, and thus impact crop growth and yield.

However, as Chamshama (1994) indicated, the benefits to crops are not always observed. The positive fertility effect may only be applicable when the tree is large, or after several years of accumulated organic matter from litter fall and animal droppings (Kessler & Breman, 1991; Jama & Getahun, 1991; Saka *et al.*, 1994). Nitrogen fixation may also not occur in areas that are too arid or in heavy clay soils (Dupuy & Dreyfus, 1992).

The leafless habit of the species during rainy seasons may also not be obligatory, and trees that retain their leaves may negatively impact crop yields (Jama & Getahun, 1991). Variation in leaf drop has been attributed to many factors, including provenances, depth of water table, age, and/or rainfall regime (Jama & Getahun, 1991; Wickens, 1969). Even for trees that do have an inverted leafing phenology, denser or overlapping canopies may compete more with crops for water and light and reduce yields than low-density canopies (Jama & Getahun, 1991; Depommier, 1998). Vandenbeldt & Williams (1992) found that even leafless branches still reduced irradiance by about 50% under the canopy. This may be beneficial in environments with extreme midday temperatures, but problematic in more moderate climates.

To complicate this picture, pollarding, a common practice in parklands, can induce leaf development that resembles normal phenology (Depommier, 1998). In Southeastern Shewa region of Ethiopia, *F. albida* generally follows the pattern seen in Sahelian regions, where the tree produces more leaves during the dry season than in the wet season (Laike, 1992). However, the common treatment for *F. albida* in this region in Ethiopia is to severely prune (pollard) branches of the trees to the trunk every 3-4 years for fencing and fuelwood (Laike, 1992), rather than to reduce competition. Pollarding usually occurs in the mid to late dry season when the trees will be less susceptible to infection (local land owners at research site, *personal communication*), which induces the trees to vigorously grow back during the rainy season (Depommier, 1998; *personal observations*). The presumed benefits of *F. albida* then might not be realized where it is a common practice to pollard trees.

While pollarding reduces light competition, regrowth can result in increased water use in later in the rainy season, and therefore increased competition with crops for water. While it is known that *F. albida* water use is reduced with leaf drop, the duration and extent of this reduction, as well as the effect of pollarding on water use, are unknown.

To address these deficiencies, we compared sap flow densities from dates in the dry and rainy seasons to assess changes of water use (1) during a rainy season in 2014, and (2) between two treatments of tree crown, unpollarded and fully pollarded. We used measurements of peak sap flow densities ( $F_{d(max)}$ ) and daily sap flow densities ( $F_{d(daily)}$ ) along with measurements of tree parameters to evaluate the dependence of water use on tree size. Based on previous sap flow measurements on *F. albida*, we expected both peak and daily sap flow densities to decrease over the course of the rainy season due to leaf drop or pollarding, with pollarded trees showing the largest decreases after pollarding. Peak and daily sap flow densities would be positively correlated with various metrics of tree size, such as height, projected crown area, and LAI. A better understanding of how *F. albida* uses water during the rainy season, and how the patterns differ in pollarded trees, could lead to recommendations on pollarding to better manage competition between the trees and field crops.

## MATERIALS AND METHODS

### *Study area*

The site is situated in the Great Rift Valley of Ethiopia, between the western and eastern highlands of central Ethiopia, 11 km south of Mojo. Six mature *Faidherbia albida* trees were used for sap flow measurements; the trees were located in two different fields 1 km apart. Three were at located at 8°30'29.56"N 39°04'21.77"E, 1690 m elevation, and the other three at 8°30'17.35"N 39°03'51.15"E, 1674 m elevation. The site is characterized by a semi-arid to sub-humid climate with around 800-1000 mm of rain a year, with over 80% occurring between April and September (World Bank, 2013; Mengistu, 2006). The rainy season occurs July to September, the cold dry season is from October to February, and the hot season from

March to June. The region is known to have erratic rainfall, frequent drought, and a harsh cropping environment. This area has unimodal rainfall, although there can be sporadic rains in March, April, May, and June but most rainfall occurs in July, August, and September (World Bank, 2013). The mean temperature is from 18 to 24 °C, and the predominant annual agricultural crops are teff, wheat, and maize (Mengistu, 2006). The soil types for the district are eutric fluvisols and luvic phaeozems (Jones *et al.*, 2013).

#### *Species description*

*Faidherbia albida* can grow to a height of about 30 m, though 15-20 m is more typical, has spreading branches with and inverted crown when young, and a hemispherical shape when older; roots can grow 40 m deep, and the trees can live 70-90 years, but some up to 150 years old have been found (Orwa *et al.*, 2009; Vandenbeldt, 1992). The tree has a reverse leafing phenology, where it is foliated in the dry season, and leaf drop occurs at the start of the rainy season. The species also flowers at the start of the dry season, and the seed pods become ripe at the end of the dry season (Orwa *et al.*, 2009). Trees can be pollarded twice a year, and pollarding stimulates vigorous regrowth.

*F. albida* grows on banks of seasonal and perennial rivers, in vertisols and sandy alluvial soils. Found in dry areas, where altitudes range between 270 to 2700 m, temperature range between 18-30 °C, and with mean annual rainfall of 250-1200 mm (Orwa *et al.*, 2009). It is native to parts of West, East, and Southern Africa, and it is exotic in South America (Peru) and the Indian subcontinent. In Africa, the species range is mostly in sub-Saharan Africa. There are also two ecotypes; upland (in West Africa) and riparian (in East, South, and Southwestern Africa), however there are many intermediate forms so overall they have been left as one species. Most of the distinguishing characteristics are in branching pattern of young branches, flower parts, and leaflet shape (Wood, 1992; Ibrahim *et al.*, 1997). In the Southeast Shewa region of Ethiopia, the species has the same uses as other areas, but it can also be used to shade coffee plants, and is seen as a holy tree by some, so it is generally protected on farms for wood and not felled (Laike, 1992). It is commonly found on



seasonally waterlogged land, riverbanks, woodland and grassland areas. It is also usually associated with *Acacia tortillis*, *Acacia seyal*, and *Balanites aegyptica*.

#### *Tree characteristics*

The six trees were given a letter code based on pollarding treatment, either pollarded (P) and unpollarded (UP), and a number (1, 2, or 3). Three of the trees were pollarded in May 2014 (P3 on May 17, and P1 and 2 on 27 May), and the other three were left unpollarded. Tree crown pollarding was done before the rainy season started, and was done as a complete pollarding of the tree (100% branch removal to main trunk). Trees in this area are normally pollarded every two years for fuel wood or fencing, therefore the unpollarded trees in this study had two years of growth.

Tree height (after pollarding; measured on May 31, June 23, August 27, and September 14) and crown radius (measured on May 31, August 27, and September 14), bark thickness, DBH, and crown projected area are given in Table 1. Tree height was obtained using the similar sides rule for triangles; a rope was attached to the base of the trunk and to the bottom of a handheld pole. The top and bottom of the pole was sighted to the top and bottom of the tree. Height was then calculated by dividing distance from tree base to pole bottom by the distance from pole bottom to eye, and then multiplied by the length of the pole.

Crown radius was the mean of four measurements of the distance from the middle of the trunk to the crown edge at the four cardinal directions. Crown projected area was then calculated by using the crown radius from each date to find the area of the circle under the tree. Bark thickness was taken by removing a small section of bark and measuring its depth near the sap flow gauge (installed at 1.3 m) and on the opposite side of the trunk. These values were averaged to get the average bark depth.

#### *Leaf area index*

Leaf area index (LAI) was estimated with the AccuPAR-LP80 ceptometer (Decagon Devices, Pullman WA). The ceptometer uses above (outside) and multiple below canopy measurements of photosynthetically active radiation (PAR; wavelengths of 400-700 nm) and other parameters to calculate LAI (Decagon Devices, 2014). The AccuPAR measures PAR as  $\mu\text{mol m}^2 \text{s}^{-1}$  and LAI as area of leaves per unit area of soil surface, which is a unit-less measure.

The other parameters the ceptometer uses are the zenith angle ( $Z$ ), fractional beam value ( $F_b$ ), a ratio from the PAR measurements ( $\tau$ ), and a leaf area distribution value ( $X$ ). The zenith angle is automatically calculated by AccuPAR based on time of day, day of year, and global position; for our study site this was  $8^{\circ}30' \text{ N } 39^{\circ}04' \text{ E}$ . Fractional beam value is also automatically calculated by the AccuPAR, as a ratio of the direct beam radiation from the sun to that coming from all other sources (i.e. reflected from surfaces).  $\tau$  is measured as automatically and is the ratio of the below canopy to above canopy PAR value.  $X$  is used to characterize the distribution of leaf angles in a specific canopy, and is estimated by observing the amount of light that penetrates a representative section of canopy.

$X$  was calculated as:

$$X = \ln(t_0)/\ln(t_{90}) \quad \text{Equation 1}$$

Where  $t_0$  is the vertical gap fraction (the percentage of light seen vertically), and  $t_{90}$  is the horizontal gap fraction (the percentage of light seen horizontally). Randomly distributed canopies have a  $X$  of about 1, more vertical canopies have a  $X$  of less than 1, and more horizontal canopies have a  $X$  greater than 1. For the tree canopy, we estimated using half the tree crown, and observed 30% vertical and 50% horizontal values, for a  $X$  of 1.73. The above canopy reading was taken 8 m away from the tree, then two below canopy readings were taken at each cardinal direction, perpendicular to the direction, for a total of eight below canopy readings for the tree. The data for each measurement were stored on the device and downloaded at the end of the study. Measurements were made between 0930 and 1300 h on 15/9/2014.

#### *Sap flow measurements*

Sap flow density through the sap wood ( $\text{kg dm}^{-2} \text{ hr}^{-1}$ ) was measured in six trees on 17 April, 2014, and from 12 May to 17 September 2014. We used SFM1 (Sap Flow Meter -1, ICT International), which uses the heat ratio method (HRM) principle. The heat ratio method is a modification of the Compensation Heat Pulse Method (CHPM), where a pulse of heat is used as a tracer to measure heat pulse velocity (Marshall, 1958; Barrett *et al.*, 1995; Smith & Allen, 1996). A heater element

that releases the heat pulse is installed radially in a plant stem, with two heat sensor probes placed in the upstream and downstream positions relative to the direction of sap flow. CHPM uses an asymmetric sensor alignment and the time until the heat sensors warm to the same temperature to calculate heat pulse velocity. HRM is similar, but uses the ratio of the increase of temperature of two symmetrically placed sensors to calculate heat pulse velocity (Burgess *et al.*, 2001; Burgess & Downey, 2012). The gauges were installed by ICRAF staff on 16 April, 2014 following standard procedures (Burgess & Downey, 2012), with sensors placed 0.5 cm from the heater.

The heat pulse velocity,  $V_h$  (cm hr<sup>-1</sup>), is logarithmically related to the ratio of temperature increases up and downstream from the heater by

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) \times 3600 \quad \text{Equation 2}$$

where  $k$  is the thermal diffusivity of fresh wood,  $x$  is the sensor distance from the heater, and  $v_1$  and  $v_2$  are the increase in temperature of the upstream and downstream sensors, respectively, from their initial temperature. This first calculation was done by the microprocessor in the SFM1 gauge after each measurement (which occur every 30 minutes), using a thermal diffusivity reference value of  $2.5 \times 10^{-3}$  cm<sup>2</sup> s<sup>-1</sup>, and the data stored on an SD card. Measurements were taken every 30 minutes, and data were recorded on 17 April, 2014, and from 12 May through 17 September, 2014.

#### *Converting heat pulse velocity to sap flow velocity*

With the data from the gauges we used the Sap Flow Tool (SFT) software, a program designed for processing data from some of ICT International's gauges, to convert  $V_h$  to sap flow velocity,  $V_s$  (ICT International, 2012). SFT uses Equation 2 to calculate  $V_s$  from  $V_h$ :

$$V_s = \frac{k}{0.0025} B \frac{\rho_b (c_w + m_c \cdot c_s)}{\rho_s \cdot c_s} V_h \quad \text{Equation 3}$$

$V_s$  is the sap velocity (cm hr<sup>-1</sup>),  $k$  is the thermal diffusivity (cm<sup>2</sup> s<sup>-1</sup>) of the sapwood, 0.0025 the reference thermal diffusivity (cm<sup>2</sup> s<sup>-1</sup>),  $B$  the wound correction factor,  $\rho_b$

the density of wood ( $\text{kg m}^{-3}$ ),  $c_w$  the specific heat capacity of wood matrix ( $1200 \text{ J kg}^{-1} \text{ C}^{-1}$ ),  $c_s$  the specific heat capacity of sap (water only,  $4182 \text{ J kg}^{-1} \text{ C}^{-1}$ ),  $\rho_s$  the density of water ( $1000 \text{ kg m}^{-3}$ ),  $m_c$  the water content of the sapwood ( $\text{kg kg}^{-1}$ ), and  $V_h$  the heat pulse velocity ( $\text{cm hr}^{-1}$ ) at a given position.

To obtain sapwood water content, density, and thermal diffusivity for Equation 3, sapwood fresh weight, volume, dry weight, and water content were derived from core samples. Core samples on each tree were taken to the center of the trunk with a 40 cm increment corer with a 5 mm diameter. Samples were stored in sealed bags, covered in foil, and weighed 8 hours later. After three days of drying until constant weight was reached, the final weight was taken. The entire core sample for each tree was moist, and there was no distinction between sapwood and heartwood, similar to findings of Roupsard *et al.* (1999). Roupsard *et al.* also found sap flow to be substantial deep in the wood of the trunk, cores from large branches had open vessels to the center, and staining showed all these vessels were still functional. Therefore the entire moist core, with phloem removed, was used for calculations of sapwood density and thermal diffusivity.

#### *Accounting for wounding and sensor misalignment*

Since damage done to the xylem during probe installation, and the subsequent plant response, can affect the measurement of  $V_h$ . Burgess *et al.* (2001) developed a model that gives correction coefficients for wounding based on the diameter of the wound around the probe. Since the probes would not be extracted for many months beyond this study we were unable to measure the wound response from the probes themselves. Instead, we inserted dummy needles of the same diameter, following the same installation practice for the probes, into each tree on 12/07/2014. Four weeks later we extracted three needles with a small amount of the surrounding wood (approximately  $1 \text{ cm}^3$ ), and measured the wound diameter. After another three weeks we extracted the remaining needles to see if the wound response changed. It did not, and a wound diameter of 0.19 cm (averaged from six needles) was used in SFT to get the wound correction factor.

Measurements are also affected by misalignment of the sensors in relation to the heater, as in when the distance between the heater and a sensor is greater than or

less than 0.5 cm. The probes need to be installed radially like the heater, but they also need to be on the same longitudinal plane, parallel to the heater to keep a constant 0.5 cm distance between the heater and the sensors.

Probe spacing should be calculated at  $V_h=0$  as

$$x_2 = \sqrt{\left(4kt \cdot \ln\left(\frac{v_1}{v_2}\right) + x_1^2\right)} \quad \text{Equation 4}$$

where  $V_h$  at zero flow is imposed by severing the stem.  $x_1$  and  $x_2$  are the correctly and incorrectly spaced probes, respectively, and  $t$  is measurement time. Once  $x_1$  and  $x_2$  are solved for, corrected  $V_h$  can be calculated from:

$$V_h = \frac{4kt \cdot \ln\left(\frac{v_1}{v_2}\right) - x_2^2 + x_1^2}{2t(x_1 - x_2)} 3600 \quad \text{Equation 5}$$

This corrected  $V_h$  at zero flow gives a simple linear relationship which can then be used to correct the remaining data. In SFT this can be done to all data at once for a sensor set by using a multiplier and an offset (ICT International, 2012).

However, because extraction of the sensors would not occur until many months beyond this study, and because the tree owners would not allow the trees to be felled, we were unable to obtain a  $V_h=0$  for each gauge. At installation, the gauges were checked for alignment visually using overly long probes inserted into the holes, with no misalignment reported. Given the situation, the only correction we could make was to do a simple offset for each  $V_h$  data set based on visualization of the data in SFT to account for needle misalignment. Since  $V_h$  should reach zero at times of zero flow, night time  $V_h$  in the predawn hours (0200-0500 h) should be near zero (A Downey, *personal communication*). Using  $V_h$  data from the months of August and September, when the rains occurred most frequently, but avoiding dates with heavy rainfall as reverse flow was more likely, we added or subtracted a small offset to the  $V_h$  data for each sensor set to align the presumed time of zero flow to the zero line. The greatest offset was by 2 cm hr<sup>-1</sup>, with the majority of offsets being less than 1 cm hr<sup>-1</sup>.

We also made a few other minor corrections to the data using SFT. When one or a few measurements were missing or erroneous (e.g. a sudden drop to zero), an interpolation between existing measurements was made. In the case of a few hours of missing data, as occurred at night on a few occasions when the SFM's internal battery did not recharge fully during the day from the solar charger, nighttime data from the most recent dry night was used to fill the missing data. The purpose of these corrections was to still be able to make comparisons between trees based on cumulative water use. The missing data occurred on 3/9/2014 and 9/9/2014 for P1, on 4/9/2014 for UP1, and on 4/9/2014 and 5/9/2014 for P2. UP1 also appeared to have erratic night time data starting 22/5/2014.  $V_h$  could change up to 3 cm hr<sup>-1</sup> between half hour measurements, with the positive and negative swings usually centering along the zero line when visualized. This variation in flow was not observed during the day time for the tree when flows were higher, nor in other trees. Therefore we also interpolated nighttime flows on many dates for UP1; in the case where the measurements rapidly increased and decreased, we interpolated nearby measurements to obtain a velocity that was closer to the mean of these swings.

*Converting sap flow velocity to sap flow density*

There are two sensor positions for each SFM1 gauge; an outer set, 1.25 cm deep into the sapwood, and an inner set, 2.75 cm deep into the sapwood, with a distance of 1.5 cm between them. To convert  $V_s$  to sap flow density, first the  $V_s$  for each measurement time was multiplied by the cross sectional area of the annulus of sapwood that each sensor position was located in to get sap flow rate. The annulus radius was 2 cm for outer sensors and 1.5 cm for the inner sensors. SFT produces a sap flow rate for the outer and inner  $V_s$  at each measurement time in cm<sup>3</sup> hr<sup>-1</sup>, therefore sap flow rate was converted to sap flow density ( $F_d$ ) by

$$F_{d_i} = \frac{F_i}{1000} / \frac{A}{100} \quad \text{Equation 6}$$

where  $F_{d_i}$  is the sap flow density at time  $i$  (kg dm<sup>-2</sup> hr<sup>-1</sup>),  $F_i$  is the sap flow rate at time  $i$  (cm<sup>3</sup> hr<sup>-1</sup>), and  $A$  is the cross sectional area that the sensor(s) is located in (cm<sup>2</sup>). For comparisons, kg dm<sup>-2</sup> hr<sup>-1</sup> is used since these were the units used by Roupsard *et al.*

(1999), the only other study that has done sap flow measurements on *F. albida*. A combined flow rate was obtained based on the flow rate from the outer and inner positions. The peak (maximum) sap flow density,  $Fd_{(max)}$ , for individual dates was calculated from the peak combined flow rate of the two sensor sets between 1200-1600 h. Similarly, minimum sap flow density,  $Fd_{(min)}$ , was calculated from the lowest combined flow rate of the two sensor sets between 0200-0630 h. SFT also produces a daily cumulative volume from the combined flow rate from integrating hourly  $F$  over the course of the day, and a running cumulated volume from the combined flow rate for the entire study. These values were also converted from volume to density per day ( $Fd_{(daily)}$ ) for the two sensor sets, or per time period ( $Fd_{(XD)}$ ), where  $X$  corresponds to the number of days in the period.

#### *Data Analyses*

Simple linear regression was used to test correlation between tree parameters of height (collected on four dates; May 31, June 23, August 27, and September 14), crown area (collected on three dates; May 31, August 27, and September 14) and LAI (collected on one date; September 14), to  $Fd_{(max)}$  and  $Fd_{(daily)}$ . Dates in May and June correspond to hot or hot-rainy season transition, and dates in August and September correspond to late-rainy season. Statistical analysis were conducted in R, version 2.15.1 (2012-06-22).

To see the general pattern of water use during the rainy season for each tree, we compared  $Fd_{(max)}$  ( $\text{kg dm}^{-2} \text{hr}^{-1}$ ) and  $Fd_{(daily)}$  ( $\text{kg dm}^{-2} \text{d}^{-1}$ ) values from select dates using percentages with observations of leafing phenology. All dates used were dry days (days with no precipitation), and included dates from the hot/dry season prior to pollarding (17 April, 12 and 16 May), dates immediately after pollarding (17-19 May, 27-29, 31, May), dates corresponding to approximately 1-16 weeks after pollarding (3, 4, 9, 14, 23, 28 of June, 4, 8, 13, 19, 25 of July, 3, 4, 7, 19, 25 of August, 1, 6, 10, 14 of September), and dates on which tree parameters were measured on (31 May, 23 June, 27 August, 14 September). Dates in June correspond to the hot-to-rainy season transition, whereas dates in July, August, and September correspond to the rainy season. Two sample t-tests were used to compare mean differences of  $Fd_{(max)}$  and  $Fd_{(daily)}$  between pollarded and unpollarded trees on each date.

To see the magnitude of sap flows that occurred after pollarding, we compared  $F_{d(max)}$  and  $F_{d(min)}$  from 16 May (before pollarding) to  $F_{d(max)}$  and  $F_{d(min)}$  from 31 May (after pollarding) using percentages. To compare differences in nighttime and daytime flows, two sets of dates were used: one in the hot season, 16 May 0630 h to 17 May 0600 h, and the other in the rainy season, 3 August 0630 h to 4 August 0600h. We compared the sap flow density at midnight to the previous day's  $F_{d(max)}$ , and the nighttime sap flow density between 2000 and 0600 h to the daytime sap flow density between 0630 and 1930 h using percentages.

Paired t-tests were used to compare mean differences of the change of  $F_{d(max)}$ , ( $\Delta F_{d(max)}$ ), and  $F_{d(daily)}$ , ( $\Delta F_{d(daily)}$ ), between dates and between pollarded and unpollarded trees. Comparisons made include dates within the hot season (17 April to 16 May), dates before to after all trees were pollarded (16 May to 31 May), dates before to about one month after tree pollarding (16 May to 23 June), dates of hot season to lowest sap flow density of unpollarded trees (16 May to 8 July, and 16 May to 7 August), and dates of hot season to the end of the study (16 May to 14 September).

A two sample t-test was also used to compare the mean difference of cumulative sap flow densities of the entire 79 day period ( $F_{d(79D)}$ ,  $\text{kg dm}^{-2} \text{ tree}^{-1}$ ) for the long cropping season (1 July to the end of study), and for the 50 day period ( $F_{d(50D)}$ ) for the short cropping season (30 July to the end of the study) between pollarded and unpollarded trees. The start of the long cropping season is aligned with the start of the rainy season, the time crops such as maize or millet are generally sown. The start of the short cropping season is aligned with the time quick maturing crops like *Eragrostis tef* are sown.

## RESULTS

### *Tree characteristics*

Trees in this study were 39.0-54.6 cm at breast height, unpollarded trees were 8.6-11.3 m tall, and pollarded trees were 3.0-7.0 m tall after pollarding (Table 1).



Bark thickness was 1.1-1.9 cm for all trees, crown radius of unpollarded trees was 3.2-4.1 m, and after pollarding, pollarded tree crown radius was 0.4-1.2 m.

There was no relationship between LAI and  $F_d(\text{max})$  or  $F_d(\text{daily})$  across or between pollarded and unpollarded trees ( $P > 0.05$ ). Average PAR below tree canopy for pollarded trees was 28.2 % lower than outside canopy (with a range of 16-38.3 %), and 15.5 % lower for unpollarded trees (with a range of 14.5-16.3 %) for September 15.

There was a significant positive linear relationship between tree height and  $F_d(\text{max})$  or  $F_d(\text{daily})$  across all trees (slope = 0.19, 2.47,  $P = 0.00016$ , 0.00003,  $r^2 = 0.77$ , 0.84, respectively; Fig. 1a, b) on the combined late-rainy season dates (27 August and 14 September). However, within pollarding groups the relationship was only significant for pollarded trees (slope = 0.25, 2.42,  $P = 0.019$ , 0.015,  $r^2 = 0.78$ , 0.81, respectively), and not for unpollarded trees. There was also no significant relationship for pollarded or unpollarded trees on the hot/dry season dates (31 May and 23 June).

There was a significant positive linear relationship between crown area and  $F_d(\text{max})$  or  $F_d(\text{daily})$  across all trees (slope = 0.02, 0.22,  $P = 0.0012$ , 0.0003,  $r^2 = 0.67$ , 0.74; Fig. 1c, d) on the combined late-rainy season dates. Within pollarding groups, this relationship only existed for  $F_d(\text{max})$  for pollarded trees only (slope = 0.06,  $P = 0.026$ ,  $r^2 = 0.75$ ). There were no significant relationships between crown area and  $F_d(\text{max})$  or  $F_d(\text{daily})$  on the hot/dry season date.

#### *Sap flow patterns*

Peak sap flow densities were  $2.2 \text{ kg dm}^{-2} \text{ h}^{-1}$  at maximum (with a range of  $1.2 - 3.0 \text{ kg dm}^{-2} \text{ h}^{-1}$ ), which agrees with Roupsard *et al.* (1999), who reported peak flow densities of about  $2.5 \text{ kg dm}^{-2} \text{ h}^{-1}$  for the whole tree. However values in this study are for the densities obtained from the outer 3.5 cm of the sapwood only, and would decrease for whole tree values. Roupsard *et al.* were able to measure the radial sap flow profile of trees, and found a negative logarithmic relationship between relative sap flow density (sap flow deep in wood as fraction of surface sap flow) and measurement depth. Using the procedure outlined in Roupsard *et al.* we obtained a mean peak density of  $1.4 \text{ kg dm}^{-2} \text{ h}^{-1}$  with a range of  $0.8-1.7 \text{ kg dm}^{-2} \text{ h}^{-1}$  on a whole-

tree basis. However Roupsard *et al.* were only able to measure sap flow in their trees to the 15 cm (from the trunk surface) radial depth, which still had a relative flow of about  $\frac{1}{3}$  that of the surface. Zero flow, by extrapolation, would not have occurred until about 49 cm radial depth from surface. For a tree like UP1, with a radial depth of 26 cm and a hot season sap flow density of  $3 \text{ kg dm}^{-2} \text{ h}^{-1}$  at the surface of sapwood, sap flow density would be about  $0.5 \text{ kg dm}^{-2} \text{ h}^{-1}$  at the center.

For daily sap flow densities, the trees had a range from 12.1 to  $29.5 \text{ kg dm}^{-2}$  for the late hot season and 7.9 to  $25.3 \text{ kg dm}^{-2}$  for the late rainy season (Fig. 2 a, b), which are within range of those reported by Do *et al.* (2008) for *Acacia tortillis*, Roupsard *et al.* (1999) for *F. albida*, and Meinzer *et al.* (1999) for four savanna species in Brazil.

The general pattern of peak and daily sap flow densities was variable between the trees; one unpollarded tree, UP1, did have reduced sap flow densities at mid-rainy season, while the other two unpollarded trees showed relatively smaller reductions throughout the season. In contrast, the pollarded trees exhibited roughly similar patterns of sap flow densities. Since 16 May was the last day during the hot season before trees were pollarded, and before the first major rain on 22 May, comparisons are made in reference to the  $F_{d(\text{max})}$  and  $F_{d(\text{daily})}$  values for that date for each tree.

Of the three unpollarded trees, UP1 most closely followed the reverse phenology described in other literature, with leaf drop drastically reducing water use at mid-rainy season (mid-August). Between 17 April and 16 May, UP1  $F_{d(\text{max})}$  and  $F_{d(\text{daily})}$  decreased by 32% (Fig. 2a, b).  $F_{d(\text{max})}$  and  $F_{d(\text{daily})}$  remained stable after that until the first major rain event on 22 May, where  $F_{d(\text{max})}$  decreased further by 6% and  $F_{d(\text{daily})}$  by 32%.  $F_{d(\text{max})}$  and  $F_{d(\text{daily})}$  returned to the 16 May values for the rest of May, but through June until early August,  $F_{d(\text{max})}$  and  $F_{d(\text{daily})}$  decreased by 88% and 93%, respectively. By the end of the study,  $F_{d(\text{max})}$  recovered to 97% of the 16 May value, and  $F_{d(\text{daily})}$  67%.

Unexpectedly for the other two unpollarded trees, UP2 and UP3, sap flow decreased relatively little as compared to UP1. If the trees had been following the phenology that is typical for their species, UP2 and UP3 should have also showed drastic decreases of peak and daily sap flow densities at mid-rainy season. Between

17 April and 16 May,  $Fd_{(max)}$  and  $Fd_{(daily)}$  decreased by 15% each (Fig. 2a, b). Like UP1, these values remained stable until the first major rain event on 22 May, where  $Fd_{(max)}$  decreased by 6-14% and  $Fd_{(daily)}$  by 38-43%. After 22 May,  $Fd_{(max)}$  slowly decreased to 68-86% until 8 July, while  $Fd_{(daily)}$  ranged from 41-111%, but with a slight decreasing trend during that time for both trees. From 8 July to the end of the study,  $Fd_{(max)}$  recovered to approximately 95% and  $Fd_{(daily)}$  ranged between 54-86%, with either no trend (UP2) or a slight increasing trend (UP3).

In contrast to the variation of the unpollarded trees, the three pollarded trees exhibited roughly the same pattern of sap flow densities during regrowth. Between 17 April and 16 May  $Fd_{(max)}$  and  $Fd_{(daily)}$  decreased by about 30% each (Fig. 2a, b). After pollarding,  $Fd_{(max)}$  decreased to just approximately 5% of the 16 May value, and  $Fd_{(daily)}$  to slightly above or below zero for four (P3) to six weeks (P1 and P2). It was not until five to six weeks after pollarding (23 June for P3, 8 July for P1 and P2) that  $Fd_{(max)}$  and  $Fd_{(daily)}$  started to increase. By the end of the study,  $Fd_{(max)}$  recovered to approximately 95% and  $Fd_{(daily)}$  63%.

#### *Irregular diurnal flows post-pollarding*

The three pollarded trees also exhibited irregular diurnal sap flow patterns for several weeks after pollarding. The minimum sap flow densities ( $Fd_{(min)}$ ) for each day normally occur between 0300 and 0600 h, while peak (maximum) sap flow densities ( $Fd_{(max)}$ ) normally occur between 1200 and 1500 h (see Fig. 3a for an example of regular diurnal patterns). For the pollarded trees, the timing of maximum and minimum flows was either inverted (P1) or semi-inverted (P2 and P3; see Fig. 3b for an example of irregular diurnal patterns). For inverted flows,  $Fd_{(max)}$  occurred during night or predawn hours (1900-0600 h), while  $Fd_{(min)}$  occurred between 1200-1500h. Semi-inverted  $Fd_{(max)}$  occurred between 1400 and 2130 h, and  $Fd_{(min)}$  between 0400 and 1500 h. Irregular diurnal timing of  $Fd_{(max)}$  and  $Fd_{(min)}$  lasted the longest in P2, 53 days, with sap flow densities starting to increase 11 days before the regular diurnal pattern of sap flow returning. In contrast, in P1 and P3, the irregular timing lasted 28 and 38 days respectively, with sap flow density increasing 9 and 4 days after the return of diurnal flows. However, the magnitude of irregular sap flow density was low in comparison to pre-pollarding values. Using peak and minimum

sap flow densities from 16 May (before pollarding) and 31 May (4-14 days after pollarding),  $F_{d(max)}$  after pollarding were 2-6 % of the  $F_{d(max)}$  before pollarding, while  $F_{d(min)}$  after pollarding were 2-25 % of the  $F_{d(min)}$  before pollarding

#### *Nighttime flows*

Even after sunset, there was still substantial sap flow (Fig. 4a), which Rounsard *et al.* (1999) attributed to slow internal equilibration between the tree crown and soil, or nighttime transpiration. This pattern was seen most strongly during the hot season, with continuously positive night time flows for some trees. Wang *et al.* (2012) reported similar patterns in *Acacia magnum*, where dry periods have higher nighttime flows than wet periods, but that only 2.6-8.5 % of the sap flow was lost as transpiration.

On the hot season date of 16 to 17 May, sap flow densities at midnight on 17 May ranged between 17-32 % of peak sap flow densities on 16 May, while nighttime sap flow density (2000 to 0600 h) ranged from 20-30 % of the previous days' daytime sap flow density (0630 to 1930 h; Fig. 4a). Ranges were similar across pollarded and unpollarded groups.

In contrast, the mid-rainy season date had lower levels of nighttime sap flow, with noticeable differences between pollarded and unpollarded trees. Sap flow densities at midnight on 4 August ranged between -2-11 % of peak sap flow densities on 3 August, with pollarded trees ranging from -2-5%, and unpollarded trees 4-11% (Fig. 4b). Nighttime sap flow density ranged from 3-17 % of the previous days' daytime sap flow density, with pollarded trees ranging from 3-8% and unpollarded trees 7-17%.

#### *Pollarded and unpollarded trees*

For comparisons on individual dates, there were no significant differences between pollarded and unpollarded trees mean  $F_{d(max)}$  and  $F_{d(daily)}$  on 17 April, 17, 18 of May, 25 of July, 3, 4, 7, 19, 25, 27 of August and 1 of September ( $P \geq 0.05$ , Fig. 5a, b). On 19 May only, mean  $F_{d(max)}$  was not significantly different between pollarded and unpollarded trees but unpollarded  $F_{d(daily)}$  was significantly larger than pollarded ( $P = 0.044$ ). Unexpectedly, on 12 and 16 May, before pollarding, the group of trees that would be left unpollarded did have a significantly greater  $F_{d(max)}$  and

$F_d(\text{daily})$  than the group of trees that would be pollarded after these dates. On 27-29, 31 of May, 3, 4, 9, 14, 23, 28 of June, 4, 8, 13, 19 of July, and 6, 10, 14 of September, mean  $F_d(\text{max})$  and  $F_d(\text{daily})$  for unpollarded trees was significantly greater than pollarded trees ( $P \leq 0.05$ , Fig. 5a, b).

For comparisons between dates, the mean difference of  $F_d(\text{max})$  from 17 April to 16 May in the hot season,  $\Delta F_d(\text{max})$ , was significantly different from zero between the dates ( $P = 0.0018$ ) across all trees, with 17 April having larger  $F_d(\text{max})$  values. Similarly, the mean difference of  $F_d(\text{daily})$ ,  $\Delta F_d(\text{daily})$ , was significantly different between the dates ( $P = 0.002474$ ). Between 16 May and 31 May, and 16 May and 23 June, the period a few days to a month after pollarding,  $\Delta F_d(\text{max})$  and  $\Delta F_d(\text{daily})$  were significantly greater than zero across all trees, and between pollarded and unpollarded trees ( $P \leq 0.05$ ). For the comparisons between 16 May and 8 July, 16 May and 7 August, and 16 May to 14 September,  $\Delta F_d(\text{max})$  and  $\Delta F_d(\text{daily})$  were significantly greater than zero across all trees ( $P \leq 0.05$ ), but not between pollarded and unpollarded trees ( $P > 0.05$ ).

#### *Seasonal water use*

For the 79 day long cropping season,  $F_d(79D)$  of unpollarded trees was significantly larger than that of pollarded trees ( $P = 0.038$ ). For the 50 day short cropping season there were no significant differences between pollarded and unpollarded  $F_d(50D)$  ( $P = 0.1127$ ).

## DISCUSSION

### *Tree characteristics*

We expected tree size, measured by tree height, projected crown area, and LAI to be positively correlated with peak and daily sap flow densities. Instead, LAI was not found to be related to  $F_d(\text{max})$  and  $F_d(\text{daily})$ , in contrast to the findings of Allen & Grime (1995) and Do *et al.* (2008). This is likely due to both small sample sizes of trees, and only one measurement date for this parameter near the end of the study, after leaf flush in all trees. On the late-rainy season dates (27 August and 14 September), height was significantly related to pollarded tree peak and daily sap flow

densities only, indicating that sap flow was related to changes in height only for vigorously growing trees (Fig. 1a, b), whereas crown area in pollarded trees was only related to peak sap flow density (Fig. 1c). This was likely due to the regrowth habit of pollarded trees, where dense “watersprouts” off of the main trunk grow before expanding laterally.

### *Sap flow patterns*

We had expected both peak and daily sap flow densities to decrease over the course of the rainy season. On unpollarded trees, the largest decreases should have been at mid-rainy season, consistent with leaf drop occurring at the onset of rains. Peak and daily sap flow densities decreased with the onset of the rains in all three unpollarded trees, but only one tree, UP1, exhibited drastic reductions.

The onset of the decrease in sap flow was synchronous among unpollarded trees, where just after the onset of the rainy season values dropped. However, sap flow continued to decrease drastically for another month in UP1, but increased slightly or remained stable in UP2 and UP3. UP1 was also the only tree to become noticeably defoliated before starting a new flush, while UP2 and UP3 showed simultaneous leaf drop and flush. Because the trees were within 1 km of each other they were experiencing roughly the same weather conditions throughout each day and during the study. These patterns in sap flow densities thus were likely due to differences in leaf area over time, as leaf area has been strongly related to rates of sap flow (Allen & Grime, 1995; Do *et al.*, 2008). Leaves are the site of water loss through transpiration via the soil-leaf pathway, where transpiration is limited by stomata in response to atmospheric variables (especially vapor pressure deficit) and access to soil water (Meinzer *et al.*, 1999). Do *et al.* (2008) found a strong relationship between leaf area (in a qualitative assessment of “canopy fullness”) and tree water use measured from sap flow, along with no difference in hydraulic conductance between wet and dry seasons, suggesting that canopy conductance was strongly regulated by stomatal conductance and/or leaf area to cope with atmospheric changes. Roupsard *et al.* found that *F. albida* transpiration rates were large under favorable conditions, and hydraulic conductance decreased near the end of the dry season without leaf drop, indicating that stomatal control regulated transpiration during the dry season. During

the rainy season, Roupsard *et al.* also reported that leaf shedding, or reduction of leaf area, completely stopped transpiration in *F. albida* trees. Trees in the Roupsard *et al.* study had a daily flow of 239 kg in the late hot season, and 52 kg (a 78% decrease) in the early-mid rainy season as a result of leaf drop. Using the method for calculating whole tree flow as outlined by Roupsard *et al.* UP1 had a 93% decrease (from 339 to 25 kg).

Similarly, for the pollarded tree group, pollarding treatments resulted in complete removal of leaves, causing both  $F_{d(max)}$  and  $F_{d(daily)}$  to drop to roughly zero for 5-6 as expected weeks (Fig. 2a, b). Only with regrowth several weeks after pollarding did both the peak and daily sap flow densities start to increase. Since pollarding did decrease tree water use so drastically as compared to unpollarded trees, pollarding can be an effective means of limiting water competition between trees and crops in parkland systems, in addition to reducing canopy light interception.

#### *Irregular diurnal flows post-pollarding*

The cause of the unusual diurnal patterns after pollarding is unknown. However, because sap flow densities were small, less than  $0.1 \text{ kg dm}^{-2} \text{ h}^{-1}$  for P1 and less than  $0.05 \text{ kg dm}^{-2} \text{ h}^{-1}$  for P2/P3, some of this variation is likely due to exogenous temperature fluctuations or from the setup of the sensors themselves. Burgess *et al.* (2001) found that external temperatures could cause changes up to  $0.5\text{-}1 \text{ cm h}^{-1}$  in sap velocities, and in the present study, many sap velocities were less than  $2.0 \text{ cm h}^{-1}$  on pollarded trees after pollarding. However, Burgess *et al.* also found that this temperature effect was random, not correlated to any systematic or consistent pattern in sap velocities, and concluded that the relatively large temperature changes induced by the heater element override the influence of ambient temperature fluctuations.

The 0.5 cm sensor spacing used with the HRM is intended to capture high rates of flow ( $\pm 54 \text{ cm h}^{-1}$ ) that other spacings, such as 0.6 or 0.75 cm, would be less sensitive to, as the further sensors are from the heat source, the less sensitive they are to the heat (Burgess *et al.*, 2001). Since  $V_h$  is calculated from the ratio of the temperature increases of upstream and downstream probes (Equation 2), a narrower spacing allows for more sensitivity over wider spacing with high velocities (Burgess *et al.*, 2001). However, this same design would also make the method less sensitive at

low velocities, due to tempering of the temperature ratios. As a result, error in measurement might be higher with low velocities, although the relationship between the two is unknown.

#### *Nighttime flows*

Wang *et al.* (2012), like Roupsard *et al.* (1999) suggested that nighttime flows might be due in part to refilling of the stem water storage tissues, or from some nighttime transpiration. *F. albida* trees likely have the ability to store large quantities of water in their trunks, as seen by Roupsard *et al.* and ourselves that the sapwood is moist deep into their core. Since water content in the stem has been linked to pre-rainy season flushing in other species (Borchert, 1994; Broadhead *et al.*, 2003), it is possible the large nighttime sap flows during the dry season indicate trunk refilling, which in *F. albida* is used to maintain leaf water potential during the dry season, as observed by Roupsard *et al.*, rather than for leaf flush. During the rainy season when evaporative demand is lower, trunk water storage may become less depleted during the day, resulting in a smaller driving force to refill water storage tissues at night.

#### *Pollarded and unpollarded trees*

Unexpectedly, on two dates before pollarding (12 and 16 May), the group of trees that would be pollarded had significantly smaller mean peak and daily sap flow densities than unpollarded trees (Fig. 5a, b). This was contrasted by the lack of significant differences between groups on 17 and 18 of May; even though one tree, P3, of the to-be-pollarded group had been pollarded on 17 May,  $F_{d(max)}$  and  $F_{d(daily)}$  were not significantly different. If the groups' sap flow densities were truly different, then pollarding even just one tree would have amplified the difference. This highlights one of the limitations for the study, small sample sizes ( $n=3$ ) for each group, which makes drawing conclusions based on significant differences difficult.

Pollarding created the large differences observed for both peak and daily sap flow between the groups for the dates in late May, June, and July. There were also significant differences between the late-hot season date (16 May) and immediately following (31 May) and one month after (23 June) pollarding for both the pollarded and unpollarded trees. As expected, these differences were mostly attributable to the lack of leaf area for the pollarded trees, but in unpollarded trees either small amounts



of leaf drop after the sporadic rains or decreases in VPD could have reduced peak and daily sap flow densities during that time.

The lack of significant differences between group peak and daily sap flow densities on dates in the mid-rainy season (late July, August, and early September) however was due mostly to the variation between unpollarded trees'  $F_{d(max)}$  and  $F_{d(daily)}$  (Fig. 5a, b); leaf drop of U12 resulted in  $F_{d(max)}$  and  $F_{d(daily)}$  values similar to those of the newly-flushed pollarded group, giving the unpollarded group larger standard errors. Despite only one unpollarded tree showing a definite reverse phenology, the group differences did disappear during the mid-rainy season, but returned by late rainy season. The reduction in water use, per tree, from the hot season (16 May) to the late rainy season (14 September) was not different between pollarded and unpollarded trees, indicating that both pollarding and rainy-season leaf drop did reduce water use in *F. albida*, although tree water use was still larger for unpollarded trees.

#### *Seasonal water use*

Depommier (1998) found that pruning could alter the leafing phenology of *F. albida*, where pruned trees had extended leafing periods or an additional leaf flush during the rainy season. The irregular leafing phenology of UP2 and UP3 may have been due to previous pruning history, where more than one year is needed to restore the definite reverse phenology of the species. However, since UP1 did have a regular pattern, there may have been some size or age effect that allowed for quicker return to normal phenology. Despite the lack of a definite reverse phenology, UP2 and UP3 did have reduced daily sap flow densities, as compared to hot season values, through the early and mid-rainy season. Reverse phenology in UP1 did reduce water use to levels near that of pollarded trees, but this period of reduction happened within the early to mid-rainy season. (Fig. 2a, b). Within two months, defoliation and leaf flush occurred, with sap flow densities returning to their pre-defoliation levels. The period of decreased flows also occurred at different times between the unpollarded and the pollarded trees. Unpollarded trees' lowest sap flow densities occurred in mid-rainy season, while pollarded trees' lowest densities occurred from the time of pollarding until 5-6 weeks later and increase with regrowth. Since trees are usually pollarded in

the late dry season, regrowth and increased sap flow will usually coincide with the onset of the rainy season.

In terms of the cropping season, crops that are sown in the early rainy season, such as maize, millet, and sorghum, are likely to experience more water competition from unpollarded *F. albida* trees than crops sown later in the season. This competition is not only associated with the length of time the crops are in the field, but also with the timing of leaf drop of *F. albida*. If large reductions in sap flow do not occur until mid-rainy season, then in the early and late rainy season crops would experience more competition from the trees. This may be compounded where rains in the early and late rainy season are more erratic. Crops planted later, such as *Eragrostis tef*, would experience reduced competition with trees for water during establishment and early growth, but competition for water would increase towards the late rainy season. If water limitations are severe, then pollarding might be the best option to minimize competition between trees and crops if crop productivity is desired over tree products (fencing, fuel, fodder).

## REFERENCES

- Alexandre DY, and Ouedraogo SJ. 1992.** Variations in root morphology of *Faidherbia albida* in relation to soil and agronomic effects. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p107-110.
- Allen SJ, and Grime VL. 1995.** Measurements of transpiration from savannah shrubs using sap flow gauges. *Agricultural and Forest Meteorology* 75:23-41.
- Borchet R. 1994.** Soil and stem water storage determine phenology and distribution of tropical dry forest trees. *Ecology* 75(5):1437-1449.
- Brewbaker JL. 1987.** Significant nitrogen fixing trees in agroforestry systems. Gholz, H.I. Edition *Agroforestry: realities, possibilities and potentials* 31-45. *Martinus Nijhoff Publications* Dordrecht, 227pp.
- Broadhead JS, Ong CK, and Black CR. 2003.** Tree phenology and water availability in semi-arid agroforestry systems. *Forest Ecology and Management* 180:61-73.
- Butenschoen O, Scheu S, and Eisenhauer N. 2011.** Interactive effects of warming, soil humidity and plant diversity on litter decomposition and microbial activity. *Soil Biology and Biochemistry* 43:1902-1907.
- Barrett DJ, Hatton TJ, Ash JE, and Ball M.C. 1995.** Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of south-eastern Australia. *Plant, Cell, and Environment* 18:463-469.
- Burgess SSO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, and Bleby TM. 2001** An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21:589–598
- Burgess SSO, and Downey A. 2012.** SFM1 Sap flow meter manual. Armidale, NSW, Australia: ICT International Pty Ltd. Available from <http://au.ictinternational.com/content/uploads/2014/03/SFM1-wManual.pdf>
- Campa C, Diouf D, Ndoye I, and Dreyfus B. 2000.** Differences in nitrogen metabolism of *Faidherbia albida* and other N<sub>2</sub>-fixing tropical woody acacias reflect habitat water Availability. *New Phytology* 147:571-578.
- Chamshama SAO. 1994.** Early performance of *Faidherbia albida* intercropped with maize at Gairo, Morogoro, Tanzania. *Journal of Tropical Forest Science* 7(2)220-229.
- Decagon Devices. AccuPAR PAR/LAI Ceptometer, Model LP-80, Operator's Manual. 2014.** Pullman, WA: Decagon Devices, Inc. Available from [http://manuals.decagon.com/Manuals/10242\\_Accupar%20LP80\\_Web.pdf](http://manuals.decagon.com/Manuals/10242_Accupar%20LP80_Web.pdf)

**Dupuy N, and Dreyfus B. 1992.** Presence of *Bradyrhizobia* under *Acacia albida*. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p145-148.

**Depommier, D. 1998.** Etude phénologique de *Faidherbia albida* (Del.) A. Chev. Effet de l'émondage, du site et de la dimension de l'arbre sur les phénophases de l'espèce au Burkina Faso. In Actes de la réunion sur 'L'Acacia au Sénégal', Dakar, Senegal, 3–5 décembre 1996. Dakar, ORSTOM.

**Do FC, Rocheteau A, Diagne AL, Goudiaby C, and Lhomme JP. 2008.** Stable annual pattern of water use by *Acacia tortilis* in Sahelian Africa. *Tree Physiology* 28:95-104.

**Ibrahim AM, Fagg CW, and Harris SA. 1997.** Seed and seedling variation amongst provenances in *Faidherbia albida*. *Forest Ecology and Management* 97:197-205.

**ICT International.** Sap flow tool, analysis and visualization of sap flow data. 2012. Armidale, NSW, Australia: ICT International Pty Ltd. Available from <http://www.sapflowtool.com/SapFlowToolManual.html>

**Jama B, and Getahun A. 1991.** Intercropping *Acacia albida* with maize (*Zea mays*) and green gram (*Phaseolus aureus*) at Mtipwa Coast Province, Kenya. *Agroforestry Systems* 14:193-205.

**Jones A, Breuning-Madsen H, Brossard M, Dampha A, Deckers J, Dewitte O, Gallali T, Hallett S, Jones R, Kilasara M, Le Roux P, Micheli E, Montanarella L, Spaargaren O, Thiombiano L, Van Ranst E, Yemefack M, Zougmore R, editors. 2013.** Soil Atlas of Africa. Luxembourg: European Commission, *Publications Office of the European Union*. 176 pp.

**Kamara CS, and Haque I. 1992.** *Faidherbia albida* and its effects on Ethiopian highland Vertisols. *Agroforestry Systems* 18:17-29.

**Kessler JJ, and Breman H. 1991.** The potential of agroforestry to increase primary production in the Sudan-Sahelian zones of West Africa. *Agroforestry Systems* 13:41-62.

**Kho RM, Yacouba B, Yaye M, Katkore B, Moussa A, Iktam A, and Mayaki A. 2001.** Separating the effects of trees on crops: the case of *Faidherbia albida* and millet in Niger. *Agroforestry Systems* 52:219-238.

**Laike A. 1992.** *Faidherbia albida* in the traditional farming systems of central Ethiopia. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p39-41.

- Manzoni S, Vicoc G, Thompson S, Beyer F, and Weih M. 2015.** Contrasting leaf phenological strategies optimize carbon gain under droughts of different duration. *Advances in Water Resources* 84:37-51.
- Marshall DC. 1958.** Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33:385-396.
- Mengistu A. 2006.** Country profile: pasture/forage resource: Ethiopia. Rome, Italy: Food and Agriculture Organization [cited 2014 June 8]. Available from <http://www.fao.org/ag/agp/agpc/doc/counprof/ethiopia/ethiopia.htm>
- Meinzer FC, Goldstein G, Franco AC, Bustamante M, Iglar E, Jackson P, Caldas L, and Rundel PW. 1999.** Atmospheric and hydraulic limitations on transpiration in Brazilian cerrado woody species. *Functional Ecology* 13:273-282.
- Orwa C, Mutua A, Kindt R, Jamnadass R, and Simons A. 2009.** Agroforestry Database: a tree reference and selection guide version 4.0 [Internet]. Nairobi, Kenya: World Agroforestry Centre; [cited 2013 Nov 8]. Available from <http://www.worldagroforestry.org/af/treedb/>
- Poschen P. 1986.** An evaluation of the *Acacia albida*- based agroforestry practices in the Hararghe highlands of eastern Ethiopia. *Agroforestry Systems* 4:129-143.
- Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, and Dreyer E. 1999.** Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese West Africa. *Functional Ecology* 13: 460-472.
- Saka AR, Bunderson WT, Itimu OA, Phombeya HSK, and Mbekeani Y. 1994.** The effects of *Acacia albida* on soils and maize grain yields under smallholder farm conditions in Malawi. *Forest Ecology and Management* 64:217-230.
- Subrahmanyam MVR, and Bheemaiah G. 2003.** Yield and economics of rainfed maize (*Zea mays*) in African babul (*Faidherbia albida*) based agroforestry system under different fertility levels. *Indian Journal of Agricultural Science* 73:138-141.
- Smith DM, and Allen SJ. 1996.** Measurement of sap flow in plant stems. *Journal of Experimental Botany* 47:1833-1844.
- Vandenbeldt RJ. 1992.** Rooting systems of western and southern African *Faidherbia albida* (Del.) A. Chev. (syn *Acacia albida* Edl.)- a comparative analysis with biogeographic implications. *Agroforestry Systems* 14:233-244.
- Vandenbelt RJ, and Williams JH. 1992.** The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. *Agriculture and Forest Meteorology* 60:93-100.

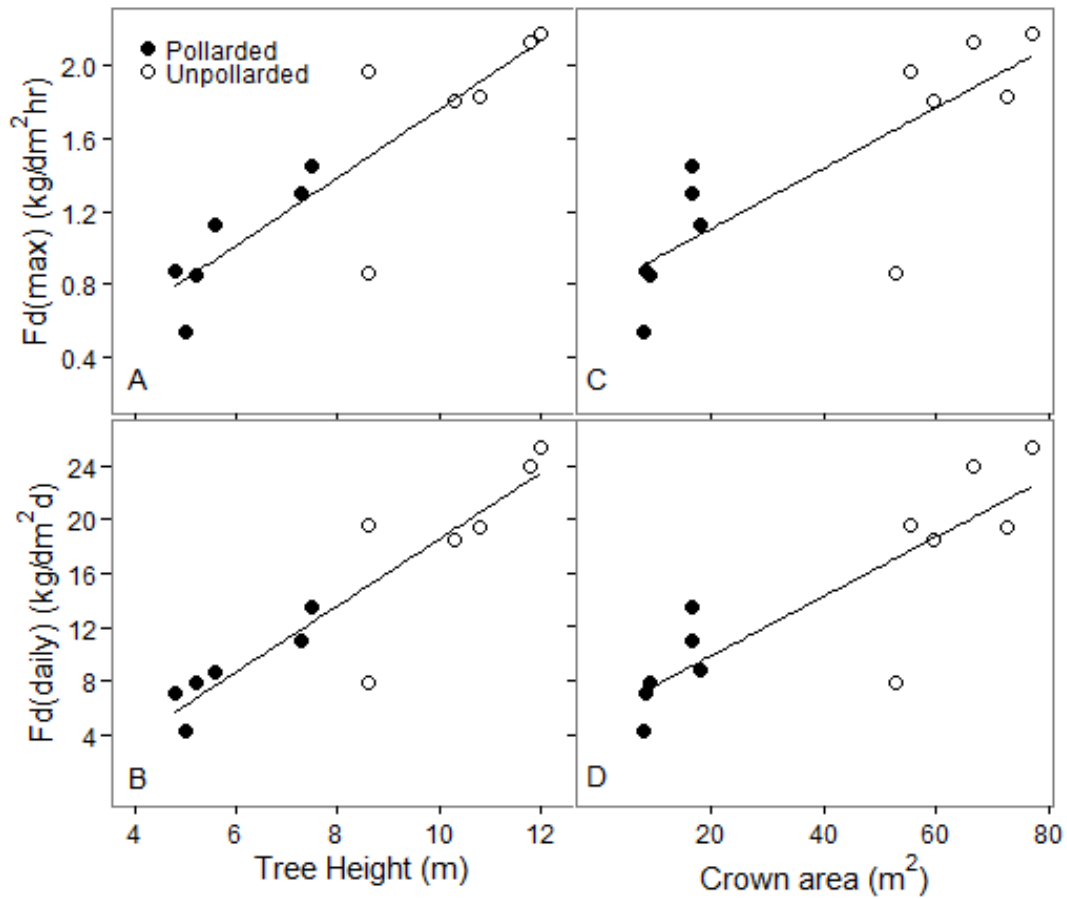
**Wang H, Zhao P, Holscher D, Wang Q, Lu P, Cai XA, and Zeng XP. 2012.** Nighttime sap flow of *Acacia mangium* and its implication for nighttime transpiration and stem water storage. *Journal of Plant Ecology* 5(2)294-304.

**Wickens GE. 1969.** A study of *Acacia albida* Del. (Mimosoidae). *Kew Bulletin* 23: 181-202.

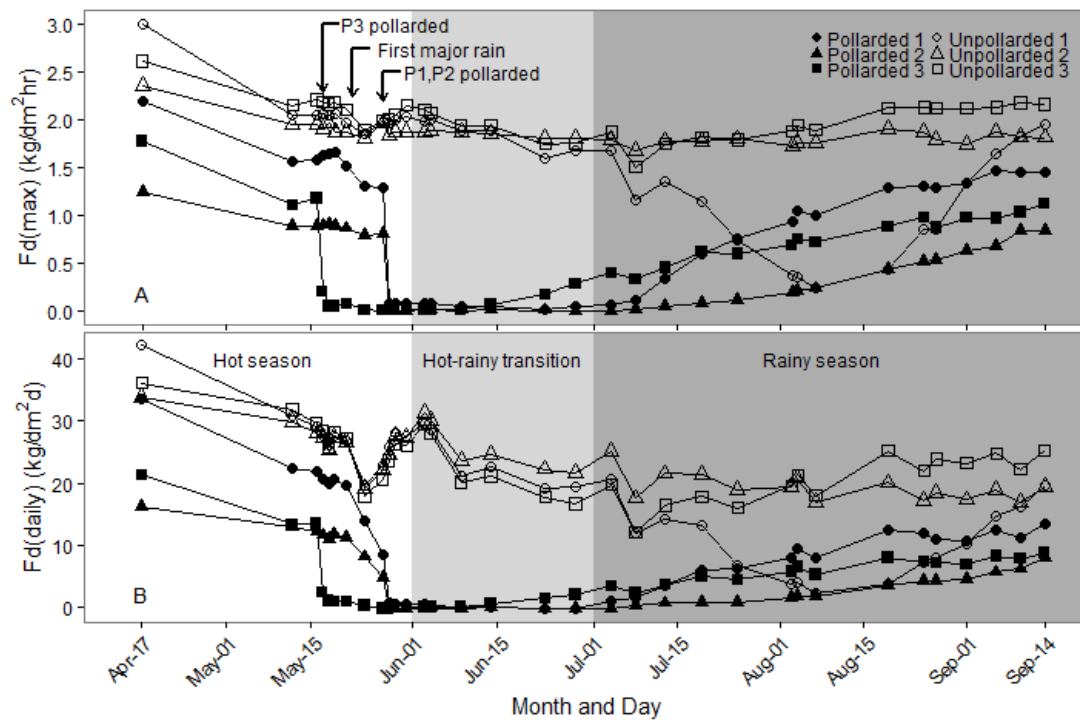
**Wood PJ. 1992.** The botany and distribution of *Faidherbia albida*. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p9-17.

**The World Bank Group:** Climate Change Knowledge Portal for Ethiopia [Internet]. c2013. The World Bank Group; [cited 2013 Nov 20]. Available from <http://data.worldbank.org/country/ethiopia>.

## FIGURES

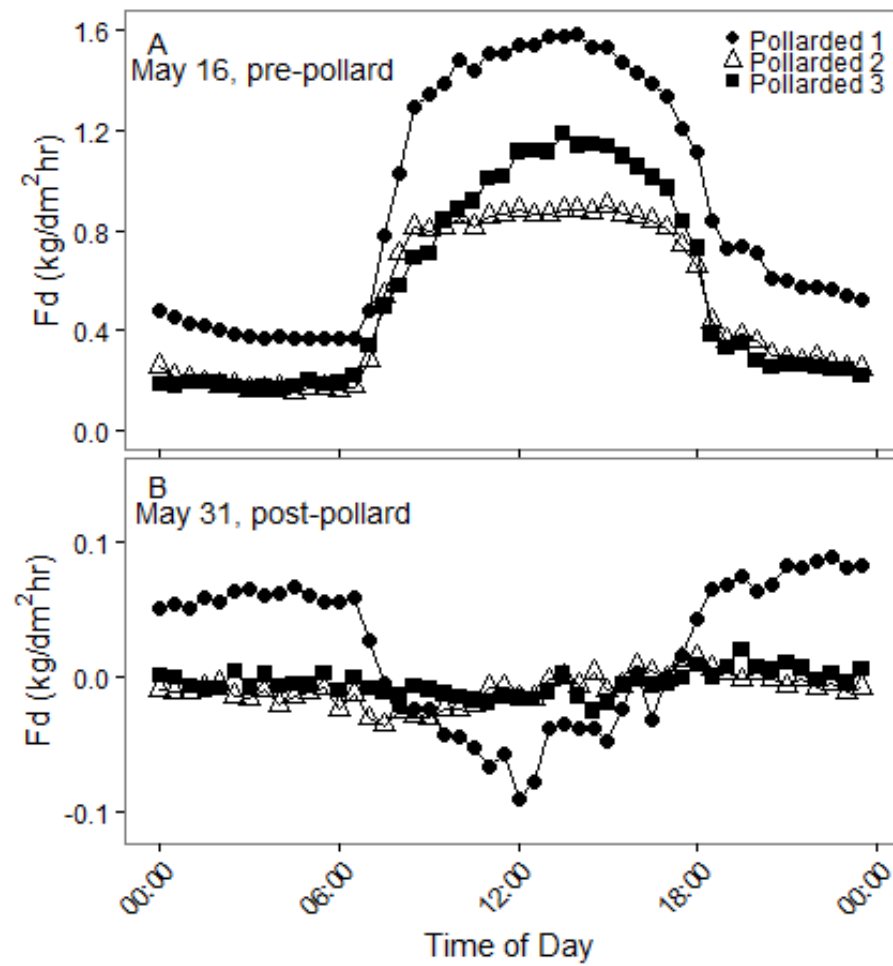


**Figure 1.** Peak sap flow density ( $F_d(\max)$ ) (A) and daily sap flow density ( $F_d(\text{daily})$ ) (B) of three pollarded and three unpollarded *Faidherbia albida* trees by tree height, and  $F_d(\max)$  (C) and  $F_d(\text{daily})$  (D) by projected crown area on 27 August and 14 September, 2014 ( $n = 3$ ).

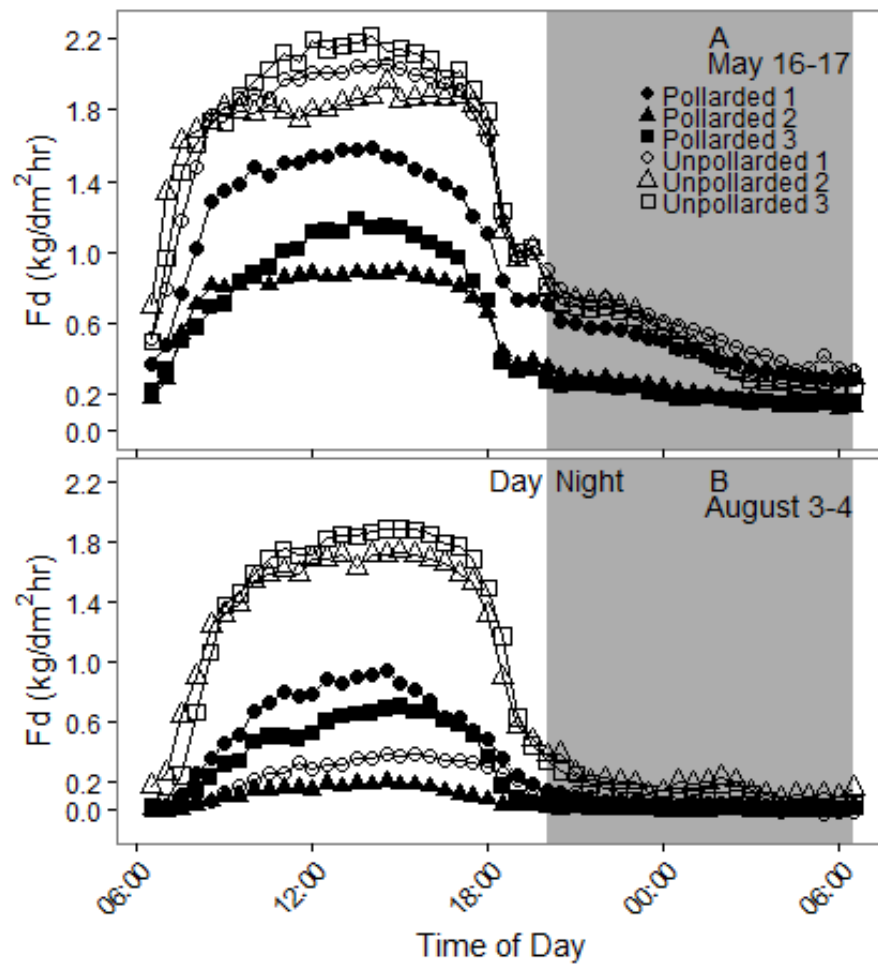


**Figure 2.** Peak sap flow density ( $F_d(\max)$ ) (A) and daily sap flow density ( $F_d(\text{daily})$ ) (B) of three pollarded and three unpollarded *Faidherbia albida* trees from 17 April to 17 September, 2014, for selected no-precipitation dates.

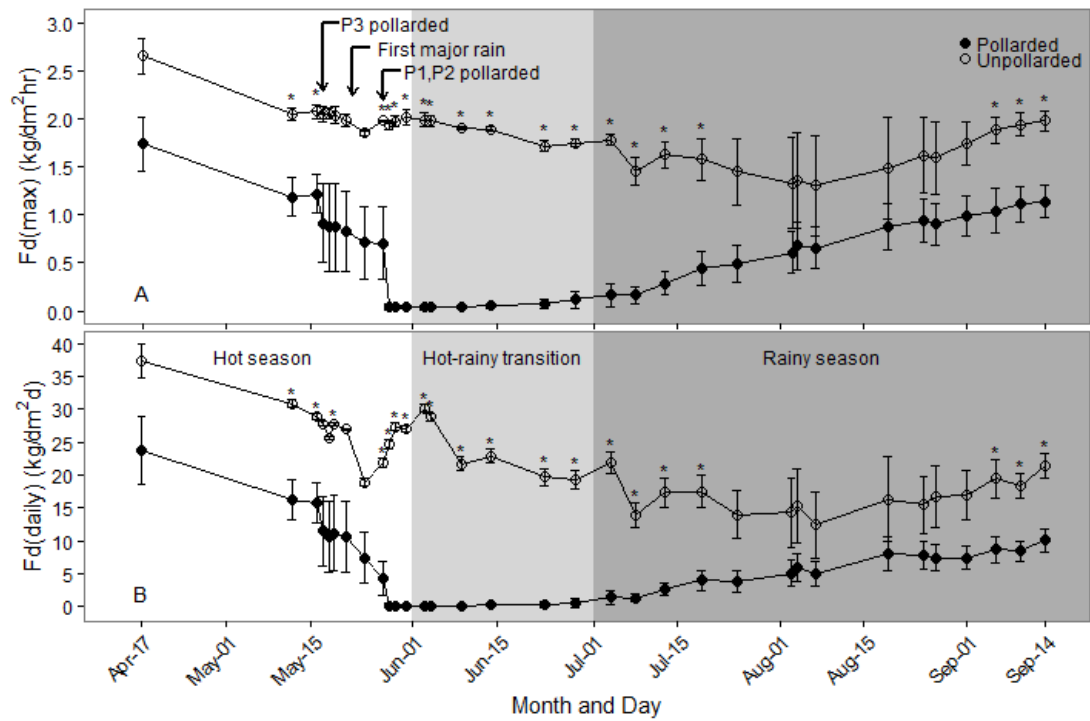




**Figure 3.** Daily time course (0000-2330 h) of sap flow density (Fd) of three *Faidherbia albida* trees (**A**) before pollarding on 16 May, and (**B**) after pollarding on 31 May, 2014.



**Figure 4.** Daily time course (0630-0600 h) of sap flow density (Fd) of six *Faidherbia albida* trees during (A) the hot season on 16 to 17 May, and (B) the mid-rainy season on 3 to 4 August, 2014. Three trees were pollarded on 17 May and 27 May. Darkened region represents nighttime hours between 2000 -0630.



**Figure 5.** Mean  $\pm$  SE of peak sap flow density ( $F_d(\max)$ ) (A) and daily sap flow density ( $F_d(\text{daily})$ ) (B) of three pollarded and three unpollarded *Faidherbia albida* trees from 17 April through 17 September, 2014, for selected no-precipitation dates. Asterisks indicate a significant difference ( $P \leq 0.05$ ) between pollarding treatments on individual dates ( $n = 3$ ).

## TABLES

**Table 1.** DBH outside bark, bark thickness, tree height, tree crown radius, circular area under tree crown, and leaf are index of each tree, with mean and SD of values of pollarded (P1, P2, P3) and unpollarded (UP1, UP2, UP3) trees.

Tree Code	P1	P2	P3			UP1	UP2	UP3		
Last pollard date	27/5/14	27/5/14	17/5/14	Mean	SD	Spring 2012	Spring 2012	Spring 2012	Mean	SD
DBHOB (cm)	53.8	39.0	39.6	44.1	8.4	54.6	44.3	41.1	46.7	7.1
Bark thickness (cm)	1.55	1.83	1.1	1.49	0.37	1.93	1.25	1.85	1.68	0.37
Height (m) 31/5/14	7.0	3.5	3.0	4.5	2.2	8.6	9.6	11.3	9.8	1.4
Height (m) 23/6/14	7.0	4.1	3.2	4.8	2.0	8.5	9.6	11.2	9.8	1.4
Height (m) 27/8/14	7.3	5.0	4.8	5.7	1.4	8.6	10.3	11.8	10.2	1.6
Height (m) 14/9/14	7.5	5.2	5.6	6.1	1.2	8.6	10.8	12.0	10.5	1.7
Crown radius (m) 31/5/2014	1.2	0.4	0.3	0.7	0.5	4.1	3.2	3.5	3.6	0.5
Crown area (m <sup>2</sup> ) 31/5/2014	4.8	0.5	0.4	1.9	2.5	52.8	31.4	39.2	41.1	10.9
Crown radius (m) 27/8/2014	2.3	1.6	1.7	1.9	0.4	4.1	4.4	4.6	4.4	0.3
Crown area (m <sup>2</sup> ) 27/8/2014	16.6	8.0	8.6	11.1	4.8	52.8	59.5	66.5	59.6	6.8
Crown radius (m) 14/9/2014	2.3	1.7	2.4	2.1	0.4	4.2	4.8	5.0	4.7	0.4
Crown area (m <sup>2</sup> ) 14/9/2014	16.6	9.1	18.1	14.6	4.8	55.4	72.4	77.0	68.3	11.4
LAI 15/9/2014	3.44	4.02	3.70	3.72	0.29	4.88	3.80	3.03	3.90	0.93

EFFECTS OF *FAIDHERBIA ALBIDA* ON *ERAGROSTIS TEF*  
GROWTH IN SUB-HUMID ETHIOPIA.

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## INTRODUCTION

The grass *Eragrostis tef* (teff) is an important food crop in much of Ethiopia. In semi-arid to sub-humid areas, teff is commonly grown in an agroecological system in association with a low-density planting of the tree *Faidherbia albida*, but the effects on teff growth and the nature of the teff-*F. albida* species interactions have not been described. Most agroforestry studies with *Faidherbia albida* have been undertaken with maize, sorghum, millet, or legumes, while few, if any, have involved *Catha edulis* (chat), or teff, crops important to Ethiopians. To our knowledge, there are no studies involving the impact on teff from associated trees, and there are few studies that relate effects of environmental stressors on teff growth or productivity. This study aims to better understand the effects of *F. albida* on teff growth, and to learn several key indicators that may suggest the nature of the species interactions. This knowledge may help with the development of management practices to improve teff productivity.

Some of the major ways in which trees may affect the plants under them include altering microclimate variables such as temperature, light, moisture and nutrient availability. Tree canopies can reduce the temperature of the air and soil under them. In a study involving millet and *F. albida*, a leafless canopy resulted in a 10 °C decrease in maximum soil temperature at the 2 cm depth; Vandenbeldt & Williams (1992) suggested that this reduction contributed to improved millet growth during seedling establishment. However, for teff grown alone Evert *et al.* (2009) found no effect of soil temperature on final biomass after 21 days at daytime soil temperatures between 19 °C and 31 °C, but did find a reduced rate of emergence in the first 9 days for plants grown below 19 °C soil temperature. Kebede (1989) reported that teff plants grown at 35 °C had the highest dry matter production after 49 days; the biomass of those grown at 25 °C and 45 °C were reduced by  $\frac{1}{3}$  and  $\frac{2}{3}$ , respectively. Reductions in soil temperature by trees may be problematic if soil temperature falls below 19 °C, but reductions in air temperature may be beneficial in areas where daytime temperatures are likely to exceed 45 °C.

These beneficial effects of tree canopies on crop growth may be offset by reductions in sunlight reaching crops. C<sub>4</sub> plants, like teff, are generally more efficient

than C<sub>3</sub> plants in terms of photosynthetic rates under high light and temperature conditions rather than low light and temperature conditions (Osmond *et al.*, 1982; Hatch, 1987) because of their higher energy requirement for carbon fixation and the presence of photorespiration in C<sub>3</sub> plants. One study showed increased photosynthesis with increased light intensity up to full sunlight, as expected with a C<sub>4</sub> species (Hirut *et al.*, 1989). If teff is grown under *F. albida* that sheds its leaves, the negative impact from light reduction on growth should be less than fully leafed canopies. It is unclear how teff would respond to the presence of *F. albida* trees that provide at least partial shade from branches.

Generally, water stress negatively affects growth and yield of crops by reducing leaf elongation, transpiration, and photosynthetic rates (Acevedo *et al.*, 1971; Ephrath & Hesketh, 1991; Mengistu, 2009). On teff, the impact of water stress is variable, and appears to be stronger on grain yield than on biomass (Araya *et al.*, 2010). Also, Yizengaw & Verheye (1994) indicated that moisture stress can limit crop yield more than radiation limitations can. Stable carbon isotope ratios ( $\delta^{13}\text{C}$ ) of leaf tissue in C<sub>4</sub> plants have been used as potential integrated measures of water stress (Saliendra *et al.*, 1996; Bowman *et al.*, 1989; Buchmann *et al.*, 1996; Monneveux *et al.*, 2007). Due to compartmentalization of carboxylating enzymes in two cell types, the mesophyll and bundle sheath, in addition to differences in carboxylase enzyme affinities for CO<sub>2</sub>, a CO<sub>2</sub> concentrating mechanism exists in leaves of C<sub>4</sub> plants (Hatch, 1987). Phosphoenolpyruvate carboxylase (PEPC) in the mesophyll has a greater affinity for CO<sub>2</sub> than RUBISCO in the bundle sheath. Carboxylation by PEPC in the mesophyll creates four-carbon acids that are transported to the bundle sheath where they are decarboxylated, creating saturating CO<sub>2</sub> concentrations for fixation by RUBISCO (Ghannoum, 2009). PEPC also has a much lower discrimination against the heavier <sup>13</sup>C isotope during carbon fixation than RUBISCO; the CO<sub>2</sub> in bundle sheath cells then is actually enriched in <sup>13</sup>C (Farquhar, 1983; Farquhar *et al.*, 1989), and C<sub>4</sub> plant discrimination against <sup>13</sup>C ( $\Delta$ ) is closer to that of PEPC (~ -5.7 ‰) than RUBISCO (~ 27 ‰). In contrast, C<sub>3</sub> plant  $\Delta$  is more dependent on the discrimination of RUBISCO. C<sub>4</sub> plant  $\delta^{13}\text{C}$  is usually between -8 and -15 ‰, and C<sub>3</sub>  $\delta^{13}\text{C}$  between -22 and -38 ‰ (Yeh & Wang, 2001). In teff, the average  $\delta^{13}\text{C}$  of plants grown at 25,

35, and 45 C was -14.4 ‰, with a tendency for  $\delta^{13}\text{C}$  to increase with temperature (Kebede, 1989).  $\Delta$  can be calculated from plant  $\delta^{13}\text{C}$  as

$$\Delta = \frac{\delta_a - \delta_p}{1 + \delta_p} \quad \text{Equation 7}$$

where  $\delta_a$  is the isotopic composition of  $\text{CO}_2$  in air (about -8 ‰), and  $\delta_p$  is that of the plant (Farquhar *et al.*, 1980). Part of the variation in observed  $\delta^{13}\text{C}$  values of  $\text{C}_4$  plants depends on the fraction of  $\text{CO}_2$  that leaks from the bundle sheath cell without being fixed by RUBISCO (Farquhar, 1983). If the ratio of enzyme activity in the bundle sheath to that of mesophyll decreases, increased leakage of previously fixed  $\text{CO}_2$  from the bundle sheath to the mesophyll occurs (Bowman *et al.*, 1989; Meinzer *et al.*, 1994; Saliendra *et al.*, 1996). This increased leakiness leads to an increase in  $\Delta$  in  $\text{C}_4$  plants because RUBISCO's higher discrimination against  $^{13}\text{C}$  is increasingly expressed; the result is a decrease in  $\delta^{13}\text{C}$  in plant tissue. Bundle sheath leakiness has been shown to increase in response to water stress (Saliendra *et al.*, 1996; Bowman *et al.*, 1989), increasing salinity (Meinzer *et al.*, 1994; Bowman *et al.*, 1989) and decreasing light (Buchmann *et al.*, 1996). Therefore an increase in  $\Delta$  or a decrease in  $\delta^{13}\text{C}$  is indicative of stress in  $\text{C}_4$  plants. Saliendra *et al.* (1996) reported a  $\Delta$  range of 3.4 to 3.7 ‰ for four sugarcane cultivars, with a  $\Delta$  increase ranging from 0.1 to 1.1 ‰ depending on cultivar and decreasing irrigation frequency. Unfortunately, to our knowledge, no studies exist that compare  $\delta^{13}\text{C}$  of teff across environmental stressors in detail.

Most studies on teff have focused on either its yield, its use as a fodder for pasture animals, and varietal genetics. Few studies have explored the interactions of trees and teff despite the tendency for small holder farmers to include scattered trees on their farms. Characterizations of crop performance usually focus on measurements of growth, leaf area, nutrient content by weight or leaf area, grain yield, and biomass. In this study, we compared plant shoot height, leaf area index, relative chlorophyll content, and  $\delta^{13}\text{C}$  of teff plots to assess the effect of *F. albida* on growth of two varieties of teff (improved and koncho) across direction (east and west) from associated tree base, and distance (from 0-8 m) from tree base. Height is taken as a



general measure of the size of plants, leaf area index as a measure to characterize plot density and biomass, and  $\delta^{13}\text{C}$  as an indicator of potential stress. The SPAD (Soil Plant Analysis Development, Minolta, Japan) meter is used to obtain estimates of relative chlorophyll content, related through SPAD values, which are indirect indicators of leaf nitrogen content. Based on the limited literature on teff response under varying environmental conditions, we expected moderate decreases in growth characteristics of shoot height and leaf area index for plots close to tree base. Since the temperature range for the site was unlikely to cause heat-related growth changes for teff, and because *F. albida* is considered to be non-competitive for water during leaf shedding, we expected light limitations due to tree crown interception to have the largest effect on teff growth close to tree base. Since  $\delta^{13}\text{C}$  decreased for other species that experienced shade stress, we expected  $\delta^{13}\text{C}$  to decrease for plots closer to tree base. *Faidherbia albida* is a nitrogen fixing species and is known for its positive effect on soil fertility, we expected SPAD values to be higher in plots closer to trees if the fertility effect of *F. albida* was large enough to alter nitrogen status of plants.

## MATERIALS AND METHODS

### *Study area*

The research site was located 11 km south of Mojo, Ethiopia, where one of the on-farm trial sites for the ICRAF/EIAR Trees for Food Security project was located (08°30'23" N 39°04'00"E). The site is characterized by a semi-arid to sub-humid climate with around 800-1000 mm of rain a year, with over 80% occurring between April and September (World Bank, 2013; Mengistu, 2006). The rainy season occurs July to September, the cold dry season is from October to February, and the hot season from March to June. The region is known to have erratic rainfall, frequent drought, and a harsh cropping environment. This area has unimodal rainfall, although there can be sporadic rains in March, April, May, and June but most rainfall occurs in July, August, and September (World Bank, 2013). The elevation is 1682m, and the site is situated in the Great Rift Valley of Ethiopia, between the western and eastern highlands of central Ethiopia. The temperature range is from 18 to 34 °C, and the

predominant annual agricultural crops are teff, wheat, and maize (Mengistu, 2006). The soil types for the district are eutric fluvisols and luvic phaeozems (Jones *et al.*, 2013).

#### *Species description*

*Eragrostis tef*, or teff, is an annual tufted or bunch grass that grows about 30-120 cm high. It has slender culms, narrow leaves 25-45 cm long, and has a shallow, fibrous root system (National Research Council, 1996). It has a loose or compact panicle, small grains with about 2500-3500 seeds per gram. It is a tetraploid ( $2n = 40$ ), and uses the  $C_4$  photosynthetic pathway. From seed to maturity can take 2-5 months depending on the variety.

The varieties used in this study were of the late-maturing group (60-120 days until harvest), but there are also very-early maturing (45-60 days) and early maturing (60-90 days) groups as well (National Research Council, 1996). There are several established cultivars of the late-maturing groups (such as koncho, DZ-Cr-387) and improved varieties available from local extension services (Assefa *et al.*, 2011). Koncho is a favorite type for its high market value in the Rift Valley region and in the rest of the country based on its high biomass and grain yield, and its white grain color which typically has a higher market value than brown types (Assefa *et al.*, 2000; Yihun *et al.*, 2013).

Teff is native to East Africa, specifically Ethiopia, but is found now in many other locations such as South Africa, the United States, Australia and India. It can tolerate a wide range of growing conditions, with an altitude range of 0-3000 m, annual rainfall from 300-2500 mm, and temperature of about 0-35 °C (optimal around 15-27 °C), and it can tolerate acidic soils below pH of 5, moderate water stress, and water logged soils (National Research Council, 1996; Tefera & Ketema, 2000).

#### *Plots*

All research was conducted on operational farms. The fields were plowed twice before sowing after rains, with a traditional oxen-drawn plow. The fields were sown on 30 July, by hand, and then weeded twice during the study. Using transects, teff plots were set up next to seven *F. albida* trees (named J1, J2, J3, J4, J5, O1, O2). Plots were 1 m wide (0.5 m to either side of transect) and 2 m long extending from

the base of the trunk to the east and west directions. Plots around five trees consisted of an improved teff variety, and plots around another two trees consisted of the koncho variety. The plots represented sub-canopy and outside canopy areas, with controls 15+ m away from any trees.

J1, J2, J3 trees had plots 2-4 m 4-6, and 6-8 m on their west side, and 2-4, 4-6 m on their east side, since small fencing prevented placement of plots 0-2 m around trees (Table 2). J4 and J5 trees had plots 0-2, 2-4, 4-6, and 6-8 m on their west side, and 0-2, 2-4, and 4-6 m on their east side. O1 and O2 trees had plots 0-2, 2-4, 4-6 m on their west side, and 0-2, 2-4, 4-6, and 6-8 m on their east side.

The associated trees' DBH ranged between 36-58 cm, with a mean of 44.5 cm, and the height between 4.8-12 m, with a mean of 7.4 m (Table 3). One tree in the improved teff field was pollarded (J1), and both trees (O1, O2) in the koncho field were pollarded, with pollarding done as complete branch removal to the trunk of the tree.

Four measurement types were made on the teff at the plot level; shoot height, leaf area index, SPAD values, and  $\delta^{13}\text{C}$  from leaf clippings. For each data collection day, we took 2-3 measurement types (e.g. shoot height and SPAD), except for days where we measured leaf area index, where that was the only measurement type done. We collected all measurements on each trees' set of plots at once to minimize trampling in the teff fields, and this typically took 30-45 minutes per tree; all measurements were done each day between 0900 and 1400 h.

#### *Shoot height*

Shoot height (SH) on teff was measured on 9, 12, and 18 September, 2014, on three individuals per plot. They were located along the midline transect, and measuring the distance from the base of the plant to the tip of the longest leaf. These three measurements were averaged for a mean SH per plot. Repeated measures on the same plants were not possible because the leaves were too soft and small to mark. Also we did attempt to mark plants with string, but being an on-farm study with children helping their parents weed, and children being always curious, the string mostly disappeared. For this reason we called the measurement mean Shoot Height,

and not growth, and represents the overall size of plants in each plot, presented average SH in cm.

#### *Leaf area index*

Leaf area index of teff plots was estimated on 4, 10, and 15 of September, 2014. For theory and measurements using the AccuPAR LP80 ceptometer, please refer to the leaf area index description on page 21. For teff, we estimated the light penetration using a cube with a roughly 0.5 m side, and observed 30% vertical and 20% horizontal values, and used Equation 6 to calculate a X of 0.74 for the teff only canopy.

For measurements of controls or teff-only plots, initial PAR above canopy reading was taken 8 m away from the tree outside of any shadows in full sun. We then took two below canopy readings (which are averaged) inside the plots, perpendicular to the transect, and below the teff canopy while avoiding uneven ground or moisture. This set of three readings (one above and two below canopy) comprised one LAI measurement. For teff plots with tree crown cover, the initial PAR above canopy reading was taken below the tree crown, then two below canopy readings as before. The data for each measurement were stored on the device and downloaded at the end of the study. Measurements were made between 0930 and 1300 h on each date.

#### *Soil Plant Analysis Development (SPAD)*

The amount of chlorophyll present in leaves, which is related to the nitrogen content, can be an indicator of the overall condition of a plant. A SPAD meter (Soil Plant Analysis Development, Minolta, Japan) measures relative chlorophyll content and gives SPAD values based on greenness of leaf tissue. The larger the SPAD value, the higher the chlorophyll content, and the value increases in proportion to the amount of nitrogen present in a leaf (Konica Minolta, 2009; Piekielek *et al.*, 1997). There is usually a close relationship between SPAD values and leaf absolute chlorophyll content, which has been demonstrated in tobacco (*Nicotiana tabacum*; Castelli *et al.*, 1996; Castelli & Contillo, 2009), and in *Poaceae* including maize (*Zea mays*; Castelli *et al.*, 1996; Chapman & Barreto, 1997; Bullock & Anderson, 1998;

Muthuri *et al.*, 2009), winter wheat (*Triticum aestivum*; Castelli *et al.*, 1996), and St. Augustinegrass (*Stenotaphrum secundatum*; Rodriguez & Miller, 2000).

Since chlorophyll has peak absorption in the blue (400-500 nm) and red (600-700 nm) wavelength regions, with none in the near infrared, the SPAD 502Plus meter can use the absorbances of the leaf tissue from red and infrared to calculate a numerical SPAD value based on the ratio of the intensities of the light transmitted.

We measured SPAD values on 1, 12, and 18 of September, 2014, by taking three readings per leaf, at  $\frac{1}{4}$ ,  $\frac{1}{2}$ , and  $\frac{3}{4}$  of the length of the leaf from the leaf base, and averaging them for one measurement. The leaves did not have a very prominent midvein, but it was avoided when possible if the leaf was wide enough. Often near the tip of the leaf the width could be 3 mm or less. The SPAD meter was recalibrated (by taking a blank calibration reading) before each tree's set of plots. We took measurements on both the 4<sup>th</sup> and 5<sup>th</sup> leaves of three plants per plot, with the measured plants selected at random, and averaged the three measurements for a mean 4<sup>th</sup> leaf and mean 5<sup>th</sup> leaf value for each plot.

The major limitation for this measurement is that based on limitations in equipment, we were unable to relate the relative chlorophyll content (SPAD values) to an absolute chlorophyll concentration in the teff leaves, so there is no calibration curve for this species. Chlorophyll concentration for leaves is usually determined by extraction from leaf samples and spectrophotometric measurements. SPAD is a relative measure of chlorophyll content, so it is presented as a dimensionless measure of  $\text{m}^2 \text{m}^{-2}$ .

#### *$\delta^{13}\text{C}$ determination*

Leaf clippings for  $\delta^{13}\text{C}$  determination were collected from plots on the 1, 9, 18 of September, 2014; a middle section about 10 cm long (after clipping off  $\frac{1}{3}$  of the total leaf length from the base and tip) was collected from 10-12 leaves per plot. Samples were taken from the 4<sup>th</sup> leaf on the first two measurement dates and from the 5<sup>th</sup> leaf on the third date due to onset of senescence in the older leaves. Leaf clippings were stored in paper envelopes by plot and measurement date. After collection, leaves were dried in the sun for 4-5 hours, then dried with a fan for another 5 hours. The leaves, in envelopes, were stored in sealed plastic bags with cobalt-indicating silica

gel. When the silica gel turned pink it was switched out for fresh gel until the gel no longer turned pink.

For  $\delta^{13}\text{C}$  determination, a subset of the samples was tested from the 2<sup>nd</sup> collection date. Five leaves per plot were cut into smaller pieces and finely ground. Approximately 1.0 mg of the leaf powder was packed into tin capsules, then combusted to  $\text{CO}_2$  in a Carlo Erba NA1500 elemental analyzer then introduced into a DeltaPlus isotope ratio mass spectrometer. The check standard was IAEA-600 caffeine and runs were calibrated using the international standards USGS40 glutamic acid and SIL sucrose. Typical error was  $\pm 0.1\%$  or better. C isotopic results are expressed in relation to the Vienna Peedee Belemnite standard.

#### *Analyses*

We compared control data from improved and koncho teff varieties by measurement type (SH, LAI,  $\delta^{13}\text{C}$ ) and measurement date (first, second, third) using Wilcoxon rank sum tests. We compared SPAD data from the two leaf positions (4<sup>th</sup> and 5<sup>th</sup>) by date and variety with two sample t-tests, and we compared SPAD data from the three dates by leaf position and variety with pairwise t-tests with a Bonferroni correction for three comparisons.

We compared data from each measurement type (SH, LAI,  $\delta^{13}\text{C}$ ) by date for improved teff associated with unpollarded Jema trees (J2, J3, J4, J5) by direction from tree (east or west), and distance from plot. Pairwise t-tests with a Bonferroni correction were used to compare mean differences in SH, LAI, and  $\delta^{13}\text{C}$  between groups and with controls. Simple linear regression was used to determine slope and intercept of SH, LAI, and  $\delta^{13}\text{C}$  versus distance without control data.

For koncho teff associated with pollarded trees (O1, O2), Wilcoxon rank sum tests with a Bonferroni correction were used to compare SH LAI, and  $\delta^{13}\text{C}$  between groups and with controls, and Kruskal-Wallis test used to determine if there was any relationship between SH, LAI, and  $\delta^{13}\text{C}$  versus distance. Statistical analysis were conducted in R, version 2.15.1 (2012-06-22).

## RESULTS

### *Improved and koncho controls*

The improved teff median SH and LAI was always larger than koncho variety for all three dates. On the first and second date, the improved median SH was significantly larger by 22.7 cm and 20.3 cm, respectively, than koncho median SH ( $P < 0.01$ ; Fig. 6a). On the second and third date, the improved median LAI was significantly larger than koncho median LAI by 2.21 and 2.47 ( $P < 0.02$ ; Fig. 6b). In comparisons between each leaf number (4<sup>th</sup> to 4<sup>th</sup>, 5<sup>th</sup> to 5<sup>th</sup>), there were no significant differences between median SPAD values across improved and koncho varieties ( $P > 0.05$ ). There was a significant difference between  $\delta^{13}\text{C}$  of improved and koncho varieties; mean  $\delta^{13}\text{C}$  of improved teff was  $-11.82 \pm 0.09 \text{‰}$ , and for koncho teff was  $-12.17 \pm 0.09 \text{‰}$ , or a  $\Delta$  of 3.87 ‰ and 4.22 ‰ ( $P = 0.038$ ).

### $\delta^{13}\text{C}$

Contrary to expectations, improved teff  $\delta^{13}\text{C}$  was negatively related to distance (slope =  $-0.046$ ,  $P = 0.031$ ,  $r^2 = 0.33$ ), but there was no significant relationship across distance for the koncho variety ( $P > 0.2$ , not shown).

### *SPAD values*

For the improved teff, between leaf positions, on the first date the mean SPAD value of the 4<sup>th</sup> leaf was significantly larger than the 5<sup>th</sup>, and on the third date this was reversed, with the mean SPAD value of the 5<sup>th</sup> leaf was significantly larger than the 4<sup>th</sup> ( $P = 0.0097$ ,  $0.00007$ , respectively; Fig. 7a, Table 4). There was no difference between the mean SPAD value between the 4<sup>th</sup> and 5<sup>th</sup> leaves on the second date. Within leaf positions and between dates, there were no differences of the 4<sup>th</sup> leaf mean SPAD value between the first and second and first and third dates, but the second date 4<sup>th</sup> leaf mean SPAD value was significantly larger than on the third date ( $P = 0.00029$ ). The 5<sup>th</sup> leaf mean SPAD value on the first date was significantly lower than on the second and third date ( $P < 0.0001$ ). There was no difference of the 5<sup>th</sup> leaf mean SPAD value between the second and third dates. Contrary to expectations, there were no significant differences among plots across direction or distance ( $P > 0.05$ ).

For koncho teff, comparisons between leaf positions were similar to improved teff. The first date mean SPAD value of the 4<sup>th</sup> leaf was significantly larger than the

5<sup>th</sup>, and on the third date the mean SPAD value of the 5<sup>th</sup> leaf was significantly larger than the 4<sup>th</sup> ( $P = 0.0097, 0.0131$ , respectively; Fig. 8a, Table 5). There was no significant difference between the mean SPAD value between the 4<sup>th</sup> and 5<sup>th</sup> leaves on the second date. There were no significant differences between dates for the 4<sup>th</sup> leaf ( $P > 0.10$ ), although the pattern of means is similar to that of improved. The 5<sup>th</sup> leaf mean SPAD value on the first date was significantly lower than the third date only ( $P = 0.00027$ ). There were no differences of the 5<sup>th</sup> leaf mean SPAD between the first and second date, or between the second and third date ( $P > 0.04$ ). Again, there were no significant differences among plots across direction or distance ( $P > 0.05$ ).

#### *Shoot Height*

Shoot height for improved teff plots was compared across direction from tree (plots extending east and west from tree base) with control plots for each measurement date. For the first, second, and third dates, there was a significant difference between east and west plot mean SH, with mean SH of west 14.45, 11.25, and 10.32 cm, respectively, larger than east ( $P < 0.01$ ; Fig. 7b, Table 4). Control mean SH was also significantly larger than both east and west mean SH on the first date, and significantly larger than east only on the second date ( $P < 0.01$ ; Table 4), but not larger than either on the third date. As expected, there was a significant positive linear relationship between plot distance from tree base and SH on the second and third dates only, with control plots excluded (slope=2.13, 2.61,  $P=0.025, 0.004$ ,  $r^2= 0.21, 0.32$ , respectively; Table 4).

Shoot height for koncho teff plot was compared in a similar manner as improved plots; for the second date only koncho west plot median SH was significantly larger than east, with west median SH being 13.5 cm larger than east ( $P = 0.008$ ; Fig. 8b, Table 5). On the first and third dates, there were no differences between east, west, and control median SH ( $P > 0.04$ ; Table 5), although median SH of west plots was always about equal to or slightly larger than that of control. Unexpectedly, there was no significant relationship between distance and SH ( $P > 0.3$ ; Table 5).



### *Leaf area index*

Like SH, Leaf area index for improved and koncho plots was compared across direction with control plots for each measurement date. In comparisons of improved teff, on all three dates there was no significant difference between east and west plot mean LAI ( $P > 0.03$ , Fig. 7c, Table 4). Control mean LAI was significantly larger than both east and west on the second date ( $P < 0.01$ , difference of means=2.10, 1.48 respectively; Table 4), and larger than east only on the third date ( $P < 0.0001$ , difference of means=2.22). Due to missing data, there was no control LAI for the first date to make comparisons. As expected, for the first and second dates, there was a significant positive linear relationship between distance and LAI (slope=0.23, 0.30,  $P=0.0009$ , 0.002,  $r^2=0.47$ , 0.36; Table 4), but not on the third date ( $P=0.227$ ).

For koncho teff, there were no significant differences between control, east, and west plot median LAI on all three dates ( $P > 0.2$ ; Fig. 8c, Table 5), nor any significant relationship between distance and LAI on any date ( $P > 0.1$ ; Table 5).

## DISCUSSION

### *Improved and koncho controls*

The improved teff appeared to be performing better under similar environmental conditions than koncho, and consistently so over the three measurement dates. For each date plot shoot height and leaf area index was larger than that of koncho (Fig. 6a, b). There were no varietal differences in SPAD values within leaf positions, in agreement with Castelli & Contillo (2009), who found no differences from variety on the relationship between SPAD values and total chlorophyll content, and between SPAD values and total N content, of leaves of tobacco. In contrast, Bullock & Anderson (1998) found significant cultivar effects for maize, and Geskes *et al.* (2013) found a strong genotype effect on SPAD values of maize with and without drought stress, while Minotti *et al.* (1994) found a large varietal effect with different N fertilization levels. Assuming that SPAD values are correlated to chlorophyll and N content in teff, it is likely that there were no differences in nitrogen status of leaf tissue between the teff varieties either.

In the open field, control plots were not light stressed any more than each other, so the difference in  $\delta^{13}\text{C}$  values was either due to some varietal difference in discrimination, or a difference in microsite edaphic features such as soil compaction, which affects water or nutrient availability, that could result in differing stress levels experienced by the plants. Since this was only the second time  $^{13}\text{C}$  isotopic analysis was used on teff, it is unknown if varietal differences in  $\delta^{13}\text{C}$  do exist for teff, as they do for other species between cultivars (Meinzer *et al.*, 1994; Saliendra *et al.*, 1996; Monneveux *et al.*, 2007). On the second measurement date, the difference in  $\Delta$  between improved and koncho plots was 0.35‰, but this was not associated with differences in SH or LAI between the cultivars. Similarly, Meinzer *et al.* (1994) reported an average 0.4‰ genotypic variation in sugarcane cultivars, which was associated with only small differences in their shoot growth rate.

#### *SPAD values*

We had expected SPAD values to increase in proximity to trees if *F. albida* had a positive fertility effect on soil properties, either from leaf drop or N-fixation. Instead, there was no difference across distance for either improved or koncho varieties. However, Muthuri *et al* (2009) found maize within 1 m of three different tree species had lower chlorophyll concentration (derived from SPAD values) than that of maize outside of the canopy, possibly due to N limitations. The chlorophyll concentration was derived from the relationship between SPAD values on leaves of various greenness and the chlorophyll content obtained from destructive sampling of those leaves. Due to logistical constraints, we could not measure leaf chlorophyll content and so we cannot directly relate SPAD values to leaf chlorophyll content for teff. However, since SPAD values also did not decrease in proximity to trees either, it seems N limitations might not have been an issue either. This lack of effect on N status of teff might be due to pollarding; a common practice after pollarding is to let livestock eat the leaves off branches while they are on the ground, before fixing the branches into fences. As a result, branches can often end up in piles or even several meters from the tree, and leaves that would have decomposed in the soil surrounding the tree instead end up as manure in another location. Assuming though that chlorophyll and N content is related to SPAD values, as has been demonstrated for

other species, and since there were no differences in SPAD values across distance or direction, the pattern in SPAD values was likely due to onset of senescence in 4<sup>th</sup> leaf, and maturation of the 5<sup>th</sup> leaf that was occurring with the transition into flowering.

$\delta^{13}\text{C}$

The slight decrease of  $\delta^{13}\text{C}$  across increasing distance for improved teff was surprising as we expected light to be a more limiting factor, which would have resulted in decreasing  $\delta^{13}\text{C}$  with proximity to tree. Instead, water stress was more likely the cause of the relationship. Although we were unable to attain soil moisture measurements for the site, we did observe a very obvious ring of moisture around the base of each tree. This ring was present most mornings of measurement dates, and sometimes until 1000 h on cool or cloudy days, so it was unlikely that teff plants near the tree base were experiencing the same degree of water stress as those further away. However, since both SH and LAI were positively related to distance, any benefit of the increased soil moisture near the tree was not enough to offset growth reductions from light interference or temperature differences.

#### *Shoot height and LAI*

As expected, teff growth was very obviously stunted near the base of trees. A possible explanation for this lies in the reduced light and soil temperature created over the course of a day around trees. In close proximity to trees, light would be reduced for at least part of the day, while soil temperature and possibly air temperature could be reduced too. Depending on the orientation of plants from trees, there will be regular daily differences in light and light-induced temperature changes, where plants on east side will have full light in the morning, and plants on west will have full light in the afternoon. This “tree shadow effect” was captured with measurements on soil temperatures by Kamara & Haque (1992) around *F. albida* trees. The authors found morning soil temperatures were lower on the west side than on the east both under and outside the canopy. In the afternoon soil temperatures were similar under and outside the canopy on the west side, but on the east side the soil temperature was lower under the canopy than outside. In general, the reduction of soil temperatures from under to outside the canopy was greater than that of the west side.

This reduction of soil temperatures is probably beneficial in extremely hot environments, as Vandenbledt & Williams (1992) reported improved growth of millet in Niger due to reductions of soil temperatures. However, in relatively cooler areas, temperature extremes might not be as inhibiting for crop growth, so proximity to tree and light interference could outweigh the benefit of reduced temperatures. This might explain the significance of the direction factor for improved teff on SH and the general pattern seen with LAI across measurement dates in the present study; assuming shading reduces soil temperatures unevenly across east and west plots (due to sun exposure on the east in the morning as opposed to afternoon), then east plots growth may have been inhibited due to low temperatures resulting from reduced radiation. PAR under tree canopy across all the trees in this study was reduced to 20.3% of the outside value (with a range of 14.5-28%). Since the distance factor became more significant over the three measurement dates also, this suggests that differences in light and temperature were compounded closer to the tree. This might also explain why the pattern of increasing SH and LAI with distance, and larger SH and LAI for west plots was weaker for koncho teff plots; the trees associated with koncho teff had been pollarded in April 2014, and despite their vigorous regrowth, height and crown size were reduced (average height for unpollarded and pollarded trees was 8.6 and 6 m, respectively), which would also reduce the shadow effect.

In contrast to our findings, Poschen (1986) did report increased yields from maize and sorghum grown in association with *F. albida* for sites in the Eastern highlands of Ethiopia, regardless of tree size or stand density. However, a total of 27 sites were used with only 2 plots per site (under and outside canopy), so variation within sites was not captured. Our findings were more similar to those involving a different tree species (*Vitellaria paradoxa*) where sorghum plant height, biomass, and yield were lowest closest to tree base (Boffa *et al.*, 2000; Kessler, 1992) despite increasing soil moisture content towards the tree. For this tree species, millet yields were increased with pruning (Bayala *et al.*, 2002), with the effect mostly related to reduction of light interference.

The *F. albida* at this site also did not display typical leafing patterns for this species, which normally involves leaf drop during the rainy season. Instead, the four

unpollarded trees displayed very little drop during the study, with most noticeable leaf drop in mid-July, two weeks before the teff was sown. This likely increased competition between the trees and teff for radiation, to the detriment of the teff. The presence of *F. albida* had a negative impact on teff growth, but the exact cause of this remains unclear.

## REFERENCES

- Acevedo E, Hsiao TC, and Henderson DW. 1971.** Immediate and subsequent growth responses of maize leaves to changes in water status. *Plant Physiology* 48:631-636.
- Araya A, Keesstra SD, and Stroosnijder L. 2010.** Simulating yield response to water of Teff (*Eragrostis tef*) with FAO's AquaCrop model. *Field Crops Research* 116: 196-204.
- Assefa K, Ketema S, Tefera H, Hundera F, and Kefyalew T. 2000.** Genetic diversity for agronomic traits in tef. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, tef research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p33-48.
- Assefa K, Aliye S, Belay G, Metaferia G, Tefera H, and Sorrells M. 2011.** Quncho: the first popular tef variety in Ethiopia. *International Journal of Agricultural Sustainability* 9(1): 25-34.
- Bayala J, Teklehaimanot Z, and Ouedraogo SJ. 2002.** Millet production under pruned tree crowns in a parkland system in Burkina Faso. *Agroforestry Systems* 54:203-214.
- Boffa JM, Taonda JB, Dickey JB, and Knudson DM. 2000.** Field-scale influence of karite (*Vitellaria paradoxa*) on sorghum production in the Sudan zone of Burkina Faso. *Agroforestry Systems* 49:153-175.
- Bowman WD, Hubick KT, von Caemmerer S, and Farquhar GD. 1989.** Short term changes in leaf carbon isotope discrimination in salt and water stressed C4 grasses. *Plant Physiology* 90(1):162-166.
- Buchmann N, Brooks JR, Rapp KD, and Ehleringer JR. 1996.** Carbon isotope composition of C4 grasses is influenced by light and water supply. *Plant, Cell, and Environment* 19:392-402.
- Bullock DG, and Anderson DS. 1998.** Evaluation of the Minolta SPAD-502 chlorophyll meter for nitrogen management in corn. *J. Plant Nutrition*. 21 (4), 741–755.
- Castelli F, Contillo R, and Miceli F. 1996.** Non-destructive determination of leaf chlorophyll content in four crop species. *Journal of Agronomy and Crop Science* 177:275-283.
- Castelli F, and Contillo R. 2009.** Using a chlorophyll meter to evaluate the nitrogen leaf content in flue-cured tobacco (*Nicotiana tabacum* L.). *Italian Journal of Agronomy* 2:3-11.

- Chapman SC., Barreto HJ. 1997.** Using a chlorophyll meter to estimate specific leaf nitrogen of tropical maize during vegetative growth. *Agronomy Journal*. 89, 557–562
- Ephrath JE, and Hesketh JD. 1991.** The effects of drought stress on leaf elongation, photosynthetic and transpiration rates in maize (*Zea mays*) leaves. *Photosynthetica* 25: 607-619.
- Evert S, Staggenborg S, and Olson BLS. 2009.** Soil temperature and planting depth effects on tef emergence. *Agronomy and Crop Science* 195:232-236.
- Farquhar GD. 1983.** On the nature of carbon isotope discrimination in C4 species. *Australian Journal of Plant Physiology* 10:205-26.
- Farquhar GD, Ehleringer JR, and Hubick KT. 1989.** Carbon isotope discrimination and photosynthesis. *Plant Molecular Biology: Annual Review of Plant Physiology* 40:503-37.
- Gekas F, Pankou C, Mylonas I, Ninouv E, Sinapidou E, Lithourgidis A, Papathanasiou F, Petrevska JK, Papadopoulou F, Zouliamis P, Tsaprounis G, Tokatlidis I, and Dordas C. 2013.** The use of chlorophyll meter readings for the selection of maize inbred lines under drought stress. *International Journal of Biological, Biomolecular, Agricultural, Food Engineering* 7(8):472-476.
- Ghannoum O. 2009.** C4 photosynthesis and water stress. *Annals of Botany* 103:635-644.
- Hatch MD. 1987.** C4 photosynthesis: a unique blend of modified biochemistry, anatomy and ultrastructure. *Biochimica et Biophysica Acta* 895:81-106.
- Hirut K, Johnson RC, and Ferris DM. 1989.** Photosynthetic response of Eragrostis tef to temperature. *Physiologia Plantarum* 77:262-266.
- Jones A, Breuning-Madsen H, Brossard M, Dampha A, Deckers J, Dewitte O, Gallali T, Hallett S, Jones R, Kilasara M, Le Roux P, Micheli E, Montanarella L, Spaargaren O, Thiombiano L, Van Ranst E, Yemefack M, Zougmou R, editors. 2013.** Soil Atlas of Africa. Luxembourg: European Commission, *Publications Office of the European Union*. 176 pp.
- Kamara CS, and Haque I. 1992.** *Faidherbia albida* and its effects on Ethiopian highland Vertisols. *Agroforestry Systems* 18:17-29.
- Kebede H, Johnson RC, and Ferris DM. 1989.** Photosynthetic response of *Eragrostis tef* to temperature. *Plant Physiology* 77:262-266.
- Kessler JJ. 1992.** The influence of karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees on sorghum production in Burkina Faso. *Agroforestry Systems* 17:97–118

- Konica Minolta. 2009.** Chlorophyll meter SPAD-502Plus. Osaka, Japan: Konica Minolta Optics, Inc. Available from [http://www.specmeters.com/assets/1/22/2900P\\_SPAD\\_502.pdf](http://www.specmeters.com/assets/1/22/2900P_SPAD_502.pdf)
- Meinzer FC, Plaut Z, Saliendra NZ. 1994.** Carbon isotope discrimination, gas exchange, and growth of sugarcane cultivars under salinity. *Plant Physiology* 104:521-6.
- Mengistu A. 2006.** Country profile: pasture/forage resource: Ethiopia. Rome, Italy: Food and Agriculture Organization [cited 2014 June 8]. Available from <http://www.fao.org/ag/agp/agpc/doc/counprof/ethiopia/ethiopia.htm>
- Mengistu DK. 2009.** The influence of soil water deficit imposed during various developmental phases on physiological processes of tef (*Eragrostis tef*). *Agriculture Ecosystem and Environment* 132:283-289.
- Minotti PL, Halseth DE, and Sieczka JB. 1994.** Field chlorophyll measurements to assess the nitrogen status of potato varieties. *Horticultural Science* 29(12):1497-1500.
- Monneveux P, Sheshahayee MS, Akhter J, and Ribaut J. 2007.** Using carbon isotope discrimination to select maize (*Zea mays* L.) inbred lines and hybrids for drought resistance. *Plant Science* 173:390-396.
- Muthuri CW, Ong CK, Craigon J, Mati BM, Ngumi VW, and Black CR. 2009.** Gas exchange and water use efficiency of trees and maize in agroforestry systems in semi-arid Kenya. *Agriculture Ecosystem and Environment* 129:497-507.
- National Research Council. 1996.** Lost Crops of Africa. Volume 1. Grains. National Academy Press, Washington, D.C.
- Osmond CB, Austin MP, Berry JA, Billings WD, Boyer JS, Dacey WH, Nobel PS, Smith SD, and Winner WE. 1987.** Stress physiology and the distribution of plants. *Bioscience* 37(1):38-48.
- Poschen P. 1986.** An evaluation of the *Acacia albida*- based agroforestry practices in the Hararghe highlands of eastern Ethiopia. *Agroforestry Systems* 4:129-143.
- Piekielek W, Lingenfelter D, Macneal K, and Fox R. 1997.** Agronomy Facts 53: The early-season chlorophyll meter test for corn. University Park, PA: *Pennsylvania State University*. 7p.
- Rodriguez IR, Miller GL. 2000.** Using a chlorophyll meter to determine the chlorophyll concentration, nitrogen concentration, and visual quality of St. Augustinegrass. *Horticulture Science* 35 (4), 751-754.
- Saliendra NZ, Meinzer FC, Perry M, and Thom M. 1996.** Associations between partitioning of carboxylase activity and bundle sheath leakiness to CO<sub>2</sub>, carbon isotope discrimination, photosynthesis, and growth in sugarcane. *Journal of Experimental Botany* 47:907-914.



**Uddling J, Gelang-Alfredsson J, Piikki K, and Pleijel H. 2007.** Evaluating the relationship between leaf chlorophyll concentration and SPAD-502 chlorophyll meter reading. *Photosynthesis Research* 91:37-46.

**Vandenbelt RJ. and Williams JH. 1992.** The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. *Agriculture and Forest Meteorology* 60:93-100.

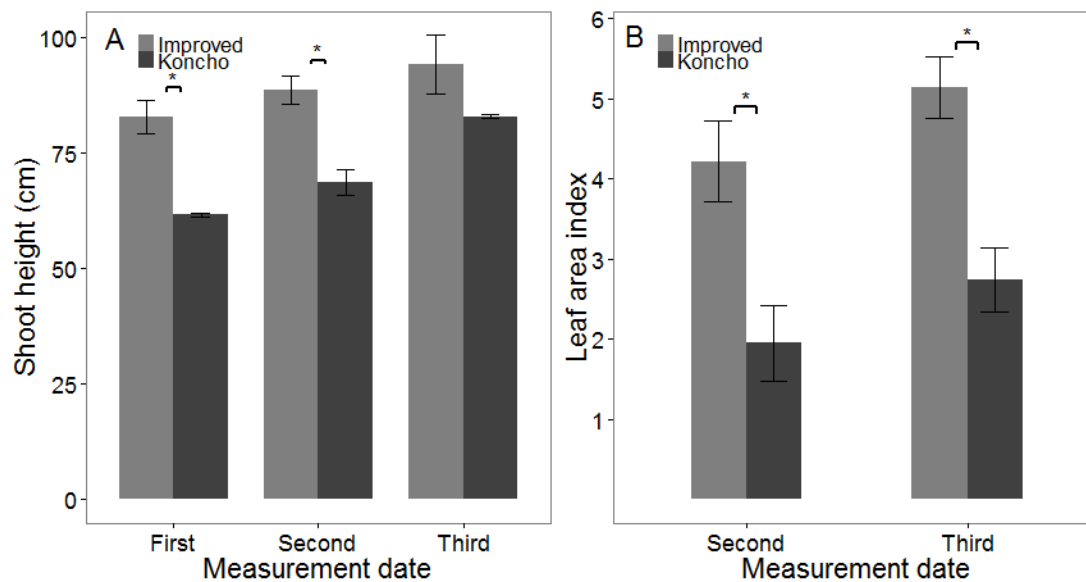
**The World Bank Group:** Climate Change Knowledge Portal for Ethiopia [Internet]. c2013. The World Bank Group; [cited 2013 Nov 20]. Available from <http://data.worldbank.org/country/ethiopia>.

**Yeh HW, and Wang WM. 2001.** Factors affecting the isotopic composition of organic matter. (1) Carbon isotopic composition of terrestrial plant materials. *Proceedings of the National Science Council, Republic of China* 25(3)137-147.

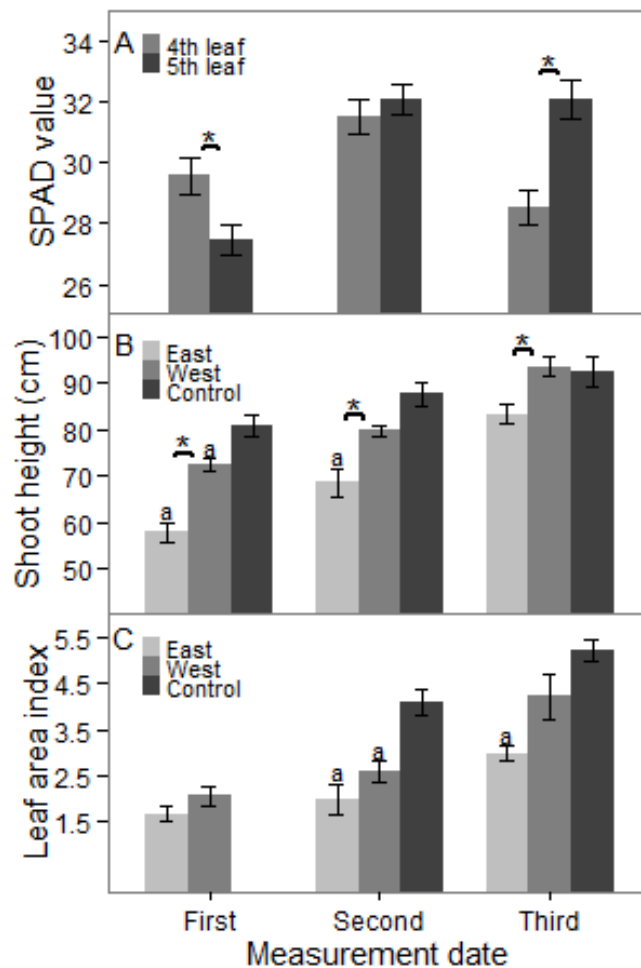
**Yihun YM, Haile AM, Schultz B, and Erkossa T. 2013.** Crop water productivity of irrigated teff in a water stressed region. *Water Resource Management* 27:3115-3125.

**Yizengaw T, and Verheye W. 1994.** Modelling production potentials of tef (*Eragrostis tef*) in the central highlands of Ethiopia. *Soil Technology* 7: 269-277.

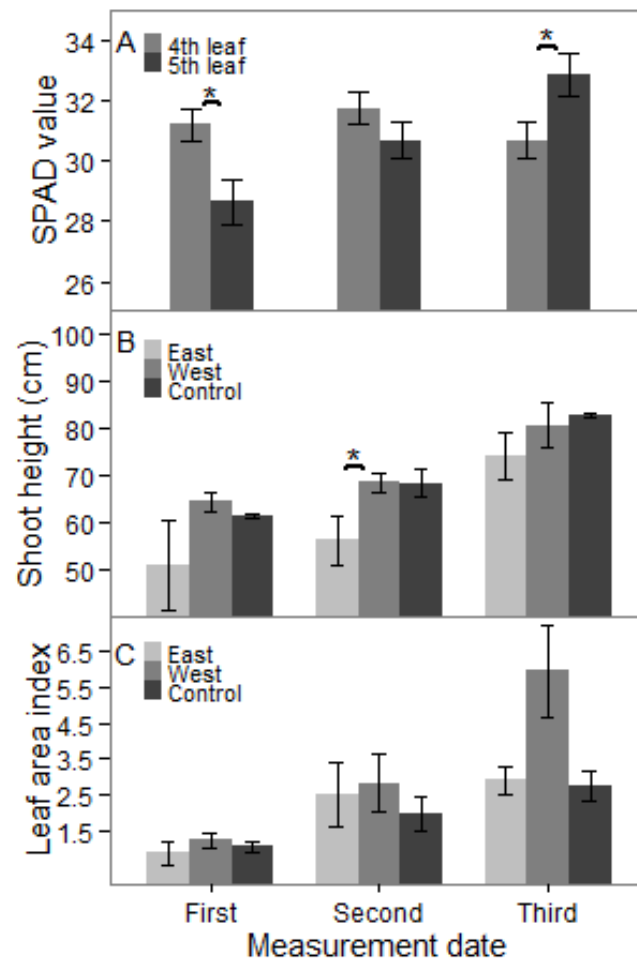
## FIGURES



**Figure 6.** Median shoot height (SH)  $\pm$  MAD (median absolute deviation) (**A**), and (**B**) median leaf area index (LAI)  $\pm$  MAD of control plots for improved and koncho teff varieties (n=6 and 4). Asterisks indicate significant differences ( $P \leq 0.05$ ) between varieties. Measurement dates for SH were 41, 44, and 50 days after sowing (DAS), and 36, 42, and 47 DAS for LAI.



**Figure 7.** Improved teff mean  $\pm$  SE SPAD value (A), shoot height (SH) (B), and leaf area index (LAI) (C) on three measurement dates. SPAD values are presented by leaf position across all plots ( $n=24$ ), SH and LAI are presented by direction from tree (east  $n=10$ , west  $n=14$ , control  $n=6$ ). Asterisks indicate significant differences ( $P \leq 0.05$ ) between 4<sup>th</sup> and 5<sup>th</sup> leaves for A, and significant differences ( $P \leq 0.0167$ ) between east and west plots for B and C. “a” indicates a significant difference ( $P \leq 0.0167$ ) between the group and the control plot for that date. Measurement dates for SPAD were 33, 44, and 50 days after sowing (DAS), 41, 44, and 50 DAS for SH, and 36, 42, and 47 DAS for LAI.



**Figure 8.** Koncho teff mean  $\pm$  SE SPAD value (A), median  $\pm$  MAD shoot height (SH) (B), and leaf area index (LAI) (C) on three measurement dates. SPAD values are presented by leaf position across all plots (n=14), SH and LAI are presented by direction from tree (east n=8, west n= 6, control n=4). Asterisks indicate significant differences ( $P \leq 0.05$ ) between 4<sup>th</sup> and 5<sup>th</sup> leaves for A, and significant differences ( $P \leq 0.0167$ ) between east and west plots for B and C. “a” indicates a significant difference ( $P \leq 0.0167$ ) between the group and the control plot for that date. Measurement dates for SPAD were 33, 44, and 50 days after sowing (DAS), 41, 44, and 50 DAS for SH, and 36, 42, and 47 DAS for LAI.

## TABLES

**Table 2.** Distribution of plots around trees, by direction (East/West) and distance (0-2 m, 2-4 m, 4-6 m, 6-8 m). Grey filled cells represent plots where measurements were taken.

West 6-8 m	West 4-6 m	West 2-4 m	West 0-2 m	Tree Code	East 0-2 m	East 2-4 m	East 4-6 m	East 6-8 m
				J1				
				J2				
				J3				
				J4				
				J5				
				O1				
				O2				

**Table 3.** Tree DBH outside bark and tree height for trees associated with teff plots.

Tree Code	J1	J2	J3	J4	J5	O1	O2	Mean	SD
DBHOB (cm)	39.4	43.9	40.8	49.1	42.8	58.9	36.8	44.5	7.4
Height (m)	5.6	10.8	12	4.8	6.5	6.3	5.6	7.4	2.8

**Table 4.** Mean SPAD values by leaf position (4<sup>th</sup> and 5<sup>th</sup>), mean shoot height (SH) and leaf area index (LAI) presented by plot direction (East and West), and slope of linear relationship between distance and SH or LAI. Asterisks indicate a significant difference between groups for SPAD, SH, and LAI, or significance of slope for each measurement date. “a” indicates a significant difference between a group and the control on that date.

Measurement Date	1st	2nd	3rd
SPAD, by leaf position (4th, 5th)	* 29.6, 27.4	31.5, 32.1	* 28.5, 32.1
SH (cm) by direction (East, West)	* 57.8 <sup>a</sup> , 72.3 <sup>a</sup>	* 68.5 <sup>a</sup> , 79.8	* 83.3, 93.7
SH (cm) by distance (m; linear slope)	1.6	2.1*	2.6*
LAI by direction (East, West)	1.7, 2.1	2.0 <sup>a</sup> , 2.6 <sup>a</sup>	3.0 <sup>a</sup> , 4.2
LAI by distance (m; linear slope)	0.23*	0.30*	0.29

**Table 5.** Mean SPAD values by leaf position (4<sup>th</sup> and 5<sup>th</sup>), median shoot height (SH) and leaf area index (LAI) presented by plot direction (East and West), and slope of linear relationship between distance and SH or LAI. Asterisks indicate a significant difference between groups for SPAD, SH, and LAI, or significance of slope for each measurement date. “a” indicates a significant difference between a group and the control on that date.

Measurement Date	1st	2nd	3rd
SPAD, by leaf position (4th, 5th)	* 31.2, 28.7	31.8, 30.7	* 30.7, 32.9
SH (cm) by direction (East, West)	51.2, 64.6	* 56.3, 68.7	74.1, 80.8
SH (cm) by distance (linear slope)	1.1	2.0	2.6
LAI by direction (East, West)	0.9, 1.2	2.5, 2.8	2.9, 5.9
LAI by distance (linear slope)	0.06	0.32	0.28



## CONCLUSIONS

*Faidherbia albida* has generally been recognized as having positive impacts on crop growth and yield, due to increasing soil fertility from leaf litter and nitrogen fixation, while remaining in low competition with crops from its reverse leafing phenology that reduces water use and canopy light interception during the rainy season. However, the benefits of reduced competition may not be realized if the trees do not drop leaves, or retain enough leaf area to continue substantial transpiration during part or all of the rainy season. As seen in this study, *F. albida* does not always adhere strictly to the species' reverse leafing phenology, and water use can remain high throughout the rainy season. It is unknown exactly what causes the irregular pattern to develop, but as Depommier (1998) suggested, pruning can drastically alter defoliation and foliation phases, with longer leaf retention periods for pruned trees.

Pollarding trees could have a similar impact to that of natural, rainy season-induced defoliation if water use and canopy light interception are decreased. However, in the present study, the timing of seasonal minimum water use was different in pollarded and unpollarded trees. In pollarded trees, the lowest rates of sap flows occurred during the 5-6 weeks after pollarding, with substantial flow returning by mid- to late-rainy season. In contrast, the lowest sap flows for unpollarded trees occurred at mid rainy season, and increases drastically with leaf flush. When taken in context with crops, if the defoliation period is short, crops are more likely to be in competition with trees for water at some point during the rainy season than if the defoliation period is longer. For the unpollarded trees in this study, crops that would be sown in the early rainy season would still have been covered by the *F. albida* canopy for at least the first month. Only crops associated with UP1 would have had the benefits of reduced water use and light interference after establishment. Crops sown around or just before mid-rainy season (short season crops) would have had these benefits during germination and establishment. Pollarded trees maintained lower levels of water use throughout the rainy season, and lower crown cover, than unpollarded trees, so crops associated with these trees would likely experience less competition for water and light than those associated with unpollarded trees, even those that do have rainy season-induced defoliation.

The teff plots in this study were negatively affected by the presence of unpollarded *F. albida*, with growth characteristics significantly reduced in proximity to trees. The only other studies that reported negative effects of *F. albida* on crops had relatively young and small trees (~ 5 years, 3-8 cm DBH), so leaf drop and decomposition, and nitrogen fixation, would only have been able to occur under these trees for a few years, and rooting systems and crowns would have been relatively small compared to other studies (Jama & Getahun, 1991; Chamshama 1994). Since the trees in this study were comparable in size to those in many other studies involving *F. albida* and crops (Poschen, 1986; Kamara & Haque 1992; Vandenbeldt & Williams, 1992; Subrahmanyam & Bheemaiah 2003), the negative effects seen 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 *F. albida* may not be seen in more moderate climates, where high temperature is not a limitation for crop growth and survival, or where farmer management alters leafing patterns and decreases litter accumulation under trees.

More research is needed to determine if teff has a similar response to the presence of other trees in similar climates, and if altered phenological cycles from pollarding *F. albida* are common. Understanding why *F. albida* has an inverted phenology, and what treatments may alter this pattern, may be key in determining whether or not *F. albida* competes with crops during rainy seasons. The typical management choices and decisions of farmers (such as pollarding intensity and cycles) should be taken into account when conducting studies on tree species that may be promoted for use in agroforestry systems.

## BIBLIOGRAPHY

- Acevedo E, Hsiao TC, and Henderson DW. 1971.** Immediate and subsequent growth responses of maize leaves to changes in water status. *Plant Physiology* 48:631-636.
- Alexandre DY, and Ouedraogo SJ. 1992.** Variations in root morphology of *Faidherbia albida* in relation to soil and agronomic effects. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p107-110.
- Allen SJ, and Grime VL. 1995.** Measurements of transpiration from savannah shrubs using sap flow gauges. *Agricultural and Forest Meteorology* 75:23-41.
- Araya A, Keesstra SD, and Stroosnijder L. 2010.** Simulating yield response to water of Teff (*Eragrostis tef*) with FAO's AquaCrop model. *Field Crops Research* 116: 196-204.
- Assefa K, Ketema S, Tefera H, Hundera F, and Kefyalew T. 2000.** Genetic diversity for agronomic traits in tef. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, tef research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p33-48.
- Assefa K, Aliye S, Belay G, Metaferia G, Tefera H, and Sorrells M. 2011.** Quncho: the first popular tef variety in Ethiopia. *International Journal of Agricultural Sustainability* 9(1): 25-34.
- Barrett DJ, Hatton TJ, Ash JE, and Ball M.C. 1995.** Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of south-eastern Australia. *Plant, Cell, and Environment* 18:463-469.
- Bayala J, Teklehaimanot Z, and Ouedraogo SJ. 2002.** Millet production under pruned tree crowns in a parkland system in Burkina Faso. *Agroforestry Systems* 54:203-214.
- Bayala J, Mando A, and Ouedraogo SJ. 2003.** Managing *Parkia biglobosa* and *Vitellaria paradoxa* prunings for crop production and improved soil properties in the sub-Saharan zone of Burkina Faso. *Arid Land Resource and Management* 17:283-296.
- Bayala J, Teklehaimanot Z, and Ouedraogo SJ. 2004.** Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. *Agroforestry Systems* 60:13-26.

- Bayala J, Bazie HR, and Sanou J. 2013.** Competition and facilitation-related factors impacts on crop performance in agroforestry parkland system in Burkina Faso. *African Journal of Agriculture Research* 8:5307-5314.
- Bazie HR, Bayala J, Zombre G, Sanou J, and Ilstedt U. 2012.** Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. *Agroforestry Systems* 84:377-388.
- Bishaw B, Neufeldt H, Mowo J, Abdelkadir A, Muriuki J, Dalle G, Assefa T, Guillozet K, Kassa H, Dawson IK, Luedeling E, and Mbow C. 2013.** Farmers' Strategies for Adapting to and Mitigating Climate Variability and Change through Agroforestry in Ethiopia and Kenya. Editors Davis CM, Bernart B, and Dmitriev A. *Forestry Communications Group*, Oregon State University, Corvallis, Oregon.
- Boffa JM. 1999.** Agroforestry parklands in sub-Saharan Africa, FAO Conservation Guide 34 [Internet]. Rome, Italy: Food and Agriculture Organization [cited 2013 Nov 10]. Available from <http://www.fao.org/docrep/005/x3940e/x3940e00.htm>
- Boffa JM, Taonda JB, Dickey JB, and Knudson DM. 2000.** Field-scale influence of karite (*Vitellaria paradoxa*) on sorghum production in the Sudan zone of Burkina Faso. *Agroforestry Systems* 49:153-175.
- Bonkougou E. 2001.** Network on agroforestry and soil conservation. Lome, Togo: Secretariat of the Convention to Combat Desertification.
- Borchet R. 1994.** Soil and stem water storage determine phenology and distribution of tropical dry forest trees. *Ecology* 75(5):1437-1449.
- Bowman WD, Hubick KT, von Caemmerer S, and Farquhar GD. 1989.** Short term changes in leaf carbon isotope discrimination in salt and water stressed C4 grasses. *Plant Physiology* 90(1):162-166.
- Brewbaker JL. 1987.** Significant nitrogen fixing trees in agroforestry systems. Gholz, H.I. Edition *Agroforestry: realities, possibilities and potentials* 31-45. *Martinus Nijhoff Publications* Dordrecht, 227pp.
- Broadhead JS, Ong CK, and Black CR. 2003.** Tree phenology and water availability in semi-arid agroforestry systems. *Forest Ecology and Management* 180:61-73.
- Buchmann N, Brooks JR, Rapp KD, and Ehleringer JR. 1996.** Carbon isotope composition of C4 grasses is influenced by light and water supply. *Plant, Cell, and Environment* 19:392-402.
- Bullock DG, and Anderson DS. 1998.** Evaluation of the Minolta SPAD-502 chlorophyll meter for nitrogen management in corn. *J. Plant Nutrition*. 21 (4), 741-755.

- Burgess SSO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, and Bleby TM. 2001.** An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21:589–598
- Burgess SSO, and Downey A. 2012.** SFM1 Sap flow meter manual. Armidale, NSW, Australia: ICT International Pty Ltd. Available from <http://au.ictinternational.com/content/uploads/2014/03/SFM1-wManual.pdf>
- Butenschoen O, Scheu S, and Eisenhauer N. 2011.** Interactive effects of warming, soil humidity and plant diversity on litter decomposition and microbial activity. *Soil Biology and Biochemistry* 43:1902-1907.
- Caldwell MM, Dawson TE, and Richards JH. 1998.** Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia* 113:151-161.
- Caldwell MM, and Richards JH. 1989.** Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. *Oecologia* 79(1):1-5.
- Campa C, Diouf D, Ndoye I, and Dreyfus B. 2000.** Differences in nitrogen metabolism of *Faidherbia albida* and other N<sub>2</sub>-fixing tropical woody acacias reflect habitat water availability. *New Phytology* 147:571-578.
- Castelli F, and Contillo R. 2009.** Using a chlorophyll meter to evaluate the nitrogen leaf content in flue-cured tobacco (*Nicotiana tabacum* L.). *Italian Journal of Agronomy* 2:3-11.
- Castelli F, Contillo R, and Miceli F. 1996.** Non-destructive determination of leaf chlorophyll content in four crop species. *Journal of Agronomy and Crop Science* 177:275-283.
- Chamshama SAO. 1994.** Early performance of *Faidherbia albida* intercropped with maize at Gairo, Morogoro, Tanzania. *Journal of Tropical Forest Science* 7(2)220-229.
- Chapman SC, Barreto HJ. 1997.** Using a chlorophyll meter to estimate specific leaf nitrogen of tropical maize during vegetative growth. *Agronomy Journal*. 89, 557–562
- Coulibaly YN, Mulia R., Sanou J, Zombre G, Bayala J, Kalinganire A, and van Noordwijk M. 2014.** Crop production under different rainfall and management conditions in agroforestry parkland systems in Burkina Faso: observations and simulation with WaNuLCAS model. *Agroforestry Systems* 88:13-28.
- Deans JD, and Munro RC. 2004.** Comparative water use by dryland trees in Parklands in Senegal. *Agroforestry Systems* 60:27-38.
- Decagon Devices. AccuPAR PAR/LAI Ceptometer, Model LP-80, Operator's Manual. 2014.** Pullman, WA: Decagon Devices, Inc. Available from [http://manuals.decagon.com/Manuals/10242\\_Accupar%20LP80\\_Web.pdf](http://manuals.decagon.com/Manuals/10242_Accupar%20LP80_Web.pdf)

- Depommier, D. 1998.** Etude phénologique de *Faidherbia albida* (Del.) A. Chev. Effet de l'émondage, du site et de la dimension de l'arbre sur les phénophases de l'espèce au Burkina Faso. In Actes de la réunion sur 'L'Acacia au Sénégal', Dakar, Senegal, 3–5 December 1996. Dakar, ORSTOM.
- Do FC, Rocheteau A, Diagne AL, Goudiaby C, and Lhomme JP. 2008.** Stable annual pattern of water use by *Acacia tortilis* in Sahelian Africa. *Tree Physiology* 28:95-104.
- Dupuy N, and Dreyfus B. 1992.** Presence of *Bradyrhizobia* under *Acacia albida*. In: Vandenbelt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p145-148.
- Ephrath JE, and Hesketh JD. 1991.** The effects of drought stress on leaf elongation, photosynthetic and transpiration rates in maize (*Zea mays*) leaves. *Photosynthetica* 25: 607-619.
- Evert S, Staggenborg S, and Olson BLS. 2009.** Soil temperature and planting depth effects on tef emergence. *Agronomy and Crop Science* 195:232-236.
- Farquhar GD. 1983.** On the nature of carbon isotope discrimination in C4 species. *Australian Journal of Plant Physiology* 10:205-26.
- Farquhar GD, Ehleringer JR, and Hubick KT. 1989.** Carbon isotope discrimination and photosynthesis. *Plant Molecular Biology: Annual Review of Plant Physiology* 40:503-37.
- Gebre Kirstos A, Demel T, Masresha F, Mitlohner R. 2006.** Adaptation of five co-occurring tree and shrub species to water stress and its implication in restoration of degraded lands. *Forest Ecology and Management* 229:259–267
- Gekas F, Pankou C, Mylonas I, Ninouv E, Sinapidou E, Lithourgidis A, Papathanasiou F, Petrevska JK, Papadopoulou F, Zouliamis P, Tsaprounis G, Tokatlidis I, and Dordas C. 2013.** The use of chlorophyll meter readings for the selection of maize inbred lines under drought stress. *International Journal of Biological, Biomolecular, Agricultural, Food Engineering* 7(8):472-476.
- Ghannoum O. 2009.** C4 photosynthesis and water stress. *Annals of Botany* 103:635-644.
- Govindarajan M, Rao MR, Mathuva MN, and Nair PKR. 1996.** Soil-water and root dynamics under hedgerow intercropping in semiarid Kenya. *Agronomy* 88:513-520.
- Hatch MD. 1987.** C4 photosynthesis: a unique blend of modified biochemistry, anatomy and ultrastructure. *Biochimica et Biophysica Acta* 895:81-106.

- Heineman AM, Otieno HJO, Mengich EK, and Amadalo BA. 1997.** Growth and yield of eight agroforestry tree species in line plantings in Western Kenya and their effect on maize yields and soil properties. *Forest Ecology and Management* 91:103-135.
- Hirut K, Johnson RC, and Ferris DM. 1989.** Photosynthetic response of *Eragrostis tef* to temperature. *Physiologia Plantarum* 77:262-266.
- Ibrahim AM, Fagg CW, and Harris SA. 1997.** Seed and seedling variation amongst provenances in *Faidherbia albida*. *Forest Ecology and Management* 97:197-205.
- ICT International.** Sap flow tool, analysis and visualization of sap flow data. 2012. Armidale, NSW, Australia: ICT International Pty Ltd. Available from <http://www.sapflowtool.com/SapFlowToolManual.html>
- Jama B, and Getahun A. 1991.** Intercropping *Acacia albida* with maize (*Zea mays*) and green gram (*Phaseolus aureus*) at Mtipwa Coast Province, Kenya. *Agroforestry Systems* 14:193-205.
- Jama B, Nair PKR, and Kurira PW. 1989.** Comparative growth performance of some multipurpose trees and shrubs grown at Machakos, Kenya. *Agroforestry Systems* 9:17-27.
- Jones A, Breuning-Madsen H, Brossard M, Dampha A, Deckers J, Dewitte O, Gallali T, Hallett S, Jones R, Kilasara M, Le Roux P, Micheli E, Montanarella L, Spaargaren O, Thiombiano L, Van Ranst E, Yemefack M, Zougmore R, editors. 2013.** Soil Atlas of Africa. Luxembourg: European Commission, *Publications Office of the European Union*. 176 pp.
- Jonsson K, Ong CK, and Odongo JCW. 1999.** Influence of scattered néré and karité on microclimate, soil fertility and millet yield in Burkina Faso. *Experimental Agriculture* 35:39-53.
- Jose S, and Bardhan S. 2012.** Agroforestry for biomass production and carbon sequestration: an overview. *Agroforestry Systems* 86:105-111
- Kamara CS, and Haque I. 1992.** *Faidherbia albida* and its effects on Ethiopian highland Vertisols. *Agroforestry Systems* 18:17-29.
- Kassa H, Gebrehiwet K, and Yamoah C. 2010.** *Balanites aegyptiaca*, a potential tree for parkland agroforestry systems with sorghum in Northern Ethiopia. *Journal of Soil Science and Environmental Management* 16:107-114.
- Kebede H, Johnson RC, and Ferris DM. 1989.** Photosynthetic response of *Eragrostis tef* to temperature. *Plant Physiology* 77:262-266.
- Kessler JJ. 1992.** The influence of karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees on sorghum production in Burkina Faso. *Agroforestry Systems* 17:97-118



- Kessler JJ, and Breman H. 1991.** The potential of agroforestry to increase primary production in the Sudan-Sahelian zones of West Africa. *Agroforestry Systems* 13:41-62.
- Kho RM, Yacouba B, Yaye M, Katkore B, Moussa A, Iktam A, and Mayaki A. 2001.** Separating the effects of trees on crops: the case of *Faidherbia albida* and millet in Niger. *Agroforestry Systems* 52:219-238.
- Kizito F, Dragila MI, Sene M, Brooks JR, Meinzer FC, Diedhiou I, Diouf M, Lufafa A, Dick RP, Selker J, and Cuenca R. 2012.** Hydraulic redistribution by two semi-arid shrub species: Implications for Sahelian agro-ecosystems. *Journal of Arid Environment* 83:69-77
- Kizito F, Dragila MI, Sene M, Lufafa A, Diedhiou I, Dick RP, Selker J, Dossa E, Khouma, M, Badiane A, and Ndiaye S. 2006.** Seasonal soil water variation and root patterns between two semi-arid shrubs co-existing with pearl millet in Senegal, West Africa. *Journal of Arid Environment* 67:436-455.
- Kizito F, Sene M, Dragila MI, Lufafa A, Diedhiou I, Dossa E, Cuenca R, Selker J, Dick RP. 2007.** Soil water balance of annual crop-native shrub systems in Senegal's Peanut Basin: the missing link. *Agriculture Water Management* 90:137-148.
- Konica Minolta. 2009.** Chlorophyll meter SPAD-502Plus. Osaka, Japan: Konica Minolta Optics, Inc. Available from [http://www.specmeters.com/assets/1/22/2900P\\_SPAD\\_502.pdf](http://www.specmeters.com/assets/1/22/2900P_SPAD_502.pdf)
- Laike A. 1992.** *Faidherbia albida* in the traditional farming systems of central Ethiopia. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p39-41.
- Lehmann J, Peter I, Steglich C, Gebauer G, Huwe B, Zech W. 1998.** Below-ground interactions in dryland agroforestry. *Forest Ecology and Management* 111:157-169.
- Lott JE, Khan AAH, Black CR, and Ong CK. 2003.** Water use in a *Grevillea robusta*-maize overstorey agroforestry system in semi-arid Kenya. *Forest Ecology and Management* 180:45-59.
- Lott JE, Ong CK, and Black CR. 2009.** Understorey microclimate and crop performance in a *Grevillea robusta*-based agroforestry system in semi-arid Kenya. *Agriculture and Forest Meteorology* 149:1140-1151.
- Ludwig F, de Kroon, Hans, Prins HT, and Berendse F. 2001.** Effects of nutrients and shade on tree-grass interactions in an East African savanna. *Journal of Vegetation Science* 12:579-588.

- Manzoni S, Vicoc G, Thompson S, Beyer F, and Weih M. 2015.** Contrasting leaf phenological strategies optimize carbon gain under droughts of different duration. *Advances in Water Resources* 84:37-51.
- Marshall DC. 1958.** Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33:385-396.
- Mathuva MN, Rao MR, Smithson PC, and Coe R. 1998.** Improving maize (*Zea mays*) yield in semiarid highlands of Kenya: agroforestry or inorganic fertilizers? *Field Crops Research* 55:57-72.
- Meinzer FC, Goldstein G, Franco AC, Bustamante M, Iglar E, Jackson P, Caldas L, and Rundel PW. 1999.** Atmospheric and hydraulic limitations on transpiration in Brazilian cerrado woody species. *Functional Ecology* 13:273-282.
- Meinzer FC, Plaut Z, Saliendra NZ. 1994.** Carbon isotope discrimination, gas exchange, and growth of sugarcane cultivars under salinity. *Plant Physiology* 104:521-6.
- Mengistu A. 2006.** Country profile: pasture/forage resource: Ethiopia. Rome, Italy: Food and Agriculture Organization [cited 2014 June 8]. Available from <http://www.fao.org/ag/agp/agpc/doc/counprof/ethiopia/ethiopia.htm>
- Mengistu DK. 2009.** The influence of soil water deficit imposed during various developmental phases on physiological processes of tef (*Eragrostis tef*). *Agriculture Ecosystems and Environment* 132:283-289.
- Millar AA, Jensen RE, Bauer A, and Norum EB. 1971.** Influence of atmospheric and soil environmental parameters of the diurnal fluctuations of leaf water status of barley. *Agricultural Meteorology* 8:93-105.
- Minotti PL, Halseth DE, and Sieczka JB. 1994.** Field chlorophyll measurements to assess the nitrogen status of potato varieties. *Horticultural Science* 29(12):1497-1500.
- Mokgolodi NC, Setshogo MP, Shi L, Liu Y, and Ma C. 2011.** Achieving food and nutritional security through agroforestry: a case of *Faidherbia albida* in sub-Saharan Africa. *Forestry Studies in China* 13: 123-131.
- Monneveux P, Sheshahayee MS, Akhter J, and Ribaut J. 2007.** Using carbon isotope discrimination to select maize (*Zea mays* L.) inbred lines and hybrids for drought resistance. *Plant Science* 173:390-396.
- Muthuri CW, Ong CK, Black CR, Ngumi VW, Mati BM. 2005.** Tree and crop productivity in *Grevillea*, *Alnus* and *Paulownia*-based agroforestry systems in Central Kenya. *Forest Ecology and Management* 212:23-39.
- Muthuri CW, Ong CK, Craigon J, Mati BM, Ngumi VW, and Black CR. 2009.** Gas exchange and water use efficiency of trees and maize in agroforestry systems in semi-arid Kenya. *Agriculture Ecosystem and Environment* 129:497-507.

- Nair PKR, Kumar BM, and Nair VD. 2009.** Agroforestry as a strategy for carbon sequestration. *Plant Nutrition and Soil Science* 172: 10-23.
- National Research Council. 1996.** Lost Crops of Africa. Volume 1. Grains. National Academy Press, Washington, D.C.
- Noumi Z, Abdallah F, Torre F, Michalet R, Touzard B, and Chaieb M. 2011.** Impact of *Acacia tortilis* ssp. *Raddiana* tree on wheat and barley yield in the south of Tunisia. *Acta Oecologia* 37:117-123.
- Ong CK, Black CR, and Muthuri CW. 2006.** Modifying forestry and agroforestry to increase water productivity in the semi-arid tropics. CAB Reviews: Perspectives in Agriculture, Veterinary Science, *Nutrition and Natural Resources* 1
- Ong CK, and Leakey RRB. 1999.** Why tree-crop interactions in agroforestry appear at odds with tree-grass interactions in tropical savannahs. *Agroforestry Systems* 45:109–129.
- Orwa C, Mutua A, Kindt R, Jamnadass R, and Simons A. 2009.** Agroforestry Database: a tree reference and selection guide version 4.0 [Internet]. Nairobi, Kenya: World Agroforestry Centre; [cited 2013 Nov 8]. Available from <http://www.worldagroforestry.org/af/treedb/>
- Osmond CB, Austin MP, Berry JA, Billings WD, Boyer JS, Dacey WH, Nobel PS, Smith SD, and Winner WE. 1987.** Stress physiology and the distribution of plants. *Bioscience* 37(1):38-48.
- Piekielek W, Lingenfelter D, Macneal K, and Fox R. 1997.** Agronomy Facts 53: The early-season chlorophyll meter test for corn. University Park, PA: *Pennsylvania State University*. 7p.
- Poschen P. 1986.** An evaluation of the *Acacia albida*- based agroforestry practices in the Hararge highlands of eastern Ethiopia. *Agroforestry Systems* 4:129-143.
- Richards JH, and Caldwell MM. 1987.** Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentate* roots. *Oecologia* 73(4):486-489.
- Rodriguez IR, Miller GL. 2000.** Using a chlorophyll meter to determine the chlorophyll concentration, nitrogen concentration, and visual quality of St. Augustinegrass. *Horticulture Science* 35 (4), 751–754.
- Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, and Dreyer E. 1999.** Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese West Africa. *Functional Ecology* 13: 460-472.
- Saka AR, Bunderson WT, Itimu OA, Phombeya HSK, and Mbekeani Y. 1994.** The effects of *Acacia albida* on soils and maize grain yields under smallholder farm conditions in Malawi. *Forest Ecology and Management* 64:217-230.

- Saliendra NZ, Meinzer FC, Perry M, and Thom M. 1996.** Associations between partitioning of carboxylase activity and bundle sheath leakiness to CO<sub>2</sub>, carbon isotope discrimination, photosynthesis, and growth in sugarcane. *Journal of Experimental Botany* 47:907-914.
- Schroth G. 1999.** A review of belowground interactions in agroforestry, focusing on mechanisms and management options. *Agroforestry Systems* 43:5–34.
- Sepúlveda B, and Carrillo A. 2015.** Soil erosion and erosion thresholds in an agroforestry system of coffee (*Coffea arabica*) and mixed shade trees (*Inga* spp and *Musa* spp) in Northern Nicaragua. *Agriculture Ecosystems and Environment* 210:25-35
- Sheperd KD, Ohlsson E, Okalebo JR, and Ndufa JK. 1996.** Potential impact of agroforestry on soil nutrient balances at the farm scale in the East African Highlands. *Fertilizer Research* 44(2):87-99.
- Sileshi G, Akinnifesi FK, Ajayi OC, and Place F. 2008.** Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant Soil* 307:1-19.
- Smith DM, and Allen SJ. 1996.** Measurement of sap flow in plant stems. *Journal of Experimental Botany* 47:1833–1844.
- Subrahmanyam MVR, and Bheemaiah G. 2003.** Yield and economics of rainfed maize (*Zea mays*) in African babul (*Faidherbia albida*) based agroforestry system under different fertility levels. *Indian Journal of Agricultural Science* 73:138-141.
- Tardieu F, Reymond M, Hamard P, Granier C, and Muller B. 2000.** Spatial distributions of expansion rate, cell division rate and cell size in maize leaves: a synthesis of the effects of soil water status, evaporative demand and temperature. *Journal of Experimental Botany* 51:1505-1514.
- Tefera H, and Ketema S. 2000.** Production and importance of tef in Ethiopian Agriculture. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, teff research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p3-7.
- Tefera A, and Tefera T. 2013.** Grain and feed and annual report for Ethiopia. United States Department of Agriculture, Foreign Agricultural Service. Available from [http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual\\_Addis%20Ababa\\_Ethiopia\\_5-24-2013.pdf](http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Addis%20Ababa_Ethiopia_5-24-2013.pdf)
- Thorlakson T, and Neufeldt H. 2012.** Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya. *Agriculture and Food Security* 1:15pp. doi:10.1186/2048-7010-1-15.

- Uddling J, Gelang-Alfredsson J, Piikki K, and Pleijel H. 2007.** Evaluating the relationship between leaf chlorophyll concentration and SPAD-502 chlorophyll meter reading. *Photosynthesis Research* 91:37-46.
- Umar BB, Aune JB, and Lungu OI. 2013.** Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia. *African Journal of Agricultural Research* 8(2):173-183.
- Vandenbeldt RJ. 1992.** Rooting systems of western and southern African *Faidherbia albida* (Del.) A. Chev. (syn *Acacia albida* Edl.)- a comparative analysis with biogeographic implications. *Agroforestry Systems* 14:233-244.
- Vandenbeldt RJ, and Williams JH. 1992.** The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. *Agriculture and Forest Meteorology* 60:93-100.
- Verchot LV, van Noordwijk M, Kandji S, Tomich T, Ong CK, Albrecht A, Mackensen J, Bantilan C, Anupama KV, and Palm C. 2007.** Climate change: linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change* 12:901-918. doi:10.1007/s11027-007-9105-6.
- Wajja-Musukwe TN, Wilson J, Sprent JI, Ong CK, Deans JD, and Okorio J. 2007.** Tree growth and management in Ugandan agroforestry systems: effects of root pruning on tree growth and crop yield. *Tree Physiology* 28:233-242.
- Wang H, Zhao P, Holscher D, Wang Q, Lu P, Cai XA, and Zeng XP. 2012.** Nighttime sap flow of *Acacia mangium* and its implication for nighttime transpiration and stem water storage. *Journal of Plant Ecology* 5(2)294-304.
- Wickens GE. 1969.** A study of *Acacia albida* Del. (Mimosoidae). *Kew Bulletin* 23: 181-202.
- Wood PJ. 1992.** The botany and distribution of *Faidherbia albida*. In: Vandenbeldt RJ editor. *Faidherbia albida* in the West African semi-arid tropics: proceedings of a workshop; 1991 April 22–26; Niamey, Niger. ICRISAT, Patancheru, India and ICRAF, Nairobi, Kenya. p9-17.
- The World Bank Group:** Climate Change Knowledge Portal for Ethiopia [Internet]. c2013. The World Bank Group; [cited 2013 Nov 20]. Available from <http://data.worldbank.org/country/ethiopia>.
- Yadeta K, Ayele G, and Negatu W. 2000.** Farming systems research on tef: smallholders' production practices. In: Tefera H, Belay G, and Sorrells M, editors. Narrowing the rift, tef research and development. Proceedings of the International Workshop on tef Genetics and Improvement; 2000 October 16-19; Addis Ababa, Ethiopia. Ethiopian Agricultural Research Organization; p9-23.

**Yeh HW, and Wang WM. 2001.** Factors affecting the isotopic composition of organic matter. (1) Carbon isotopic composition of terrestrial plant materials. *Proceedings of the National Science Council, Republic of China* 25(3)137-147.

**Yihun YM, Haile AM, Schultz B, and Erkossa T. 2013.** Crop water productivity of irrigated teff in a water stressed region. *Water Resource Management* 27: 3115-3125.

**Yizengaw T, and Verheye W. 1994.** Modelling production potentials of tef (*Eragrostis tef*) in the central highlands of Ethiopia. *Soil Technology* 7: 269-277.