Sustainable intensification of smallholder farming systems in Ethiopia: What role can scattered trees play?

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Abstract

Scattered trees dominate smallholder agricultural landscapes in Ethiopia, as in large parts of sub-Saharan Africa (SSA). While the integration of scattered trees with crops could provide a viable pathway for sustainable intensification of these farming systems, they also lead to trade-offs. Trade-off minimization and benefit maximization from these trees in the system require the processes that underlie tree-crop interactions to be unravelled. This study explored tree-based pathways for the sustainable intensification (SI) smallholder crop production systems in contrasting agroecologies of Ethiopia. Combination of methodologies from agronomy, socio-economics and conservation sciences were utilized to understand the potential roles of scattered trees in smallholder farming systems. Results indicated that farmers maintained on-farm trees because of their direct timber, fencing, fuelwood, and charcoal production values, regardless of their effect on crop productivity. A trade-off analysis revealed that economic gains from trees were not large enough to compensate for tree-induced crop yield penalties in tree-crop mixed farming systems. Under farmers' practices, most scattered trees generally had a significant negative effect on maize yield. For example, mean maize grain yields were 59%, 42% and 26% less under the canopies of *Cordia africana, Croton macrostachyus* and *Acacia tortilis,* respectively, compared with corresponding open field yields. The yield reductions dropped to as low as 5% under 'good agronomic practices', such as early planting, variety selection, improved weed management, fine seedbed preparation and higher rates of nitrogen fertilizer. Similar yield reduction was observed in maize under the canopy of *Grevillea robusta.* Application of nitrogen and phosphorus fertilizers to under canopy maize in *Grevillea robusta* and *Acacia tortilis* improved crop yields, compared with non-fertilized maize under the canopies of these tree species. However, recommended rates of nitrogen and phosphorus
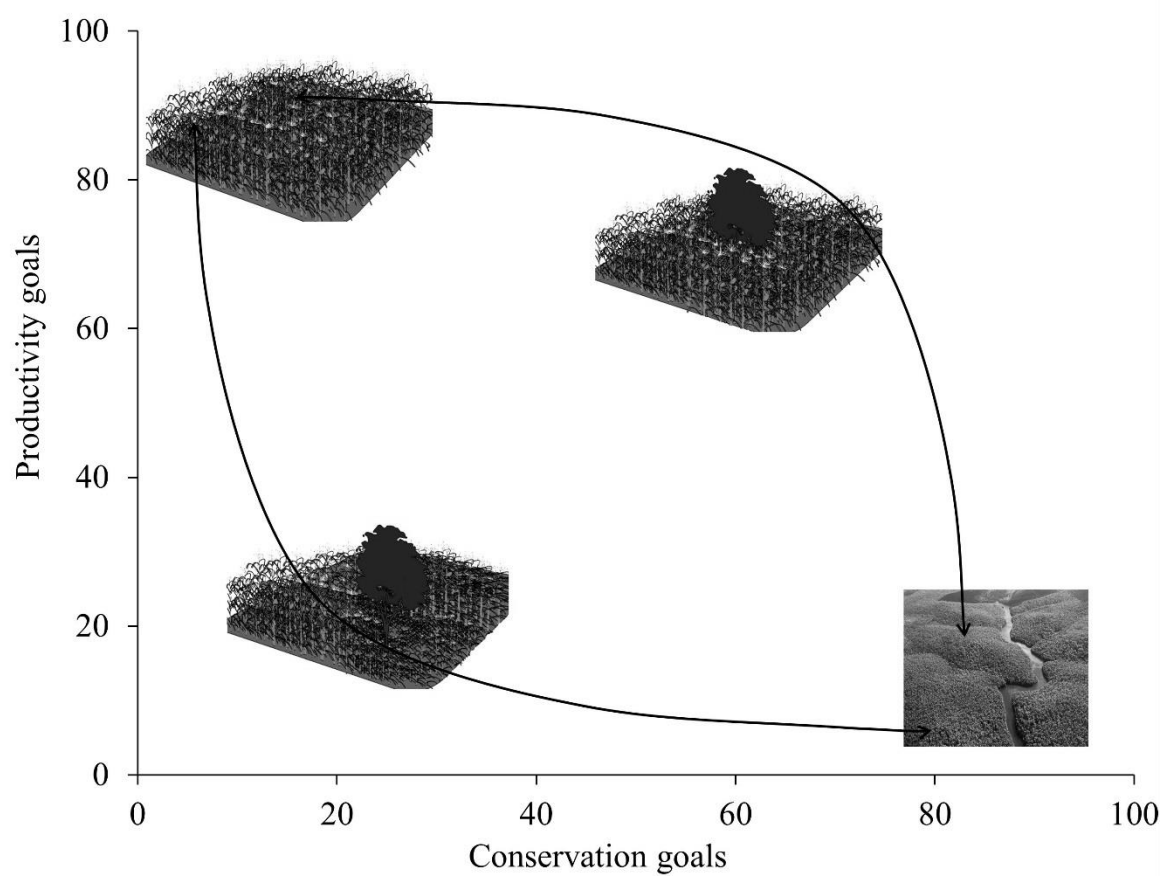
fertilizers produced significantly less maize yields compared with the open fields. *Faidherbia albida* is an exceptional scattered tree species that improved soil water, nitrogen and phosphorus use efficiencies, leading to significantly higher yields in wheat gunder tree crown. Available N was 35-55% larger close to the crowns of *Faidherbia* compared with open fields, apparently contributing as much as 64 kg ha^{-1} yr^{-1} mineral N. In addition, this tree significantly reduced photosynthetically active radiation (PAR), reaching the canopy to optimum levels for wheat growth and development. Under the crowns, midday temperature was about 6°C less compared with nearby open fields. Regardless of the triple-win effects (crop production, adaptation and mitigation) of this tree species, over-utilization caused tree population decline. Under the current management, *Faidherbia* population would decline to a critical density of less than one tree ha^{-1} within six decades. The current study underlined that conservation of scattered trees can never be achieved through promotions based on neither the trade-offs nor crop productivity benefits involved. Scattered trees can be maintained even when trade-offs with crop production are overriding. Contrarily, these trees may be endangered even if they provide all-round benefits. Thus, a 'whole sale' approach that advocates scattered trees on their theoretical environmental and crop production values could jeopardize both conservation and crop production goals. A 'process-based' rather than 'technology-based' recommendation is required to harness the promising potential that scattered trees offer as a starting point for sustainable intensification of smallholder farming systems.

Key words: Agroforestry, agronomy, sustainable intensification, Climate-smart agroforestry, tree-crop interaction, climate change, local aapation

Contents

General introduction

Chapter 1

1.1. Background

Scattered trees within crop fields are common features of smallholder agriculture, which dominates both economic and social activity for millions of farmers in Ethiopia. These dispersed trees involve both benefits and trade-offs for crop production. Smallholders face multiple production challenges. They operate under limited resources, face severe food insecurity and are highly vulnerable to climate change. In addition, fast population growth intensifies the demand for increased crop production. Between 1990 and 2014, Ethiopia's population increased by 81% (CSA 2013). Population growth is not expected to stabilize before 2100 (CSA 2013), while Ethiopia remains food self-insufficient (Luan *et al.* 2013). Increase in crop production is needed to tackle the recurrent food security problem in the country (Gebre-Medhin & Vahlquist 1977; Winer 1989; Webb & Braun 1994; Devereux & Sussex 2000; Abebaw *et al.* 2010; Thome *et al.* 2017). Expansion of land under cereal production following existing practices cannot be a viable option because of the shortage of productive land (Lavers 2012) and associated risks of land degradation with the expansion of agriculture to marginal lands (Meshesha *et al.* 2012). Although mineral fertilizer use in Ethiopian agriculture is still low compared with other regions (Abate *et al.* 2015), its increased use can be constrained by their increasing scarcity at global level (Townsend & Howarth 2010; Desmidt *et al.* 2015). For example, the energy-dependent synthesis of nitrogen fertilizers is driving their cost ever higher with the peaking oil price (Chen *et al.* 2012). Similarly, the global peak in phosphorus production is predicted to occur around 2030 (Sorrell *et al.* 2012). In addition, lack of capital and limited availability of mineral fertilizers have been recognized as major adoption problems in many countries of sub-Saharan Africa (SSA) (Muzari *et al.* 2012; Hailu *et al.* 2014).

On the other hand, experience of intensive use of mineral fertilizers from other regions confirmed its multiple threats to environmental sustainability (Pingali 2012; Mueller *et al.*

2014). Besides, the use of fertilizers under poor smallholder farming systems is often not economically feasible due to high prices and the risk of crop failure from drought (Garrity *et al.* 2010). Extremely fragmented land holding limits the returns from mineral fertilizer use (Tefera & Sterk 2010; Teka *et al.* 2013). In this study, I explored tree-based pathways that sustainably intensify smallholder systems and increase crop production in contrasting agroecologies of Ethiopia and Rwanda. The central question of this thesis is: what roles can scattered trees within crop fields play in sustainable intensification of smallholder faming systems?

1.2. The need for sustainable intensification

Agriculture, in general and smallholder agriculture in particular, has multiple goals. Although the overwhelming goal of agriculture has been food production (Luan *et al.* 2013; Jones & Ejeta 2016), interest in agricultural sustainability has risen following the negative environmental consequences of agriculture (Pretty *et al.* 2011; Fischer *et al.* 2012; Godfray & Garnett 2014; Pretty & Bharucha 2014). It is widely claimed that chemical-intensive agriculture inherently threatens the environment, endangering long-term sustainability of production systems (Pretty & Bharucha 2014). For the majority of smallholder farmers, agriculture offers community livelihood. At the same time, most smallholders in the developing countries such as Ethiopia struggle to achieve food self-sufficiency (Luan *et al.* 2013). On the other hand, smallholders are vulnerable to the negative externalities of extensive agriculture in the form of biodiversity loss (Angelsen 2010). Another challenge for smallholders is the threat from greenhouse gas emissions, which can be associated with chemical-intensive agricultural production (Brussaard *et al.* 2010; Karp *et al.* 2012). Thus, they face the double challenge of closing food self-sufficiency gap and minimizing negative externalities of both extensive and intensive agriculture. For example, Ethiopia needs to produce more than double its 2010 level cereal

production to achieve food self-sufficiency by 2050 (Van Ittersum *et al.* 2016). Whereas Ethiopia has large potentially cultivable land for extensive production by utilizing infrastructures such as irrigation (Chamberlin *et al.* 2014), it has already incurred huge cost from agricultural expansion to forested and marginal lands (Yesuf *et al.* 2005). The country needs ways of producing more food without deteriorating its biodiversity, soil, water and forest resources. Sustainable intensification, a production system that increases yield with minimal adverse environmental impact and without expansion to more land (Baulcombe *et al.* 2009), maybe one of the options.

1.3. Tree-based systems as a starting point for sustainable intensification

According to Pretty and Bharucha (2014), the main goal of sustainable intensification (SI) of agricultural systems is to produce enough food, fuel and fibre whilst having a positive impact on natural, social and human capitals. Sustainable intensification options could vary from crop variety improvement (e.g., through gene modification) to the redesign of centuries-old traditional systems (e.g., agroforestry) (Pretty *et al.* 2011). The success of a SI option depends on specific biophysical and institutional contexts of the smallholders (Shiferaw *et al.* 2009). Not all SI pathways are equally adoptable. Neither a single approach nor a marginal improvement in sustainability under the current production system can achieve sustainable intensification goals (Garnett *et al.* 2013). Numerous analysis of SI options for smallholder farming systems in SSA rightly emphasized the importance of adapting interventions to local conditions and support for farmer innovation rather than fixed prescriptions (Vanlauwe *et al.* 2007; Giller *et al.* 2011; Droppelmann *et al.* 2017). Thus, existing systems, such as tree-crop mixed systems, can be a starting point in the design and redesign of SI alternatives in smallholder farming systems (Figure 1.1).

Tree-crop mixed systems are one of the most dominant features in global agricultural landscapes. Zomer *et al.* (2014) estimated that close to 50% of global agricultural land has more than 10% tree cover. Close to one-third has more than 20% tree cover and about 7% of global agricultural land has more than 50% tree cover. Dispersed trees serve as construction material, source of energy and income. Trees on agricultural fields have also been advocated to replenish the declining soil fertility (Glover *et al.* 2012) and protect soil against degradation (Atangana *et al.* 2014). They help in climate change mitigation and adaptation (Mbow *et al.* 2014) and improve agroecosystem resilience (Jacobi et al. 2015). Importantly, they reduce crop yield gaps (Phalan *et al.* 2014), which are a major cause of poverty traps in in SSA (Tittonell & Giller 2013). While the importance of dispersed trees on environmental sustainability is uncontested (Mbow *et al.* 2014), its effects on crop yields depends on various factors. Whether tree-crop interactions lead to facilitation between the two components, depend largely on the type of tree species (Kassa *et al.* 2010; Siriri et al. 2010), agroecology (Iiyama *et al.* 2017) and crop species (Fadl 2010). Tree management (Siriri *et al*. 2010) and spatial arrangement within the agricultural landscapes (Grala *et al.* 2010; Duguma 2013) also determine the outcome of tree-crop interaction. For example, Kassa *et al.* (2010) demonstrated that higher sorghum yield was obtained in *Balanites aegyptiaca*-sorghum agroforestry compared with other tree-sorghum systems in Northern Ethiopia. Fadl (2010) found that dry matter yield for sesame and roselle were significantly reduced under intercropping with *Acacia senegal*, while groundnut yielded higher total dry matter compared with sole systems. Siriri *et al.* (2010) showed that combined shoot and root pruning increased maize yield under *Calliandra calothyrsus, Alnus acuminata* and *Sesbania sesban* mixture systems relative to maize under unpruned trees. A study from Central Ethiopia found that woodlots established outside crop fields generated the highest economic returns followed by homestead tree and shrub arrangement (also outside agricultural

fields), while boundary planting resulted in the least returns from tree-crop combinations (Duguma 2013).
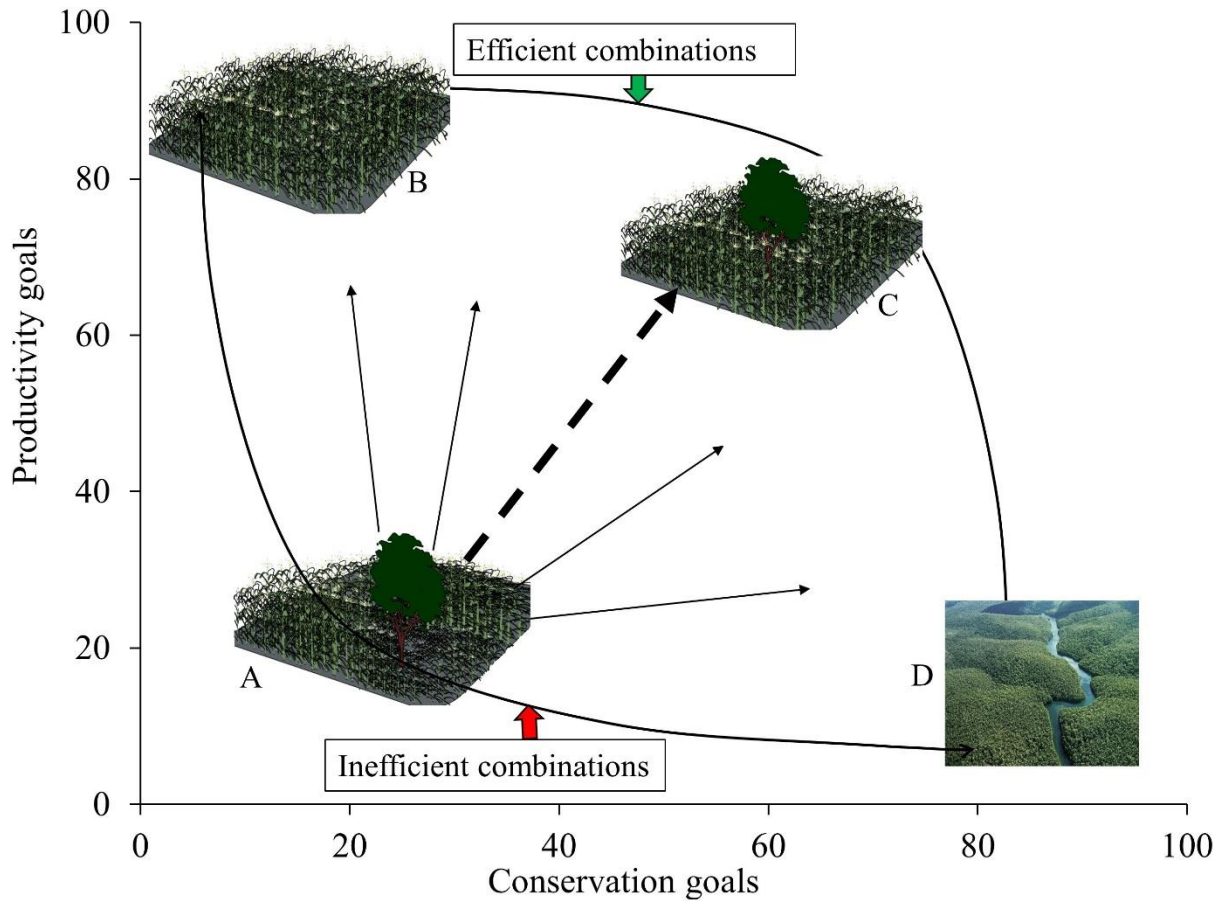
Figure 1.1 Hypothetical marginal utility maximization curves between crop production and conservation goals. Broken bold arrow represents tree-based SI pathway, while other arrows represent other hypothetical intensification/extensification pathways. A = the current tree-based system, B = intensification towards monocrops that maximizes crop production goal, C = hypothetical tree-based sustainable intensification and D = hypothetical pristine ecosystem that maximizes conservation goal.

1.4. Scattered trees in Ethiopian smallholder agriculture

Scattered trees on farms are integral parts of smallholder farming systems in Ethiopia. While their contribution to environmental sustainability is well established (Tscharntke *et al.* 2011),

their impact on agricultural productivity is often location specific (Huth *et al.* 2010), tree species dependent (Kassa *et al.* 2010; Siriri *et al.* 2010) and greatly varies with tree-crop configuration in the fields (Kassa *et al.* 2010). Although promoting scattered trees for soil conservation, biodiversity maintenance, climate change mitigation and multiple other ecosystem service is a valid goal in itself, there is a tendency for considering them as a solution for every problem that smallholder farmers face. For example, the Ethiopian government has planned to include a 100 million scattered Faidherbia *(Faidherbia albida)* trees into smallholder farms covering up to 15 million ha of land (Mekonnen *et al.* 2013). The aim was to make the economy green and climate resilient, improve food security of smallholders, adapt to and mitigate climate change. Although such political will is encouraging, studies that explore natural functionalities by which presence of trees could enhance benefits have usually been less emphasized.

1.5. General methodology and the objectives of the study

In this study, I used combination of concepts from agronomy, socio-economics and ecological sciences to understand how and why the scattered trees could be beneficial or detrimental in smallholder farming systems (Figure 1.2). I selected four dominant scattered tree species (*Cordia africana, Acacia tortilis, Croton macrostachyus* and *Faidherbia albida*) within three agroecologies in Ethiopia and one tree species (*Grevillea robusta*) from Rwanda. Rwanda was chosen because of its similarities to Ethiopia in terms of the dense population and prevalence of tree-based farming systems. In addition, the contrasting socio-economic and biophysical settings under which scattered trees are managed in the two countries can provide additional insights. *Grevillea robusta* was selected because of its dominance as a scattered tree species in Rwanda.

At farm scale, I explored the direct benefits of scattered trees to smallholder households, trade-offs that exist in tree-crop systems and the main rationale behind managing trees with crops (A). At field scale, I explored the impact of existing agronomic practices (fertilizer rates, planting dates, crop varieties, etc.) on the outcome of tree-crop interaction. This was complemented by plot level on-farm experiments, where I assessed the impact of nitrogen and phosphorus mineral fertilizer in tree-crop systems (B). In another study at plot scale, I conducted on-farm experiments to unravel how and why scattered trees could lead to increased or reduced crop yield (C).
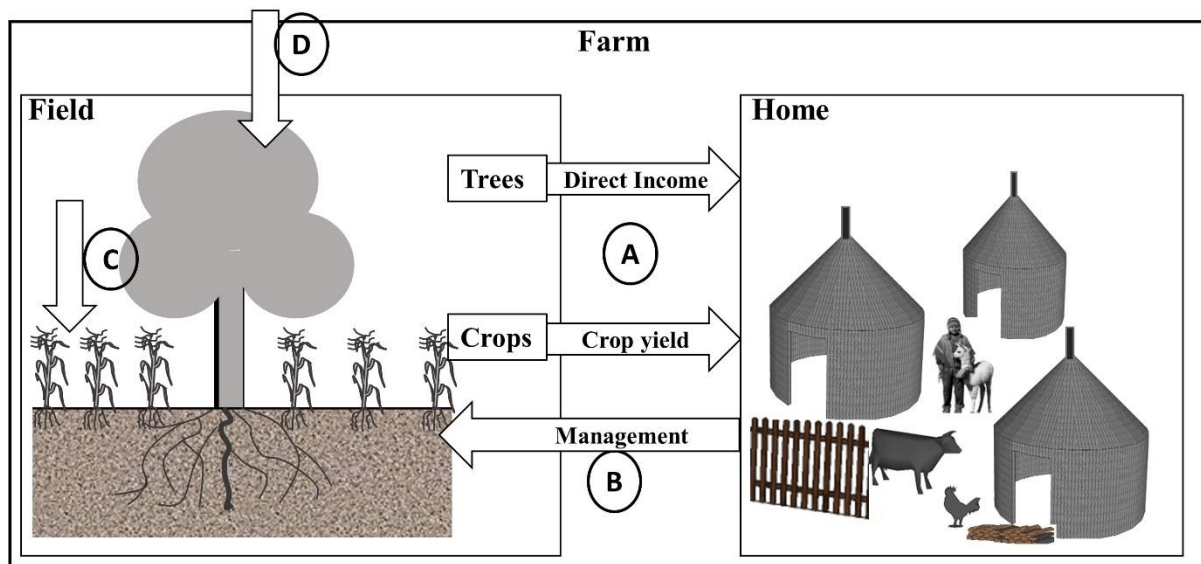
Figure 1.2 A schematic representation of a smallholder farm with scattered trees in their crop fields. Arrows show the direction of influence or decision or material flow between farm enterprises and components. Encircled letters correspond to the specific level (plot, field, farm and landscape) of focus corresponding to each of the objectives in the study.

I used combinations of long-term experiments and simulation models to explore the effects of interactions on the availability of resources (nutrients and soil moisture) and the microenvironment (temperature and radiation) in determining crop physiological and yield responses to tree canopy environment. After identifying scattered tree species that have unique

overall productivity and ecosystem benefits in the smallholder systems, I zoomed in on a single species (*Faidherbia albida*), and studied its current population status, bottlenecks for regeneration and modelled trends in its future population at landscape scale (D). Thus, I applied combinations of methodologies across different scales (from plot to landscape) to understand the dynamics of tree-crop interaction and the prospect of agroforestry as a starting point for sustainable intensification of smallholder farming systems, especially in Ethiopia.

The specific objectives of the study were:

1. To explore the main rationale for farmers to maintain on-farm trees and the role of agronomic practices in managing tree-crop trade-offs for selected scattered tree species at farm scale

2. To evaluate the effect of mineral fertilizer-tree combinations on crop yield and agronomic nutrient use efficiencies (AE) for different agroecologies, trees and crop species

3. To quantify the impact of selected scattered tree (*Faidherbia albida*) on the resources available to wheat (nutrients and water), on the microenvironment of wheat (temperature and radiation) and the productivity of understorey wheat

4. To explore the current population status, identify major regeneration bottlenecks and model future trends in population under different scenarios for a selected scattered tree species (*Faidherbia albida*)

1.6. Thesis outline

Chapter 2 quantifies the impact of scattered trees on maize under different agronomic practices. It explores the main rationale of smallholders to maintain scattered trees within crop fields under different agroecologies. This chapter also undertakes the partial analysis of tree-crop trade-offs

(Objective 1). In Chapter 3, I zoomed in on the effects of nitrogen and phosphate fertilizers on wheat and maize yield under tree-crop mixed system in a semi-arid environment in the Central Rift Valley of Ethiopia and the highlands of Rwanda (Objective 2). Chapter 4 zooms in further and explores the impact of scattered trees on soil nutrients, moisture, microclimate and associated wheat yield in semi-arid environment (Objective 3). Chapter 5 explores the population status of a scattered tree species that shows a positive outcome from tree-crop interaction (Objective 4). Chapter 6 discusses and concludes the whole study based on the findings in the previous chapters. This final chapter also comments on the role of scattered trees in sustainable intensification of smallholder systems and suggests the conditions under which these trees could be useful and conditions under which they are not.

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

Chapter 2

 Abstract

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

2.1. Introduction

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

By contrast, on-farm trees may compete with annual crops over resource utilization. Their interactions with crops involve complex management decisions in order to maximize total farm level benefits. Regardless of established ecological and provisioning contribution of trees (Bayala *et al.*, 2002), their direct contribution to increased crop yield is often contested (Coulibaly *et al.*, 2014) and context specific (Brandt *et al.*, 2012). For example, on-farm trees and crops compete for resources such as soil moisture and nutrients depending on soil type, climate and tree-crop management (Huth *et al.*, 2010). Moreover, tree shades reduce light

penetration to understory crops, limiting the rate of photosynthesis in understorey crops (Ong and Kho, 2015). While crop yield penalties are expected from tree-crop competition for resources, farmers still maintain trees on their farms. This conforms with Boffa (2000) who suggested parkland trees could be planted and maintained for their benefits in the overall farming system, not solely for their direct effects on crop yields. Den Biggelaar and Gold (1996) also showed that preferences for indigenous on-farm tree species are driven by context-specific values and utilization flexibilities rather than by sole financial and economic factors. On-farm trees are also maintained for their social and cultural values (Gustad *et al.*, 2004).

Farmers possibly minimize tree-crop competition effects by managing both crops and trees. While many studies assessing the negative effects of tree-crop interaction have focused on management practices that manipulate the tree component such as root and canopy pruning (Bertomeu *et al.*, 2011), studies exploring the potential impact of manipulating the crop component are scarce. Changes in crop planting schedules, and adaptations of crop genetic characteristics such as maturity class, competition tolerance, vulnerability to pests, and sensitivity to tree shade can be utilized (Rosenzweig *et al.*, 2004). We hypothesized that manipulating agronomic practices such as field preparation, planting date, fertilization rate, variety selection, weeding, and cultivation could minimize trade-offs in tree-crop interactions. Thus, the general objective of the study was to understand the influence of agronomic practices on crop production in an agroforestry system of semi-arid and sub-humid agricultural landscapes in Oromia, Ethiopia. We specifically aimed: 1) to explore beyond yield rationale of farmers to maintain on-farm trees; 2) to quantify the impact of agronomic practices on the outcome of tree-crop interaction; and 3) to analyse partial economic trade-offs for selected on-farm tree species at farm scale.

2.2. Materials and Methods

2.2.1. Study area

We used a combination of household survey and field measurements in two contrasting ecosystems (semi-arid and sub-humid) in Ethiopia (Table 2.1). The semi-arid site – Meki – is located in the Central Rift Valley of Ethiopia, while the sub-humid site – Bako – is located in the western part of the country. On-farm trees are dominant features of agricultural landscapes in both areas.

Table 2.1 Summary of the general characteristics of the study areas

Site features	Site names	
	Meki	Bako
Region	Central Rift Valley of Ethiopia	Western Ethiopia
Geographic location	8.156°-8.208°N & 38.855°-38.889°E	9.083° - 9.127° N & 37.065° - 37.106° E
Agroecology	Semi-arid	Sub-humid
Mean annual rainfall	731 mm	1283.4
Mean annual maximum T°	28.4 C°	30.5
Mean annual minimum T°	13.6 C°	13.5
Annual mean T°	21 C°	22
Dominant soil type	Andosols	Nitisols
Altitude range a.m.s.l.	1500 - 1650 m	1500 - 2000 m
Dominant on-farm tree species	*Acacia tortilis, Faidherbia albida*, other *Acacia spp.*	*Croton macrostachyus, Cordia africana, Ficus spp.*
Tree species studied	*Acacia tortilis*	*Croton macrostachyus* and *Cordia africana*
Major crops	Maize, *teff*, beans, wheat, sorghum	Maize, *teff*, sorghum, *Nug*
Number of fields surveyed	45	90

2.2.2 Sampling and data collection

2.2.2.1. Sampling and yield estimation

We purposively selected three on-farm tree species, which were the most dominant in each of the sites. *Cordia africana* (Cordia) and *Croton macrostachyus* (Croton) were the most dominant species in Bako, whereas *Acacia tortilis* (Acacia) was the most dominant in Meki. To simplify reporting, we used genus names (given in the parenthesis) when referring to these species in the rest of the paper. For each species, we selected 45 farmers who owned and managed trees on maize fields, creating a combined sample of 135 farms. We selected one field from every farm for data collection mainly using the criteria: (1) the tree species of interest was grown within maize fields, (2) the selected tree was located in maize field isolated from other on-farm trees at least by 40 m, and (3) open field and under canopy plots had similar characteristics, except for the presence of trees. In addition, trees were selected in such a way that the trees were quasi-identical with the corresponding trees selected from other farms. We measured tree heights and canopy diameters (East-West and North-South) for the sampled trees.

We set three plots, each 4 m^2 in size, for each of the 135 farms. We set one plot for maize in the open field, which was at least 40 m away from the nearest tree. We set two other plots, from which a single average yield was computed to account for under canopy heterogeneity, at a distance of 2 m from tree trunk for maize grown under tree canopies. We collected maize yield and yield components from all plots. Maize samples were oven-dried for 48 hours at 60°C to determine total dry biomass and grain yields.

2.2.2.2. Soil moisture and solar radiation

For all plots described in the previous section, we measured topsoil moisture content three times between silking and physiological maturity using ML3 ThetaProbe$^©$ moisture sensors (Delta-T-Devices, 2013). Soil moisture was sampled from five spots to estimate average moisture content for the whole plot. Photosynthetically active radiation (PAR) was measured above

maize canopies using sensors from SunScan© Canopy Analysis System (Webb *et al.*, 2013) at similar interval. This measurement was made simultaneously over canopies of under storey maize and maize in the open using Beam Fraction Sensor (BFS) that was wirelessly connected to the main scanner.

2.2.2.3. Household survey

Each household whose field was selected for data collection was surveyed for socio-economic characterization. Farm level information such as land holding, family size, livestock holdings and total number of trees on the farms were recorded. The agronomic management of the selected fields such as field preparation, planting date, fertilization rate, variety selection, weeding, and cultivation were recorded. In addition, we used a questionnaire to explore the main rationale of maintaining selected scattered on-farm tree species. We also quantified the direct economic gains from trees in the form of charcoal, timber, fencing material and firewood from this survey.

2.2.3. Statistical analysis

2.2.3.1. Farmers' rationale to maintain on-farm trees

To explore farmers' beyond yield rationale of planting and maintaining on-farm trees, we used a Generalized Linear Model (GLM). We examined the likelihood of a farmer maintaining on-farm trees as a function of perceived values and utilities of those trees. In the regression model, we assumed density of on-farm trees as a dependent variable, which could be driven by farmers' preferences for each tree species. We assumed perceived or stated importance of each species, quantified using Likert scale (Gliem and Gliem, 2003), as independent variables. We performed the regression analysis with log-transformed values of on-farm tree density to satisfy the parametric assumption (Equation 2.1).

Chapter 2

$$Y_{ijklmnpqrs} = \alpha + \beta TM_i + \mu CC_j + \partial SF_k + \gamma CY_l + \delta FD_m + \eta CV_n + \rho FW_p + \tau FN_q$$

$$+ \lambda SH_r + \pi SM_s + R \tag{2.1}$$

Where, $Y_{ijklmnpqrs}$, is log-transformed on-farm tree density, TM_i is the ith value for timber production, CC_j is the jth value for charcoal production, SF_k is the kth value for soil fertility improvement/maintenance, CY_l is the lth value in improving yield, FD_m *is* the mth value as source of animal fodder, CV_n is the nth value as cultural utility, FW_p is the pth value as source of firewood, FN_q is the qth value as source of fencing material, SH_r is the rth value as animal/human shade and SM_s is the sth value as soil moisture improvement/maintenance, while *α, β, μ, ∂, γ, δ, η, ρ, τ, λ* and *π* represent regression coefficients, and R is the residual of the model. We fitted the models for each tree species separately, as the rationale of maintaining each of them could be species-specific.

2.2.3.2. Generalized Linear Mixed Models (GLMM)

We used a generalized linear mixed model (GLMM) to assess the impact of different agronomic practices on the variability of maize yield (Equation 2.2).

$$Y_{ijklmnpqrstx} = \alpha + \beta SP_j + \partial TR_k + \gamma UR_l + \delta DAP_m + \theta OF_n + \rho DP_p + \varphi CV_q + \lambda HF_r$$

$$+ \Psi NC_s + \mu NP_t + \pi WF_x + \omega SP_j : TR_k + \chi SP_j : UR_l + \vartheta SP_j : DAP_m$$

$$+ \Lambda SP_j : DP_p + \eta SP_j : CV_q + \tau SP_j : HF_r + \mathfrak{z} SP_j : WF_x + R \tag{2.2}$$

Where, $Y_{ijklmnpqrstx}$, is square-root-transformed maize yield, SP_j is the jth tree species, TR_k is the kth treatment (i.e. presence or absence of a tree), UR_l is the lth rate of urea fertilizer, DAP_m *is* the mth rate of DAP fertilizer, OF_n is the nth rate of organic amendment, DP_p is the pth date of maize planting, CV_q is the qth type of maize variety, HF_r is the rth frequency of herbicide application, NC_s is the sth frequency of cultivation, NP_t is the tth number of ploughing for seedbed preparation and WF_x *is* the xth frequency of hand weeding, while *α, β, ∂, γ, δ, θ, ρ, φ, λ, Ψ, μ, π, ω, ϑ, Λ, η, τ, χ* and *ʒ* are coefficients of fixed and random effects, and R is the residual of the model. The components in the fixed effects part of the model represented a vector of variables of agronomic

practices. Although the model was applied to square-root-transformed values of grain yield to satisfy the normality assumption, mean comparison was made on back-transformed least squared mean, i.e. on the mean that was adjusted for other factors. We used the probability level of 0.05 to test the significance of each effect in the model, unless otherwise stated. Interactions and main effects that had small explanatory power, i.e., variables with F-values of less than 0.1, were removed.

2.2.3.3. Partial trade-off analysis

To make partial economic analysis, we first computed the total area of the farm covered by tree canopies. To calculate this area, we computed the mean canopy diameter from North-South and East-West canopy extensions of the sample trees. We extrapolated this area for the total number of trees on the farm to get the total area of the farm under the influence of tree canopies. We calculated the reduction in maize yield under canopies for this area and computed total yield penalty because of the presence of trees. We made major assumptions: (1) that all trees within a farm have approximately similar mean canopy diameter and (2) that maize under the other tree canopies would be affected in a similar manner to our samples. Based on the household survey, we estimated the direct tree-based benefits of timber, charcoal, firewood and fencing material from these trees in monetary terms. We used local units and local market prices of these products (Appendix Table S2.1) to calculate the total farm-level income from each tree species. For incomes that will be earned in the future, such as timber, we performed discounting and used the Net Present Values (NPV) in the current analysis. Farm gate maize prices were used to estimate losses in maize yield associated with trees (Appendix Table S2.1). We plotted total farm level income from tree products against total farm level loss of income because of trees.

2.3. Results

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

Although densities of on-farm trees could be higher when other tree species are considered, the current densities for Cordia (*Cordia africana*), Croton (*Croton macrostachyus*) and Acacia (*Acacia tortilis*) were 4.6, 3.7 and 2.6 trees ha^{-1}, respectively (Figure 2.1). However, the on-farm tree densities varied from farm to farm with the perceived utilities of each tree species (Table 2.2-2.4). The density of Cordia was significantly higher on farms where farmers rated its direct use as timber, fencing material and firewood to be highly important ($P < 0.05$). Farmers who rated Cordia to be highly important for its timber, fencing and firewood values, respectively, were 27%, 24% and 10% more likely to maintain significantly higher density of Cordia on their farms compared with farmers who rated otherwise (Table 2.2).

Table 2.2 Summary of the result of a regression model showing the variation in on-farm density of *Cordia africana* (Cordia) as a result of its perceived utilization values. Probabilities with significant effects (P < 0.05) are indicated in bold.

Variables	Coefficients	Std. Error	F-values	P-values
(Intercept)	0.07	0.55	0.14	0.8930
Soil fertility maintenance	0.06	0.05	1.17	0.2514
Maize yield improvement	-0.18	0.05	-3.59	**0.0010**
Human and animal shade	-0.12	0.12	-1.01	0.3188
Timber production	0.27	0.06	4.38	**0.0001**
Cultural value	0.02	0.07	0.23	0.8226
Firewood production	0.10	0.05	2.07	**0.0454**
Fencing material	0.24	0.11	2.08	**0.0444**
Charcoal production	-0.02	0.05	-0.34	0.7335

On the other hand, farmers who perceived Cordia to have a negative impact on maize yield were 18% less likely to own and maintain this species on their farms comparted with farmers that perceived otherwise ($P < 0.01$).

The density of Croton was significantly higher (P<0.01) on farms where farmers perceived it was highly important as a source of firewood and fencing material (Table 2.3). From the coefficients in Table 2.3, the density of Croton was 30% more likely to be significantly high on farms where it was valued for its use as firewood production. Farmers who valued Croton for its use as a fencing material were 22% more likely to maintain significantly higher density of Croton on their farms.
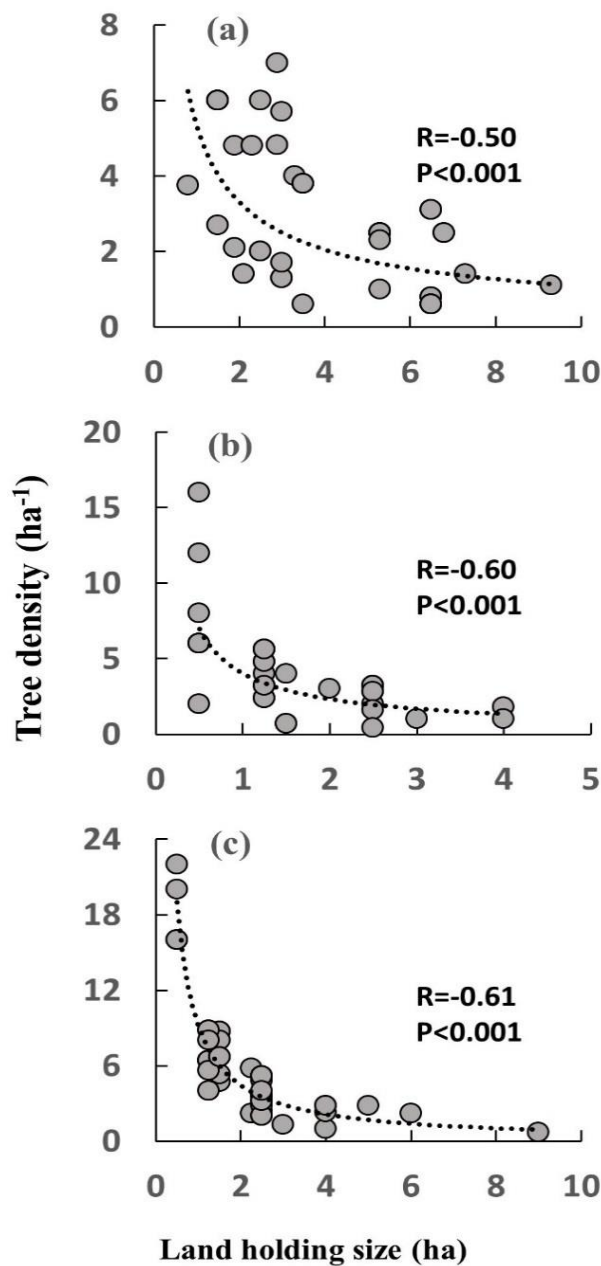

Figure 2.1 Relationship between households land holding size and the density for three on-farm tree species: *Cordia africana* (a), *Croton macrostachyus* (b) and *Acacia tortilis* (c).

Table 2.3 Summary of the result of a regression model showing the variation in on-farm density of *Croton macrostachyus* (Croton) as a result of its perceived utilization values. Probabilities with significant effects (P < 0.05) are indicated in bold.

Variables	Coefficients	Std. Error	F-values	P-values
(Intercept)	0.21	0.60	0.35	0.7332
Soil fertility maintenance	0.02	0.05	0.39	0.6997
Maize yield improvement	0.02	0.05	0.31	0.7568
Human and animal shade	0.12	0.10	1.17	0.2541
Timber production	-0.01	0.05	-0.24	0.8144
Cultural value	-0.24	0.16	-1.45	0.1596
Firewood production	0.30	0.10	3.10	**0.0049**
Fencing material	0.22	0.09	2.34	**0.0279**
Charcoal production	-0.03	0.06	-0.47	0.6443

The density of Acacia was significantly higher ($P < 0.01$) on farms where it was valued for shade provision, fencing material, firewood and charcoal production (Table 2.4). Farmers who valued Acacia for its use as human and animal shade, firewood production, fencing material and charcoal production, respectively, were 20%, 18%, 16% and 16% more likely to own significantly higher density of on-farm Acacia compared with farmers who rated otherwise (Table 2.4).

In addition to their utilities, incorporation of trees into crop fields appeared to be dictated by land size (Figure 2.1). Households who had less than 1.5 ha of land (the 1st quartile for Cordia-dominated site) owned an average of 6.8 Cordia trees ha^{-1}. This was in contrast with households that had farms larger than 3 ha (the 4th quartile for this site), who owned less than 2 trees ha^{-1} in average. Similarly, farmers with small land sizes (1st quartile for their land sizes) had higher densities of on-farm trees than farmers with large land sizes (4th quartile for their land sizes) for both Croton-dominated and Acacia-dominated sites (Figure 2.1).

Table 2.4 Summary of the result of a regression model showing the variation in on-farm density of *Acacia tortilis* (Acacia) as a result of its perceived utilization values. Probabilities with significant effects (P < 0.05) are indicated in bold.

Variables	Coefficients	Std. Error	F-values	P-values
(Intercept)	-1.30	0.22	-6.04	**0.0000**
Soil fertility maintenance	-0.03	0.03	-1.08	0.2858
Maize yield improvement	-0.02	0.03	-0.61	0.5461
Human and animal shade	0.20	0.05	3.74	**0.0007**
Soil moisture conservation	-0.02	0.03	-0.86	0.3959
Cultural value	-0.05	0.03	-1.46	0.1548
Firewood production	0.18	0.05	3.55	**0.0011**
Fencing material	0.16	0.06	2.49	**0.0180**
Charcoal production	0.16	0.06	2.92	**0.0062**

2.3.2. Consequences of on-farm trees on crop performance

Our results indicated that trees had a general negative effect on the total aboveground biomass and grain yields, both in sub-humid and semi-arid agroecologies (Figure 2.2). As indicated in Table 5, grain yield was significantly higher ($P < 0.01$) in the open field (average grain yield of 3289 kg ha^{-1}) than under tree canopies (average grain yield of 1795 kg ha^{-1}), regardless of the tree species. However, the model output in Table 5 showed that the interaction between tree species and treatment (i.e., presence or absence of trees) was highly significant ($P < 0.01$), highlighting species-specific effects of trees. For example, the reduction in mean grain yield was the highest for Cordia: 1683 kg ha^{-1} and 4063 kg ha^{-1} under and away from tree canopy, respectively, which was a 78.9% reduction. The second highest reduction in mean grain yield was for Croton: 1683kg ha^{-1} and 3414.9 kg ha^{-1} under and away from tree canopy, respectively, which was a 41.6% reduction. The presence of Acacia resulted in mean grain yield reduction

of 27.5% (i.e., an average grain yield of 1751.8 kg ha^{-1} under its canopy compared with the average grain yield of 2418.2 kg ha^{-1} in an open field).
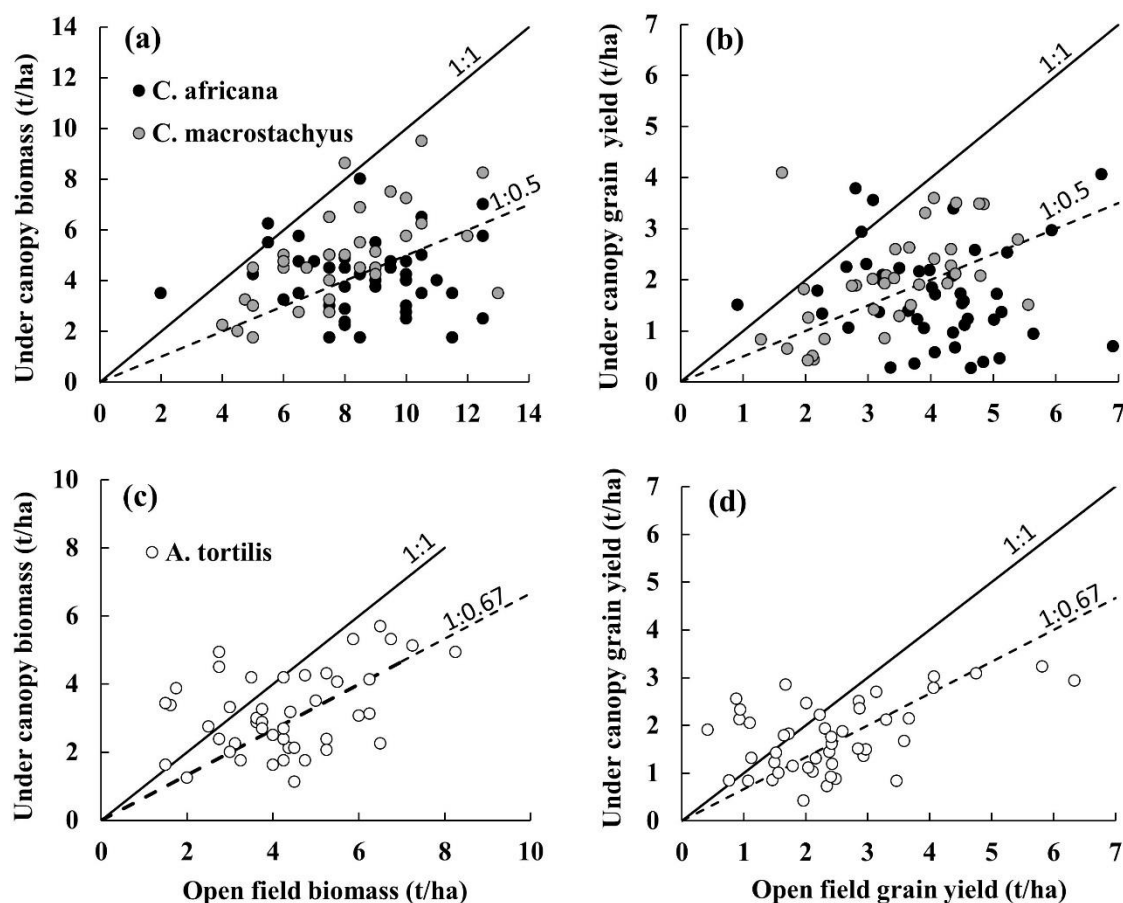

Figure 2.2 Comparison of total aboveground biomass (a) and grain yield (b) between open field and under canopy for *Cordia africana, Croton macrostachyus*, and total aboveground biomass (c) and grain yield (d) between open field and under canopy for *Acacia tortilis*. Solid lines represent the 1:1 relationship, while broken lines represent fitted values for maize yield in the open fields and under tree canopies.

2.3.3. Impact of agronomic management practices on tree-crop interaction

From Table 2.5, there was a highly significant interaction effect between treatment and date of maize planting (P < 0.01). Planting dates, which ranged from April 23 to June 21 in the study area, were categorized into early planting dates (earlier than the 3rd of May), medium planting dates (3rd to 11th of May) and late planting dates (later than May 11th) for analysis. Late planting

date (later than May 11th) resulted in the highest yield penalty (62% reduction) because of tree presence (least squared means of 3811 kg ha^{-1} and 1436 kg ha^{-1} for open field and under canopy grain yields, respectively). Planting earlier than the 3rd of May, resulted in a 46% yield reduction associated with the presence of trees (least squared means of 3611 kg ha^{-1} and 1942 kg ha^{-1} for open field and under canopy grain yields, respectively). A yield reduction of 26% due to presence of trees was observed for the planting window of 3rd-10th of May. However, this window of planting resulted in the lowest mean grain yield of all the planting periods for open field (least squared mean of 2668 kg ha^{-1}).

Table 2.5 Summary of the results of a GLMM model explaining the variability grain yield as a result of agronomic management for maize grown in open and under shades of different tree species (*Acacia tortilis*, *Croton macrostachyus*, and *Cordia africana)*. Treatment = presence or absence of trees, No. ploughing = number of ploughing for seedbed preparation, No. cultivation = number of maize cultivation, No. weeding = number of hand weeding operations, No. herbicide application = number of application of herbicide, and DAP = Diammonium Phosphate fertilizer. Probabilities of significant effects ($P < 0.05$) are indicated in bold.

Effects	DF	F-value	P-value
Treatment (tree or no tree)	1	199.3	**0.0000**
Tree species	2	17.9	**0.0000**
Rate of Urea	1	0.2	0.6780
Rate of DAP	1	0.6	0.4588
Rate of organic fertilizer	1	2.5	0.1177
Date of planting	2	2.4	0.0985
Type crop variety	8	23.2	0.0680
No. herbicide application	1	15.4	**0.0001**
No. cultivation	1	0.3	0.5907
No. ploughing	1	7.2	**0.0087**
No. weeding	1	4.8	**0.0306**
Species : Treatment	2	35.8	**0.0000**
Treatment : rate of urea	1	8.1	**0.0053**
Treatment : date of planting	2	7.1	**0.0013**
Treatment : type of crop variety	8	4.3	**0.0001**
Treatment : herbicide application	2	13.1	**0.0000**
Treatment : No. cultivation	1	15.3	**0.0002**
Treatment : No. ploughing	1	27.2	**0.0000**
Treatment : No. weeding	1	9.4	**0.0027**

The model in Table 2.5 also showed that there was a highly significant interaction effect ($P < 0.01$) between treatment and application rate of urea. At low rate of urea (0-50 kg ha^{-1} urea), both under canopy (least squared mean 1765 kg ha^{-1}) and open field (least squared mean 2809 kg ha^{-1}) grain yields were low. In this case, tree presence reduced yields by 37%, which was still significant ($P < 0.01$). For medium rate of urea (50-125 kg ha^{-1} urea), grain yield in the open field increased to 3990 kg ha^{-1}, while under canopy grain yield remained almost similar to the under canopy yield with low rate of urea (1785 kg ha^{-1}). This was a 55% reduction in maize grain yield under tree canopy compared with open field conditions. At higher rates of urea (125-200 kg ha^{-1} urea), under canopy grain yield (least squared mean 3440 kg ha^{-1}) was only 20% lower compared with open field grain yield (least squared mean 4341 kg ha^{-1}). From this result, there is an indication that maize grown under the canopy only responded to the highest rates of urea.

From the model results, the type of maize variety had a highly significant interaction effect with the presence or absence of trees ($P < 0.001$). High-yielding hybrid varieties such as BH-661 (76.7% reduction), BH-660 (74.1% reduction), BH-540 (69.5% reduction) and BH-543 (62.3% reduction) appeared to be the varieties most severely affected by tree presence. By contrast, varieties such as 'Shone' (29.5% reduction), 'Militia' (14.4% reduction) and 'Limmu' (1.7% higher under the canopies, i.e., almost no impact of tree presence) appeared to be affected less severely by tree presence.

Agronomic practices with a potential to suppress competition from weed and tree roots such as tillage frequency, herbicide application, repeated cultivation and weeding frequency had interacted positively with presence of trees ($P < 0.01$).

2.3.4. Partial economic trade-off for on-farm trees

2.3.4.1. Income from annual crops and tree products

Annual farm level income from maize decreased with an increase in tree density for all species (Figure 2.3 a, c and e). On the other hand, the discounted direct annual income from trees increased with tree density, although the magnitude varied with tree species (Figure 2.3 b, d and f). Direct income from Cordia was the highest (Figure 2.3 a) followed by Acacia (Figure 2.3 e). Croton generated the lowest direct annual income from tree products (Figure 2.3 c).
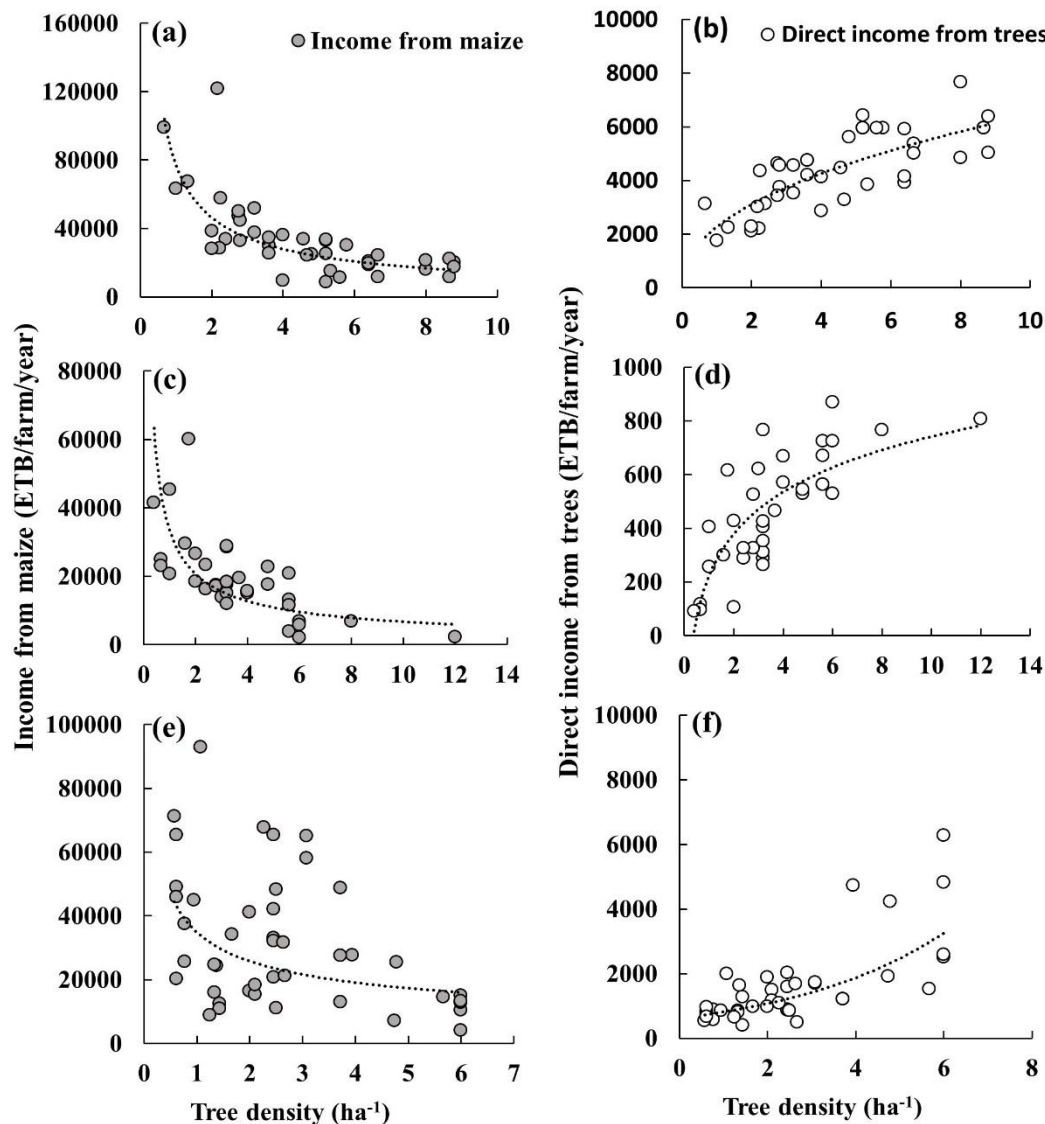

Figure 2.3 Relationship between total annual farm income from maize and on-farm tree density (a, c, e) and Net Present Values of annual direct income from tree products (b, d, f) for *Cordia africana* (a-b), *Croton macrostachyus* (c-d) and *Acacia tortilis* (e-f). Broken lines represent fitted curves. ETB = Ethiopian Birr (20ETB = 1USD, 2016).

As the proportion of income from trees increased, the income obtained from maize tended to decrease (Figure 2.4), with the trade-off curve concaving towards the origin.
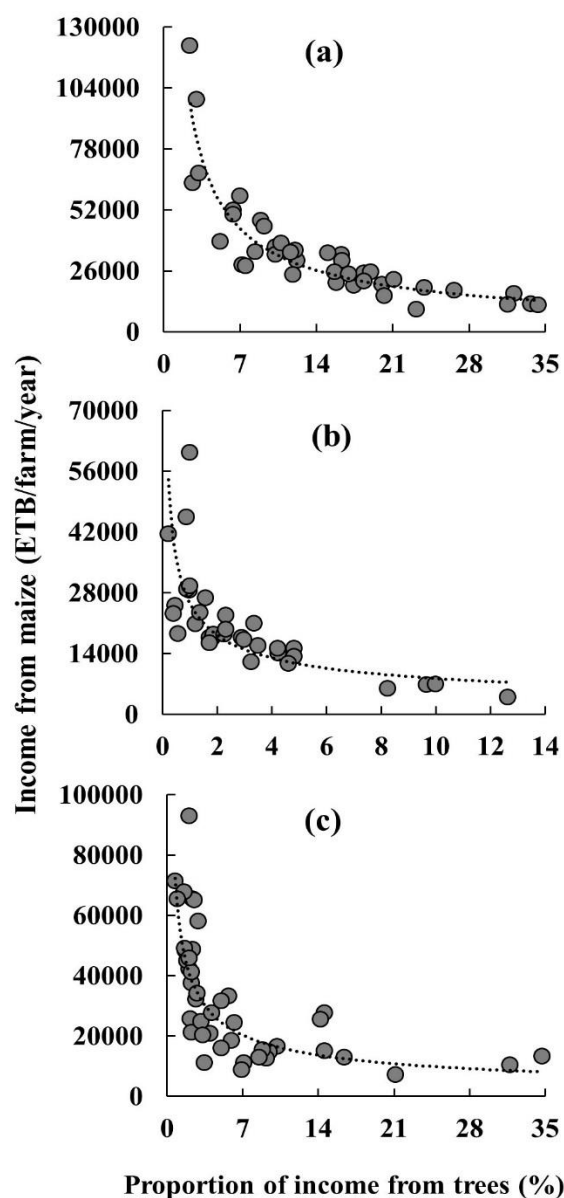

Figure 2.4 Relationship between proportional income from trees (as a percentage of combined income from maize and from trees) and income from maize for *Cordia africana* (a), *Croton macrostachyus* (b), and *Acacia tortilis* (c) based farming systems. The dotted lines represent the fitted points. ETB = Ethiopian Birr (20ETB = 1USD, 2016).

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

For Cordia (Figure 2.5 a) and Croton (Figure 2.5 b), direct income from tree products was inversely correlated to the opportunity cost associated with trees. The relationship between direct income from trees and associated opportunity cost appeared to be linear for Acacia

(Figure 2.5 c). Close to 3000 ETB (~130 USD) year[-1] from Cordia, 1000 (~45 USD) ETB year[-1] from Acacia and 300 (~13 USD) ETB year[-1] from Croton can be obtained without causing significant trade-off with maize yield at farm level. Any combination beyond the vertical line for income earned from trees was dominated by negative trade-offs (Figure 2.5).
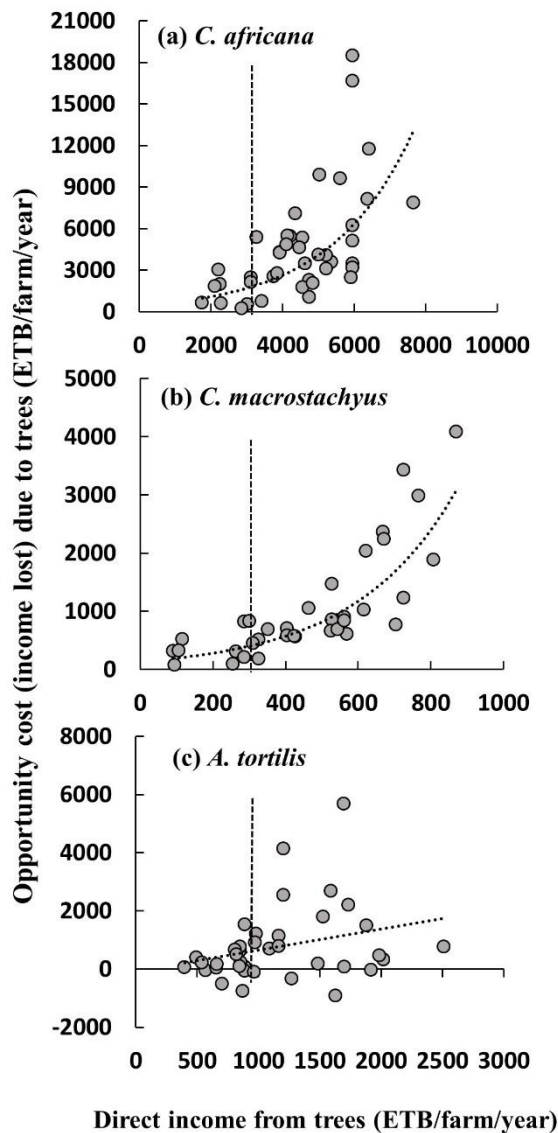

Figure 2.5 Relationship between direct income from trees and tree-related opportunity cost for tree species *Cordia africana* (a), *Croton macrostachyus* (b), and *Acacia tortilis* (c). The vertical broken line represents the level of direct income derived from trees at no significant opportunity cost as a result of trees. The dotted line represents the fitted points. ETB = an Ethiopian currency (20ETB = 1USD, 2015).

2.4. Discussions

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

In general, the current study highlighted that on-farm trees reduced maize yield (Figure 2.2). However, farmers still maintained trees on their farms apparently because of their income

generation values (Tables 2.2-2.3). A previous work on tailoring agroforestry technologies to the diversity of smallholder agriculture reported that compatibility with crops was one of the criteria used to select tree species incorporated in the farms (Bucagu *et al.*, 2013). The current result, however, suggested that on-farm trees are not solely maintained because of their compatibility with annual crops. We found they were generally kept for their direct utilization values such as timber, firewood, charcoal and fencing material. However, it is important to underline that most of these utilities are not substitutable through local market mechanisms. Traditionally, the income generation services of trees inclined towards tree products that can be traded beyond local levels in the form of products that are normally used as industrial inputs (Alavalapati *et al.*, 2004; Gustad *et al.*, 2004). Our results, in addition, hinted that locally traded tree products such as fencing material and firewood may motivate smallholder farmers to practice mixed tree-crop systems. Den Biggelaar and Gold (1996) similarly reported that integration of trees into farms was highly dependent on utilization flexibility of the trees rather than on their direct economic contribution. In addition to their contribution in income generation, on-farm trees reduce labour drudgery on women and girls by providing onsite source of fuelwood (Leakey, 2012; Zimmerer *et al.*, 2015).

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

Although tree-induced trade-offs were pervasive in the system under study, on-farm trees still dominate the smallholder agricultural landscapes. The trend remained the same even under situations where tree-based utilities apparently led to inferior returns in cash equivalents compared with returns from sole annual crops. This could suggest that the main objectives of poor rural households, especially under remote locations where markets are imperfect, may not necessarily follow economic rationale and optimization behaviour (Klapwijk *et al.*, 2014).

Under the current study setting, where smallholders are constrained by various institutional and environmental factors (Stahl, 1990; Gebreselassie, 2006), these trees could provide a mechanism against volatility in grain prices, which is a common characteristic of many countries in SSA (Minot, 2014). Furthermore, on-farm trees provide households with income 'safety net' and are used as relatively stable source of household income when annual crops fail (Cadisch *et al.*, 2004). Although small compared with income from annual crops, income from on-farm trees could provide a diversified income option. Such rationale, whereby smallholders managed risk through the practice of economies of scope (i.e., preference of small but low risk incomes over higher, but more risky incomes) rather than economies of scale that could be achieved through specialization, were also reported from elsewhere (Chavas and Di Falco, 2012).

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

Tree-based systems could be preferred for income diversification and other ecosystem services such as regulating and amenity values, regardless of their significant trade-off with the

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

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

Our results have clearly indicated that the impact of on-farm trees on maize yield was extremely variable from farm to farm (Figure 2.2). Results presented in Table 5 highlighted that much of the yield variability can be explained by differences in crop management (Table 2.5). Although results from one season data may not be conclusive enough, the current finding highlighted the possibility of reducing trade-offs from tree-crop interactions through the application of particular agronomic practices. For example, change in rate of urea from low (0 - 50 kg ha^{-1} urea) to medium (50 - 125 kg ha^{-1} urea) under tree canopies did not result in yield gain (only a marginal increase in maize grain yield of 1%). Change in rates of urea from medium to high (125-200 kg ha^{-1} urea) was accompanied by a 93% increase in under canopy maize grain yield. On the other hand, change in rates of urea from low to medium was accompanied by a 42% increase in maize grain yield for open field. For maize in the open field, change in the rate of urea from medium to high was, however, accompanied by only a marginal increase of about 10% in maize grain yield. This indicates that the response of maize grain yield to changes in rates of urea is different for maize grown under tree canopy and in the open field. These results suggest that nitrogen rates that are currently recommended for open field conditions are sub-optimal for tree-crop systems. This is not surprising, as the current recommendations for maize production were made based on optimum open field conditions. However, results could be

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

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

2.4.4. Segregate or integrate trees into crop fields?

One of the intensely debated issues in agricultural production systems has been whether it is possible to meet the growing demand for agricultural products without compromising other ecosystem services. Whether to integrate or segregate trees and crops has been hotly contested (Fischer *et al.*, 2008; Phalan *et al.*, 2011; van Noordwijk *et al.*, 2012; Ekroos *et al.*, 2016). The general negative impact of on-farm trees on maize grain yield from the current study may point towards a recommendation to 'segregate'(Lefroy and Hobbs, 1998), whereas the stable income and diverse utilities received from these trees may lead to propose to 'integrate' (Primdahl, 1990) trees and crops. In figure 2.4, the trade-off curve between income from maize and the proportional income earned from trees concaves towards the origin. According to van Noordwijk et al (1995), multifunctional solutions that lead to potentially efficient interactions

rather display convex trade-off curves between "relative agronomic functionality", i.e., functionalities from annual crops and "relative ecological functionality", i.e., functionalities from on-farm trees. This implies that the current system would be better-off with segregation and simplification rather than integration (van Noordwijk et al., 2012). On the other hand, segregation may aggregate perennial trees over small area and reduce the overall benefit from trees because of intraspecific competition (Pulido *et al.*, 2001). As hinted in section 4.3 above, farm/crop management may modify the concave shape of the trade-off curve, stretching it towards a linear and eventually convex shape, leading to synergies between tree and crop. The findings from our study, which suggested such a possibility where crop management practices minimize tree-crop trade-offs, could be utilized to create an integrated system of 'eco-agricultural landscapes', which is described by Scherr and McNeely (2008) and Cunningham *et al.* (2013).

2.5. Conclusions

Although our analysis included only the direct tree-based economic benefits, the current results have indicated that economic gains from trees were not large enough to compensate for tree-induced crop yield penalties in tree-crop mixed farming systems. Farmers still maintained trees on their farms possibly because of three main reasons. First, direct benefits of trees in the form of timber, fuelwood, charcoal and fencing materials cannot be substituted through current local market mechanisms. Second, on-farm trees offer stable and diversified sources of household income, unlike annual crops that frequently fail or undergo price fluctuations. Third, under the ever diminishing per capita land size, farmers maintain on-farm trees by integrating agronomic practices that minimize trade-offs from tree-crop interactions. As these trees were proved to enhance the overall productivity of a system through other ecosystem services, the possibility of using certain agronomic practices to minimize tree-crop trade-offs appears as an important area to explore further. The current results also underlined that crop breeding and agronomic

research may need to account for the needs of smallholders, where natural within field heterogeneity is probably intensified by presence of trees. On the other hand, a comprehensive analysis that includes the quantification of non-income values of on-farm trees (such as regulation and cultural ecosystem services) would probably lead to less pronounced trade-offs. Future research that explores optimum fertilization, tillage frequency and planting dates under tree-crop integrated systems may improve our understanding.

Acknowledgements

Fertilization options to reduce tree-crop competition for selected agroforestry systems in Eastern Africa

Chapter 3

Abstract

Agroforestry has been suggested an entry point for sustainable intensification of smallholder farming systems in sub-Saharan Africa (SSA), where insufficient nutrient input is one of the major causes for low crop yields. Although tree-crop systems generate benefits such as timber and energy, crop yield penalties are common. We hypothesized that facilitative and competitive interactions are affected by the use of mineral fertilizers in tree-crop systems. Tree-crop-fertilizer interactions were explored for wheat growing under *Faidherbia albida,* maize growing under *Acacia tortilis* and *Grevillea robusta* through omission trials of Nitrogen (N) and phosphorus (P) in open field and in under canopy plots, using a split plot design. Treatments were replicated four times and over two seasons. Our results demonstrate that presence of *Faidherbia* significantly improved N and P use efficiencies, leading to significantly higher (*P < 0.001*) yields in wheat. This tree species apparently contributed mineral N in the magnitude of 64 kg ha^{-1} yr^{-1}. In addition, the P use efficiency of wheat under *F. albida* was double that of open field wheat. Although application of no fertilizer, P alone, N alone and combined N-P fertilizers resulted in significantly progressive increase (*P < 0.001*) in maize yield under the canopy of both *Grevillea* and *Acacia*, these trees generally lowered maize nutrient use efficiencies, leading to significantly smaller (*P < 0.001*) maize yields compared with open field maize receiving the same fertilization . Probabilities of critically low crop yields and complete failures were significantly larger (*P < 0.001*) for maize growing under the canopy of these species than in open field conditions. Our results showed that current rates of fertilization did not result in positive gains for *Grevillea* and *Acacia*, while it enhanced facilitation in *Faidherbia*-wheat systems. However, there is an evidence that higher fertilizer rates had minimized competition in the former two species.

3.1. Introduction

In many smallholder farming systems of sub-Saharan Africa (SSA), loss of soil fertility is a major limitation to crop production (Rockström *et al.*, 2009). Insufficient nutrient input is one of the major causes for low crop yields (Vanlauwe *et al.*, 2011), fuelling vicious cycle of poverty and low productivity in the region. The problem is compounded by the limited resources for farmers to use mineral fertilizers (Sileshi *et al.*, 2009; Yirga and Hassan, 2010). Even where farmers apply usually small amount of inorganic fertilizers, soils in many parts of the tropics are non-responsive (Vanlauwe *et al.*, 2011). About 30% of soils in SSA are non-responsive due to loss of biological functions, undermining immediate gains from application of mineral fertilizers (Tittonell and Giller, 2013). In the past, expanding crop production to new lands was a common practice. Increased production through expansion to new fragile land is not sustainable, while further increase in fertilizer purchase puts extra pressure on household income. An alternative intensification model that conserves natural resources and is affordable to smallholders is required. From the large basket of sustainable intensification options, the use of agroforestry trees has been suggested as viable for SSA (Lahmar *et al.*, 2012).

In addition to improving soil nutrients through direct input by atmospheric nitrogen (N) fixation (Giller, 2001), agroforestry trees may improve soil fertility by increasing soil organic matter (Teklay *et al.*, 2006; Gnankambary *et al.*, 2008). Organic resources accumulating from decomposing plant parts play a critical role in both short-term nutrient availability and longer-term maintenance of soil productivity in most smallholder farming systems in the tropics (Sanchez *et al.*, 1997; Palm *et al.*, 2001). Organic inputs from *Gliricidia sepium*, for example, resulted in higher N and phosphorus (P) uptakes by maize in Malawi (Akinnifesi *et al.*, 2007). As these trees also compete with crops for soil resources (Bertomeu *et al.*, 2011), understanding the interactions between on-farm trees and mineral fertilizer can provide a useful insight in

managing tree-crop interactions (positive or negative) in agroforestry systems. Thus, we hypothesized that facilitative and competitive interactions are affected by the use of mineral fertilizers in tree-crop systems. In addition, these tree-crop interactions could vary depending on agroecology, tree species and crop species.

Most studies conducted so far to improve tree-crop interactions have focused on tree management practices, in particular, root and canopy pruning (Jackson *et al.*, 2000). On the other hand, studies exploring the impact of combining trees with mineral fertilizers on crop performance have been scarce. Because on-farm trees create a modified microenvironment leading to heterogeneous soil fertility gradients within fields, targeted application of inorganic fertilizer with trees may provide a starting point for sustainable intensification of smallholder farming systems. Thus, the current study aimed to (i) understand the impact of different combinations of N and P fertilizers on tree-crop interactions and (ii) evaluate mineral fertilizer-tree combinations that maximize agronomic nutrient use efficiencies (AE) for different agroecologies, tree species and crop species.

3.2. Materials and methods

3.2.1. Site description

This study was conducted in two countries, Ethiopia and Rwanda, under three different agroecologies, where retaining scattered trees in crop fields have been practiced for centuries. Meki is located in the Central Rift Valley of Ethiopia (8.1855º N and 38.86º E) at an elevation of 1,500 m above mean sea level (a.m.s.l), and is characterized by a semi-arid climate. The annual average temperature is 19.3ºC with an average annual rainfall of 775 mm. The area is dominated by savannah woodland vegetation type, where the retention of scattered trees during conversion to agriculture created agroforestry parklands. Although, the farming systems are characterised by diversity of crops in rotation, maize (*Zea mays*), bean (*Phaseolus vulgaris*)

and sorghum (*Sorghum bicolor*) are the most dominant crops. Maize with *Acacia tortilis* represents the most dominant agroforestry practice in this area, and was thus, selected for our investigation in this area.
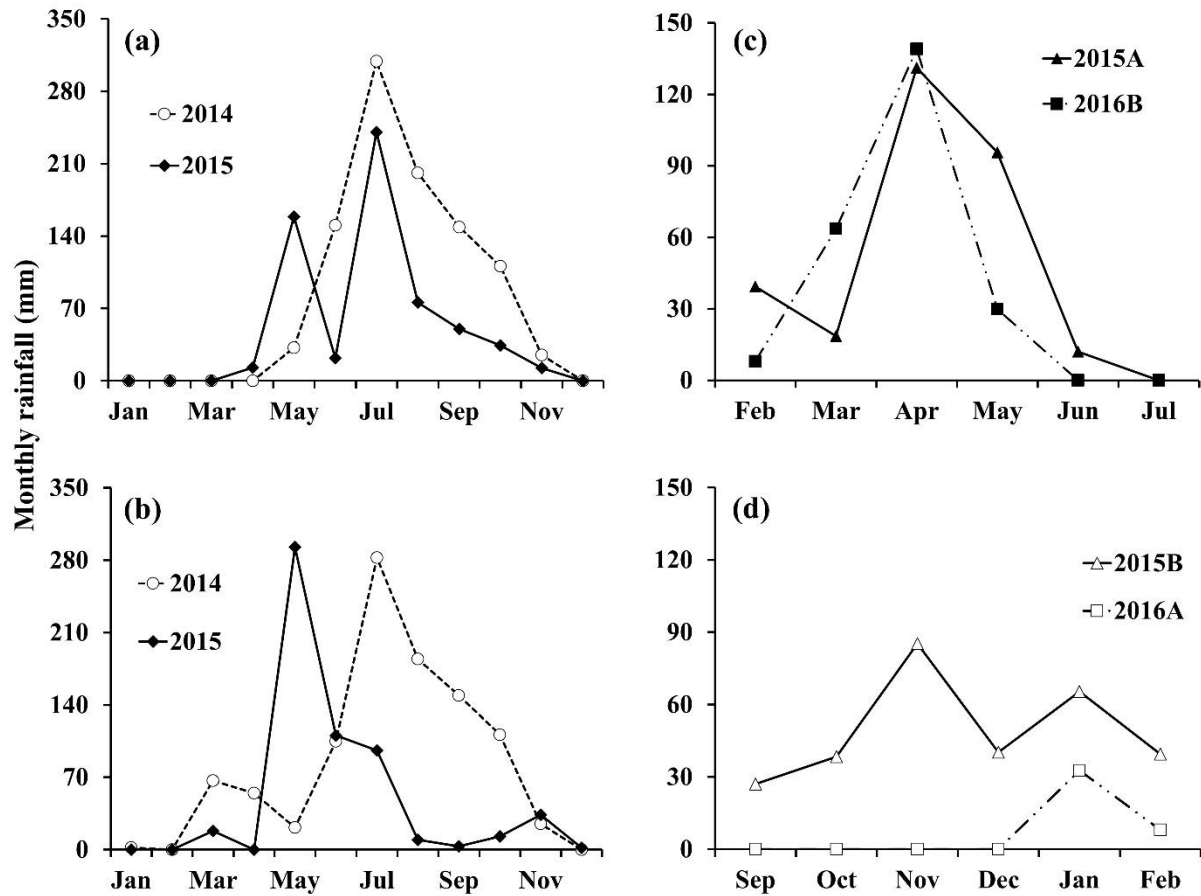
Figure 3.1 Inter-seasonal variabilities in rainfall in Meki (a) and Mojo (b) in Ethiopia and Bugesera (c-d) in Rwanda. The experiment was carried out for two seasons in Ethiopia, 2014 and 2015, while it was extended over four seasons in Rwanda, 2015A, 2015B, 2016A and 2016B. Season A runs from October - January and season B from March - June.

Mojo (8.509° N and 39.071° E) is also located in the Central Rift Valley of Ethiopia to the Northeast of Meki at an elevation of 1665 m a.m.s.l. The climate is semi-arid with average annual rainfall of 700 mm yr^{-1} falling mainly between June and October. The long term mean daily temperature is 24.2°C and the mean maximum daily temperature is 31°C. Temperature may peak above 35°C. Andosol is the dominant soil type (RSO, 2003), characterized by poor

water holding capacity. Sparsely distributed *F. albida* is the main agroforestry species to which wheat (*Triticum aestivum var aestivum*) and *teff* (*Eragrostis tef)* are integrated in the area.

A similar study was conducted in Bugesera, Rwanda (2.354° S and 30.265° E), at an elevation of 1397 m. The area is located on a large plateau culminating at an altitude range of 1,300-1,500 m and is dominated by a semiarid climate, characterized by bimodal rainfall with primary and secondary peaks in April and November, respectively. A short dry season - from January to mid-march – is followed by a long rainy season – from mid-march to June. A long dry season – from mid-June to September is followed by a short rainy season – from mid-October to December. The annual rainfall ranges from 850 to 1,000 mm. This area has a dry season lasting for three months and an average temperature of 21 °C (Verdoodt and Van Ranst, 2003). Some of the dominant agroforestry tree species include *Grevillea robusta*, *Senna spectabilis* and *Euphorbia spp*. Soils at Bugesera are humic and haplic Ferralsols with depth ranging from 100-200 cm. In Bugesera, the current study explored interactions between *Grevillea robusta* and maize under different types of inorganic fertilizer.

The three sites displayed variation in rainfall amount and distribution during the periods of observation (Figure 3.1).

3.2.2. Tree selection and experimental setup

Tree-crop-fertilizer interaction was explored for wheat growing under crowns of *Faidherbia albida* (Mojo, Ethiopia), maize growing under *Acacia tortilis* (Meki, Ethiopia) and *Grevillea robusta* (Bugesera, Rwanda). To simplify reporting, we used genus names, *Faidherbia, Acacia* and *Grevillea* in the rest of the paper when referring for to *Faidherbia albida, Acacia tortilis* and *Grevillea robusta*, respectively. For each species, selected trees were located in a single field within a farm, and had approximately similar ages, crown structures, and pruning history.

Plots measuring 10 x 10 m were established around each tree, with the tree at the centre. Within the same field, another plot of the same size was established in an open field, at least 40 m away from any tree. Each of these plots (under tree canopy and the open field conditions) was split into four sub-plots, measuring 2 x 2 m. The 10 x 10 m plots were considered as main plots, while fertilization was a sub-plot factor. Inorganic fertilizers were applied as treatments to the sub-plots such that: no fertilizer (Z), P only, N only and combined P and Nfertilizers (N-P) was applied for both open field and under canopy plots (Figure 3.2). The fertilizer treatments were randomly allocated within the main plots. In Ethiopia, this setting was replicated in four farms and repeated over two seasons. In Rwanda, the experiment was replicated in three farms and repeated over four seasons.
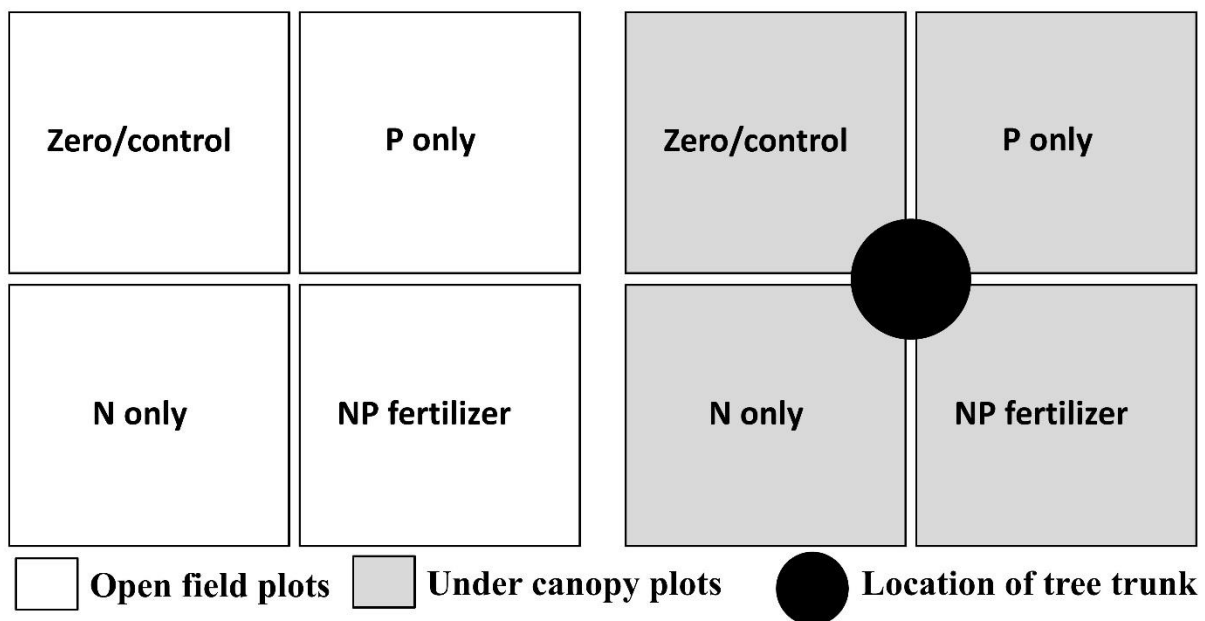
Figure 3.2 Field layout for fertilizer-tree combinations. Zero/control, P only, N only and NP fertilizer represents no fertilization, 30 kg ha^{-1} P, 64 kg ha^{-1} N, and 30 kg ha^{-1} P with 64 kg ha^{-1} N fertilization rates, respectively.

Trees were managed following farmers' typical practices and plots were managed following recommended practices. Wheat variety 'Kilinto', maize varieties 'Melkasa-2 and PAN4M21, which were well-adapted to the respective environmental conditions, were used in Mojo, Meki

and Bugesera, respectively. Plots where N was used as a treatment were fertilized with 64 kg

ha^{-1} N (split applied 50% at sowing and the remaining side dressed six weeks after planting).

In plots where P was used as treatment, 30 kg ha^{-1} P was broadcasted at sowing. For wheat in

Mojo, seed was drilled at a spacing of 20 cm between rows at the rate of 150 kg ha^{-1}. For maize

in Meki and Bugesera, a recommended spacing of 70 cm between rows and 30 cm between

plants was used. All plots were kept weed free.

3.2.3. Data collection

Crop growth and development data were collected at two weeks interval starting 30 days after

planting. At harvest, both fresh and dry biomass and grain yield were estimated on fresh and

dry matter basis. Dry matter contents were estimated by collecting fresh subsamples and drying

them at 65°C for 48 hours.

3.2.4. Data analysis

Because our data were generated from contrasting seasons and agroecologies, we made

comparisons of treatment effects for each site separately. We used split plot ANOVA for mean

separation in R (R Core Team, 2015). In the model (Equation 3.1), treatment (i.e. under canopy

vs open field) and season were considered main plot factors, while fertilization was treated as

a sub-plot factor.

$$Y_{ijk} = \alpha + \beta TR_i + \gamma FR_j + \lambda SS_k + \tau(TR_i * FR_j) + \delta(TR_i * SS_k) + \mu(FR_i * SS_k)$$
$$+ \varepsilon \tag{3.1}$$

where, Y_{ijk} represents maize or wheat grain yield, TR_i is the ith treatment (i.e., under tree canopy

or in open field), FR_j is the jth type of fertilizer, SS_k is the kth season and ε is the residual and

where, α, β, γ, λ, τ, δ and μ represent regression coefficients for the main and interaction effects.

The effect 'season' was used as a grouping variable and was added as a fixed effect in the main

model. Farms were treated as replications in the model. Interactions and main effects that had

little explanatory power, i.e., variables with *F*-values of less than 0.1, were removed. Statistical analysis was performed with square-root-transformed values for maize biomass yield from Meki to follow normal distribution. For Bugesera, the grain yield did not satisfy the normality assumption with any of the common transformations and, thus, Poisson distribution was used in the model. Where data were transformed, mean comparison was made on a back-transformed least squared mean, i.e. on the mean that was adjusted for other factors.

In addition to causing variations in yield, the treatments are likely to be associated to crop failures or extremely low yields. The probabilities of crop failure and low yields were computed using equations 3.2 and 3.3.

$$P_0 = \left(\frac{Y_0}{Y_t}\right) \tag{3.2}$$

Where, P_0 is the proportion of plots characterized by crop failure for a given treatment, Y_0 is number of plots with yield failure (i.e. plots yielding no grain harvest at all) and Y_t is the total number of plots in the whole experiment.

$$P_i = \left(\frac{Y_i}{Y_t}\right) \tag{3.3}$$

Where, P_i is proportion of plots characterized critically low crop yield under a given treatment, Y_i is total number of plots with critically low crop yield and Y_t is the number of plots in the whole experiment. All yields that were two standard deviations lower than the long term mean grain yield were considered critically low.

We also computed agronomic nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) for under canopy and open field treatments using equation 3.4 and 3.5, respectively (Vanlauwe *et al.*, 2011). This was mainly because we hypothesized that the possible increase in organic matter content under the canopies of trees may improve nutrient use efficiencies in agroforestry.

$$NUE = \left(\frac{Y_N - Y_C}{F_{APN}}\right) \qquad\qquad (3.4)$$

where, **NUE** represents agronomic use efficiency for nitrogen (kg/kg), Y_N represents grain yield (kg ha^{-1}) from treatments where nitrogen fertilizer was applied, Y_C represents grain yield from the control (open field treatments where no fertilizer was used [kg ha^{-1}]) and F_{APN} represents the amount of nitrogen fertilizer applied as a treatment (kg ha^{-1}).

$$PUE = \left(\frac{Y_P - Y_C}{F_{APP}}\right) \qquad\qquad (3.5)$$

Where, **PUE** represents agronomic use efficiency for phosphorus (kg/kg), Y_P represents grain yield from treatments where phosphorus fertilizer was applied (kg ha^{-1}), Y_C represents grain yield from the control (open field treatments where no fertilizer was used [kg ha^{-1}]) and F_{APP} represents the amount of phosphorus fertilizer applied in the treatment (kg ha^{-1}).

3.3. Results

3.3.1. Effects on N-P fertilizer combinations on crop yield in tree-crop systems

3.3.1.1. Effect of N-P fertilizers on wheat yield in Faidherbia-wheat systems

Presence of *Faidherbia* trees, fertilizer application and season showed a statically significant main effect ($P < 0.05$) on wheat grain yield in Mojo (Table 3.1). Mean wheat yield was significantly higher under tree canopies than in open fields and during relatively wet year (2014) compared with relatively dry year (2015). However, the type of N-P fertilizer used had a statistically significant interaction effect with both the presence of *Faidherbia* trees ($P < 0.001$) and the season ($P < 0.05$).

In the relatively wet season 2014, mean separation analysis in Table 3.2 showed that under canopy grain yield was significantly higher ($P < 0.001$) than grain yield from the open field, when both treatments did not receive any fertilizer. Application of P only to wheat under canopy produced significantly larger ($P < 0.001$) grain yield than any open field treatments, except the

combined N-P application. For example, application of P only to under canopy wheat resulted in twice as much grain yield as wheat in open field plots receiving the same fertilization.

Table 3.1 Summary of the results of GLMM models for explaining the effect of N-P fertilizers in combination with on-farm agroforestry species on wheat (*F. albida* in Ethiopia) and maize yields (*A. tortilis* in Ethiopia and *G. robusta* in Rwanda).

Tree sppecies	Effects	Df	F-value	P-value
F. albida				
	Treatment (tree)	1	46.9	**0.0000**
	Fertilizer	3	19.6	**0.0000**
	Season	1	4.9	**0.0317**
	Treatment : fertilizer	3	8.7	**0.0001**
	Treatment : season	1	4.2	**0.0469**
	Fertilizer : season	3	1.6	0.1981
A. tortilis[1]				
	Treatment (tree)	1	11.8	**0.0016**
	Fertilizer	3	0.8	0.4926
	Season	1	109.8	**0.0000**
	Treatment : fertilizer	3	0.3	0.8544
	Treatment : season	1	0.6	0.4276
	Fertilizer : season	3	0.4	0.7550
G. robusta				
	Treatment (tree)	1	8693.8	**0.0268**
	Fertilizer	3	1887.0	**0.0000**
	Season	3	8114.7	**0.0000**
	Treatment : fertilizer	3	801.5	**0.0015**
	Treatment : season	3	370.6	**0.0002**
	Fertilizer : season	9	78.5	**0.0000**

[1]For *A. tortilis* statistical analysis was conducted with aboveground biomass, not grain yield

The N only treatment resulted in comparable wheat grain yield in open field and under canopy treatments, indicating that N fertilization of wheat under canopy did lead to yield gain, commensurate with P fertilization. Combined application of N and P resulted in significantly larger ($P < 0.001$) grain yield for wheat under canopy of *Faidherbia* compared with wheat in open field conditions. The combined N-P treatment under canopy produced significantly larger

yield than any other treatments, whether in open field or under canopy conditions. The exception was the under canopy wheat that received P only fertilizer, which produced a comparable wheat yield with combined N-P fertilizer applied to under canopy plots. Open field wheat did not respond to application of P only fertilizer, resulting in yields that were comparable with the control (Zero) treatment (Table 3.2) and significantly smaller than wheat under canopy receiving no fertilization (Zero).

Table 3.2 Mean comparison for wheat grain yield [mean (sd)] as affected by combinations of N-P fertilizers under and outside the canopies of *F. albida* in 2014 and 2015 in Mojo, Ethiopia.

Canopy	Fertilizer	Wheat grain yield (kg ha^{-1})	
		Season 2014	Season 2015
Open field			
	Zero	1090 (225)^a	718 (127)^a
	Only P	1078 (179)^a	1020 (108)^a
	Only N	1829 (177)^b	1717 (135)^b
	Combined NP	2267 (133)^c	1993 (77)^b
Under canopy			
	Zero	1496 (148)^d	1370 (313)^c
	Only P	2493 (408)^{ce}	2482 (191)^d
	Only N	1716 (157)^b	1865 (283)^b
	Combined NP	2585 (203)^e	2502 (71)^d
	LSD (kg ha^{-1})	226.6	303.7
	CV (%)	12.1	19.0

Means followed by similar letters within a column are not significantly different at the 5% probability level.

While most of the above trends remained similar in the relatively dry season of 2015 (Table 3.2), open field treatments that did not receive any fertilization (control) resulted in the lowest wheat yield of all treatments during that year. Unlike the relatively wet year, open field wheat yield under combined N and P fertilizers application was significantly less compared with under

canopy wheat that received P only. Wheat that received N only produced comparable yields, regardless of tree canopy and season. Interestingly, under canopy wheat responded similarly to all fertilizer applications both during relatively wet and relatively dry seasons.

3.3.1.2. Effect of N-P fertilizers on maize yield in Acacia-maize systems

For *Acacia* trees in Meki (Table 3.1), presence of trees caused smaller maize yields compared with maize yields in open fields ($P < 0.001$). In addition, biomass yield (analysis for inter-seasonal variation was limited to biomass only, because we did not have grain yield for 2015 season due to crop failure) showed a statistically significant difference ($P < 0.001$) between relatively wet and relatively dry years.

In 2014, which was a relatively wet season, mean maize grain yield in the open field was significantly ($P < 0.05$) larger than maize grain yield under the canopy of *Acacia*, regardless of the N and P treatment used. Similarly, open field treatments resulted in larger maize biomass than under canopy maize, regardless of the type of fertilization used in 2015, which was an El Niño year. However, mean biomass for corresponding fertilizer treatments were significantly lower for 2015 compared with 2014 ($P < 0.001$).

In 2014 (Table 3.3), maize grain yield was generally larger in the open field than under canopy conditions. However, there was no statistically significant difference in grain yield between open field and under canopy plots with no fertilization (Zero). In addition, none of the fertilizer treatments showed significant effect for under canopy conditions. Conversely, N alone and combined N-P applications to the open fields resulted in significantly more yields compared with the open field control (Zero), under canopy control (Zero), under canopy P alone, under canopy N alone and combined under canopy N-P. Furthermore, N only and combined N-P fertilizers applied to under canopy plots resulted in maize grain yields that were only comparable to open field plots without any fertilization. Application of P only to open field

produced similar grain yields with under canopy maize. Under canopy maize that received P only, resulted in significantly more yields than under canopy plots that did not receive any fertilization. All the other fertilizer treatments in under canopy plots showed comparable yields.

Table 3.3 Mean comparison for yield [mean (se)] as affected by combinations of N-P fertilizers under and outside the canopies of *A. tortilis* in 2014 (grain yield) and 2015 (stover) in Meki, Ethiopia.

Canopy	Fertilizer	Yield (kg ha^{-1})	
		Season 2014	Season 2015*
Open field			
	Zero	2076 (421)^{ac}	1656 (126)^a
	Only P	2802 (644)^{bc}	1844 (632)^a
	Only N	3170 (502)^b	2479 (201)^b
	Combined NP	3465 (555)^b	3854 (545)^c
Under canopy			
	Zero	1518 (201)^d	1146 (112)^a
	Only P	2386 (460)^{ac}	1354 (339)^a
	Only N	1951 (307)^{ac}	1396 (229)^a
	Combined NP	2102 (192)^{ac}	1563 (222)^a
	LSD (kg ha^{-1})	710.0	771.2
	CV (%)	31.2	39.0

Means followed by similar letters within a column are not significantly different at the 5% probability level.

* In 2015 maize failed because of El Niño and only the maize stover was analyzed

Although the trend for biomass production in 2015 was generally similar to 2014, none of the under canopy plots responded to fertilizer applications in 2015 (Table 3.3). All under canopy treatments that received fertilizers showed comparable biomass yields to open field plots treated with no fertilizer (Zero) and P only fertilizer. Application of N only and combined N-P fertilizer to the open field showed significantly larger biomass yields than all of the other open field and under canopy treatments.

3.3.1.3. Effect of N-P fertilizers on maize yield in Grevillea-maize systems

For *Grevillea* in Bugesera (Table 3.1), presence of trees, fertilizer application and season showed a statically significant main effect ($P < 0.05$) on maize grain yield. Presence of *Grevillea* trees significantly reduced maize grain yield ($P < 0.05$), regardless of the fertilization used. In addition, season and the type of N-P fertilizer used had statistically significant effects ($P < 0.001$) on maize grain yield. The interaction effects between fertilizer and treatment (presence of *Grevillea* trees), season and treatment, and fertilizer and season were all statistically significant ($P < 0.001$).

During relatively wet seasons of 2015A and 2016B, different combination of N and P fertilizers had a similar general effect on maize yields in *Grevillea*-maize systems (Table 3.3). All under canopy treatments resulted in significantly ($P < 0.001$) lower maize yield compared with any of the treatments in the open fields. The only exception during these years was under canopy maize that received combined N-P fertilizers, which was the highest yielding among all under canopy treatments. It resulted in comparable (only 5.4% lower) maize yield with open field maize that did not receive any fertilization (Zero).Compared with open field maize where no fertilizer was applied, the presence of *Grevillea* trees resulted in 75.7%, 61% and 50% reduction in grain yield for no fertilizer, P only and N only fertilizer uses, respectively. For open fields, separate application of either N or P fertilizers resulted in comparable maize yields. By contrast, application of N only resulted in significantly more maize yield than application of P only to under canopy.

In seasons 2015A and 2016B, which had very low rainfall (Figure 3.1), under canopy and open field maize grain yields with fertilizer application were generally similar with that in 2015B and 2016A (Table 3.4). Under the canopy of *Grevillea,* all treatments resulted in extremely low grain yields of 127.4 kg ha^{-1}, 185.5 kg ha^{-1} and 344.7 kg ha^{-1} for P only, N only and N and P

applications, respectively. While this increase was statistically significant ($P < 0.001$), all under canopy treatments produced significantly lower maize grain yield compared with even the lowest yield in open field condition, which was recorded from a treatment that received N only. For 2016A, maize under the canopy of *Grevillea* that did not receive any fertilizer failed completely.

Table 3.4 Mean comparison for maize grain yield [log-mean (se)] as affected by combinations of N-P fertilizers under and outside the canopies of *G. robusta* in the seasons of 2015A, 2015B, 2016A and 2016B in Bugesera, Rwanda.

Treatments		log-grain yield (kg ha^{-1})			
		Seasons			
Canopy	Fertilizer	2015A	2015B	2016A	2016B
Open field					
	Zero	7.5 (0.013)[a]	6.4 (0.023)[a]	5.9 (0.031)[a]	7.5 (0.014)[a]
	Only P	7.7 (0.012)[b]	6.7 (0.020)[b]	6.1 (0.028)[b]	7.5 (0.013)[a]
	Only N	7.7 (0.012)[b]	6.8 (0.019)[b]	6.1 (0.027)[b]	7.6 (0.013)[ab]
	Combined NP	7.9 (0.011)[c]	7.0 (0.017)[c]	6.4 (0.024)[c]	7.9 (0.011)[b]
Under canopy					
	Zero	6.3 (0.025)[d]	4.6 (0.059)[d]	0.1 (0.577)[d]	5.8 (0.032)[c]
	Only P	6.4 (0.023)[d]	5.4 (0.039)[e]	3.5 (0.100)[e]	6.7 (0.021)[d]
	Only N	6.7 (0.020)[e]	5.7 (0.033)[f]	4.2 (0.071)[f]	7.0 (0.017)[e]
	Combined NP	7.4 (0.014)[a]	6.4 (0.023)[a]	4.6 (0.059)[g]	7.4 (0.014)[a]
	logLik	-4869.5	-7292.6	-3989.4	-6019.3
	AIC	9756.9	4613.8	7996.7	2056.5

Means followed by similar letters are within a column not significantly different at the 5% probability level.

Results from the season 2015B, which was a relatively dry season, followed a similar trend to seasons 2015A and 2016B in that under canopy treatment receiving combined N-P fertilizers (i.e., the highest yielding among all under canopy treatments) resulted in a comparable yield with open field treatment that received no fertilizer (i.e., the lowest yielding among all open

field treatments). In contrast, during the other relatively dry season 2016A, the highest yielding treatment under *Grevillea* canopy (i.e., combined application of N-P fertilizers), resulted in significantly smaller yield than all open field treatments, including the treatment without any fertilization (Zero).

An interesting result from both relatively wet and relatively dry seasons was that with the use of no, P only, N only and combined N-P fertilizers, maize grain yield under the canopy of *Grevillea* showed a progressively significant increase (*P < 0.001*). This can hint that fertilizer rates higher than currently recommended for the area may enhance productivity of maize in *Grevillea*-maize systems in the area.

3.3.2. *Maize yield reductions and failures as influenced by tree-crop-fertilizer interactions*

No crop failure nor critically low yield was recorded from *Faidherbia*-wheat systems. However, the probabilities of maize yield reduction in *Acacia*-maize and *Grevillea*-maize systems was influenced by the presence or absence of trees, the type of mineral fertilizer used and the season (Figure 3.3 and Figure 3.4).

In *Acacia*-maize systems and during relatively wet season of 2014 (Figure 3.3a), open field maize did not fall below 1.5 t ha^{-1} for fertilizer treatments. By contrast, the probability of obtaining maize grain yields below 1.5 t ha^{-1} for under canopy treatments that received zero, P only and N only was 50%. Such low yield was improbable when combined N-P fertilizer was applied to under canopy treatments.
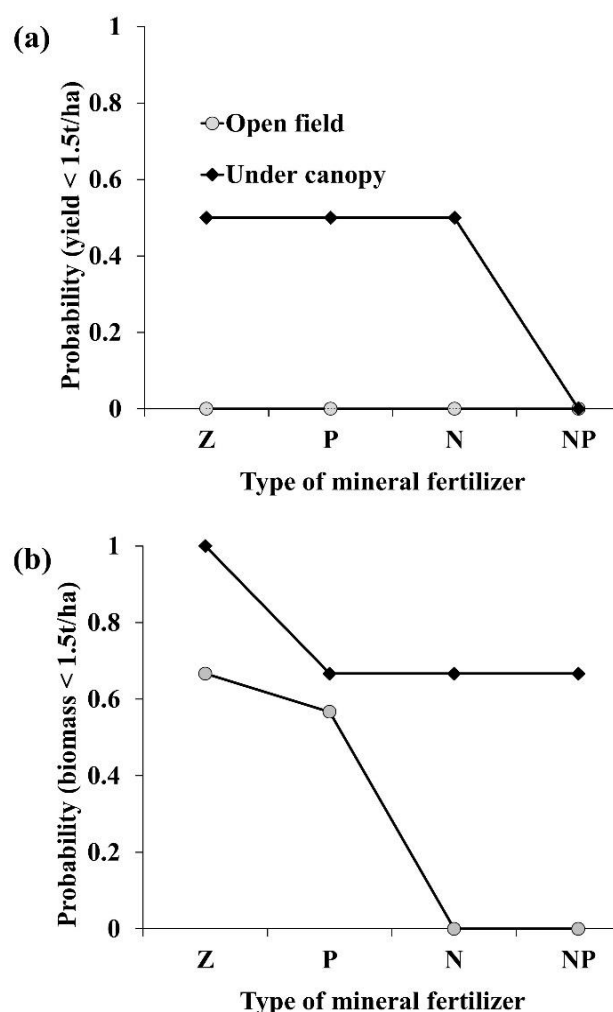
(a)

(b)

Figure 3.3 The probability of grain yield (a) and biomass (b) falling below 1.5 ton ha^{-1} with different N-P fertilizer combinations for maize growing under the canopy of *A. tortilis* and in the open field.

In the relatively dry season of 2015, the probability of obtaining a maize biomass yield smaller than 1.5 t ha^{-1} when no fertilizer was applied to under the canopy maize was 100%. The probability of obtaining such a low yield was 57% for open field treatments with the same treatment. The probabilities of maize biomass yield to fall under 1.5 t ha^{-1} with P only, N only and a combination of N and P to under canopy maize were all 67%. By contrast, only the treatment that received P only showed 57% probability of a biomass harvest less than 1.5 t ha^{-1} for maize in the open field. The probability of obtaining a biomass yield less than 1.5 t ha^{-1} in treatments where N only and N-P combinations were applied to open field maize was null.
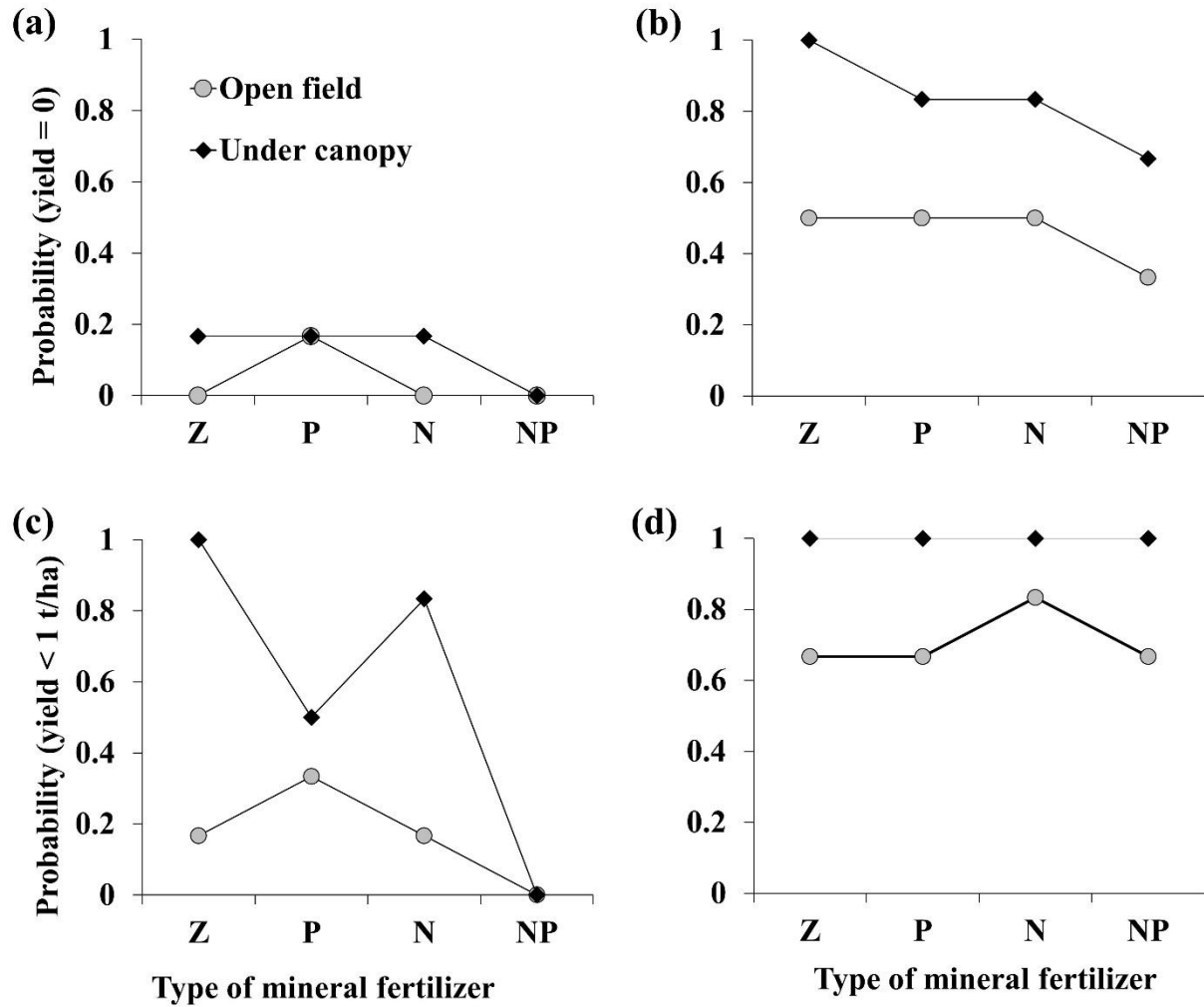
Figure 3.4 The probability of crop failure during normal rainfall season (a) and dry season (b), and probability of yield falling below 1 ton ha^{-1} during normal season (c) and dry season (d) with different N-P fertilizer combinations for maize growing under the canopy of *G. robusta* and in the open field.

In *Grevillea*-maize systems and during relatively wet rainfall seasons (Figure 3.4 a), there was a 17% probability of crop failure in maize with no, P only and N only under tree canopy plot. Such a probability of crop failure in maize was recorded only for P only in the open field. On the other hand, there was no crop failure when no and N only fertilizer were applied to the open field maize. Similarly, no crop failure was observed under combined N-P fertilizer treatments from both open field and under canopy conditions. During these seasons (Figure 3.4 c), the probabilities of maize yield falling below 1 t ha^{-1} for under canopy treatments that received

zero, P only and N only were 100%, 50% and 83%, respectively. The probabilities of such a

low yield were relatively lower for the corresponding open field treatments. It was 17%, 33%

and 17%, respectively, for the open field treatments that received no, P only and N only. During

the normal rainfall seasons, no yield reduction to less than 1 t ha^{-1} was observed for treatments

that received combined N-P fertilizer in both under canopy and open field conditions (Figure

3.4 a & c).

In *Grevillea*-maize systems, the probabilities of crop failure (Figure 3.4 b) and critically low

yields (Figure 3.4 d) were higher during relatively drier seasons. The probabilities of failure in

maize yield when no, P only, N only and combined N-P fertilizers were applied to under canopy

treatments were 100%, 83%, 83% and 67%, respectively, during dry seasons (Figure 3.4 c). For

open field treatments, in comparison, the probabilities of yield failure were smaller for all

fertilizer combinations (i.e., the probability of yield failure was 50% for open field treatments

that received zero, P only and N only fertilizers). For open field treatment that received

combined N-P fertilizers, the probability of yield failure was 33%. The probability of under

canopy yield to fall below 1 t ha^{-1} was 100% for all fertilizer applications (Figure 3.4 d). For

open field, the probability of obtaining the yield of less than 1 t ha^{-1} was 67% for both zero and

P only fertilizers. The probabilities of such a low yield for N only and combined N-P fertilizer

applications to open field treatments were 83% and 67%, respectively (Figure 3.4 d).

3.3.3. Tree-crop interactions and agronomic fertilizer use efficiencies

NUE and PUE varied across seasons and tree-crop systems (Figure 3.5). In *Faidherbia*-wheat

systems (Figure 3.5 a), NUE was 17.4% higher for under canopy compared with open field

treatments in the relatively dry season of 2015 (i.e. 23 kg grain for every kg of applied N for

the open field condition, while it was 27 kg under tree canopy). NUE was 10% higher under

tree canopy compared with open field conditions during the relatively wet season of 2014 (i.e.

every additional kg of N resulted in an increase in wheat grain yield of 22 kg under open the field conditions, while the increase was 24 kg under tree canopy).
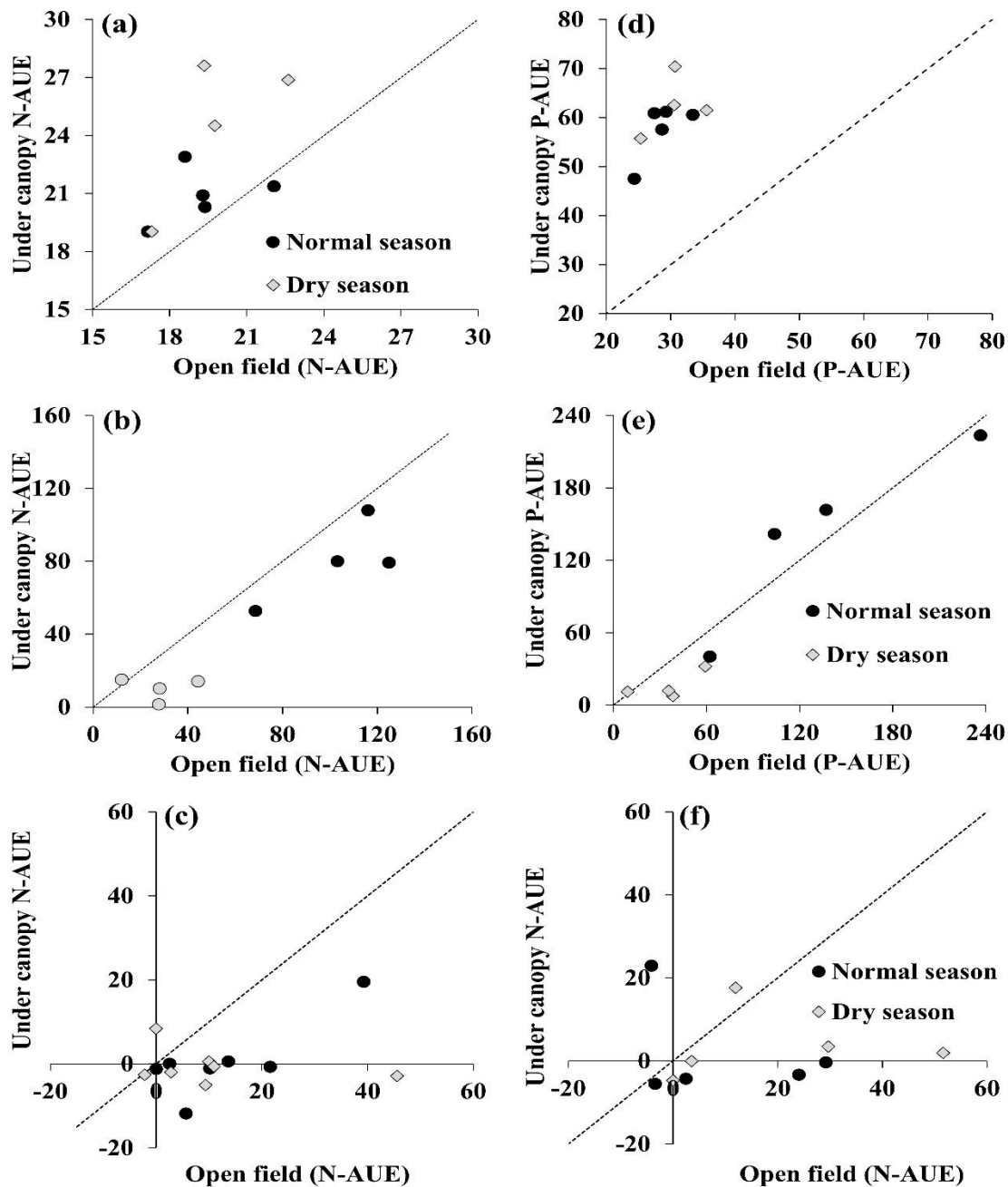

Figure 3.5 Different nitrogen use efficiencies (NUE) for *Faidherbia*-wheat (a), *Acacia*-maize (b) and *Grevillea*-maize (c); and phosphorus use efficiencies (PUE) for *Faidherbia*-wheat (d), *Acacia*-maize (e) and *Grevillea*-maize (f) systems for seasons with variable amounts of rainfall. Broken line denotes a 1:1 relationship between nutrient use efficiencies of open field and under canopy plots.

From Figure 3.5b, PUE increased 100% by the presence of *Faidherbia* trees (39.2 kg of grain for every additional kg of P added) compared with open fields (19.3 kg of grain for every additional kg of P added). There was no significant difference in PUE between relatively dry and relatively wet seasons.

In *Acacia*-maize systems, under canopy treatments showed consistently lower NUE values compared with open field conditions (Figure 3.5 b). On the other hand, PUE for a season with above average rainfall (Figure 3.5 e) was 11% higher under tree canopy (37.5 kg of grain for ever kg of P added) compared with open field plots (33.9 kg of grain for every kg of P). Both NAUE and PAUE were significantly higher during good rainfall compared with relatively dry season (Figure 3.5 b & e).

In *Grevillea*-maize systems, both NUE (Figure 3.5 c) and PUE (Figure 3.5 f) were generally negative under tree canopy. The only exception was during the season 2016B, although the agronomic use efficiencies were still smaller under tree canopy than in open field conditions.

3.4. Discussions

3.4.1. Crop response to N and P fertilization differs in agroforestry systems and in open field conditions

Results from our omission trials in *Faidherbia*-wheat systems revealed that N is strongly limiting in the soils of the study area (Table 3.2). For example, under canopy treatments that received no fertilizer and open field plots that received N only resulted in comparable wheat yields. This suggests that this tree contributes mineral N in the order of 64 kg ha^{-1} N. This conforms to recent findings by Yengwe *et al.* (2017), which showed *Faidherbia* to fix about 96 kg N ha^{-1} year^{-1} (i.e., 18 kg N ha^{-1} year^{-1} from litter decomposition in addition to about 78 kg N ha^{-1} year^{-1} from native soil organic matter).

Application of P only caused a contrasting response in wheat yield of under canopy and open field conditions. Open field plots that received P only fertilization did not respond compared with the open field control, while addition of P only to under canopy plots resulted in large gains in wheat yield. This contrasts with the suggestion that these *Faidherbia* trees might selectively establish on initially fertile spots (Nair, 1993). While natural fertility gradients could affect all nutrients including P, the fertility gradient observed from this trial appeared to be created by the nitrogen fixing ability of this species (Giller, 2001). Although, Dangasuk *et al.* (2011) reported *Faidherbia* to improve available P underneath its canopy, the evidence from our study suggests that phosphorus availability could limit under canopy yield, regardless of improved N. This shortage of phosphorus could be attributed to possible depletion of this nutrient because of increased crop uptake and completion from tree roots.

Our results imply that wheat yields may be improved under *Faidherbia* with minimum N fertilization. However, further research is needed to assess what is the optimum stage is to apply this small amount of N: e.g., at planting, booting or first node stage (three stages when N uptake by wheat is high). These results also suggested that farmers practicing agroforestry with *Faidherbia* might invest their limited resources on localized P application instead of N fertilization.

In *Acacia*-maize systems, under canopy grain yield was not statistically different between all fertilizer treatments, suggesting that shortage of nutrient may not be a yield limiting factor in these systems. Although *Acacia* is known to fix nitrogen (Schulze *et al.*, 1991), the current study did not demonstrate any positive impact of the tree on the crop growing under its canopies. Tree canopies had a clear negative effect on maize. This could be explained by the dense root system of *Acacia* in the top soil (unlike roots of *Faidherbia* that penetrate deep) overlapping with maize roots, intensifying competition not only for nutrients but also for other resources such as soil water (Belsky, 1994). Stressing the importance of competition for soil

moisture under *Acacia,* Noumi *et al.* (2011) demonstrated that wet season wheat yields were significantly higher compared with dry season yields. The current finding agrees with Larcher (2000) who showed soil water availability to be the most important factor determining crop yield grown under the canopies of this tree.

While fertilization rates under the current study were those recommended under conventional conditions, our results suggest that the application of fertilizer in combination with *Acacia* did not influence maize yield. In addition to tree canopy and root management to reduce tree-crop competition (Lehmann *et al.*, 1998; Jackson *et al.*, 2000), further study on other fertilization rates in *Acacia*-maize systems may reduce tree-crop competition.

In Rwanda, the presence of *Grevillea* resulted in an average yield decline of 75%, 61%, 59% and 38% for control, N only, P only, and combined N-P fertilizers, respectively, compared with maize outside the canopy with similar treatments. While maize yields for N only and P only treatments were mostly comparable, the highest yields were always recorded in the treatments that received combined N-P for both under the canopy and the open field. The lowest yield decline (38%) under the canopy of *Grevillea* as compared with the corresponding open field treatment was observed for combined N-P fertilizer application, suggesting that higher N and P rates might reduce tree-crop competition. This result corroborates earlier findings where grain yield of maize was affected by shade at kernel setting stage (Andrade *et al.*, 2002). A recent study also reported that the shade from trees may affect grain formation negatively by decreasing kernel rows per head and kernels per row (Cui *et al.*, 2015), although additional negative effects from root competition is expected in agroforestry systems (Callaway and Walker, 1997). An interesting trend in *Grevillea*-maize system was that there was a significant increase in yield for every addition of fertilizer, suggesting that fertilizer rates other than currently recommended for open field systems might optimize under canopy maize yield. As *Grevillea* is known for its timber (Bertomeu, 2006) and phosphorous mobilization values

(Lambers and Shane, 2007), other rates could improve its contribution in the overall productivity of the system.

3.4.2. The effect of fertilizer-tree-crop interactions on crop performance depends on rainfall, tree species, and crop species

Our results clearly demonstrated that different on-farm tree species had unique interactions with crops and showed different responses to N and P fertilization. With the exception of *Faidherbia*, perhaps the most ideal agroforestry species, the other two species under the current study raised the old question of tree-crop compatibility for optimum productivity (German *et al.*, 2006). While maintaining these trees in the system is beneficial for biodiversity and associated ecosystem services (Pattanayak and Mercer, 1998; Bhagwat *et al.*, 2008) and income generation (Steffan-Dewenter *et al.*, 2007), our results may raise at least two main concerns. The first is whether fertilizer recommendations should consider tree-induced heterogeneity in many farming systems in SSA to address the negative effects of these trees on crops. The second is whether these systems require redesign such that trees are rearranged in ways that minimize their negative effects on crops.

On the other hand, tree-crop compatibility appears to be dictated by the type of crop used. Wheat, which is a shade tolerant C3 crop, responded positively under tree-crop combinations. This was not the case for the C4 maize, suggesting that selecting maize varieties that are tolerant to competition and shade might improve the outcome of tree-crop interaction. Similarly, Noumi *et al.* (2011) reported from the Mediterranean ecosystem that *Acacia* shades suppressed yields in wheat, but not in barley, indicating the selective response of crops to tree-mediated environment.

The current study revealed that maize yield in tree-crop systems could be influenced by seasonal effects. Although, the season effects were significant for all the three tree-crop systems, the

important effects were the interaction of tree presence with season (Table 3.1). Such a statistically significant interaction effect, except in the *Acacia*-maize system, could be an evidence that the impact of trees on understorey crops depended on the amount of seasonal rainfall. For example, open field mean wheat yields for 2014 (wet season) and 2015 (dry season) in *Faidherbia*-wheat agroforestry system were 1566 kg ha^{-1} and 1363 kg ha^{-1} (i.e., 15% less yield in the relatively dry season). By contrast, under canopy mean wheat yields were 2072 kg ha^{-1} for 2014 and 2055 kg ha^{-1} for 2015 ((i.e., only 3% less yield in the relatively dry season). This result agrees with a recent finding, which demonstrated the importance of *F. albida* in buffering wheat against extreme climatic conditions (Sida *et al.*, 2018). This indicates that *F. albida* improves the productivity of wheat in the semi-arid area by not only improving soil fertility and fertilizer use efficiencies, but also by making the system more resilient against the recurrent drought.

In *Acacia*-maize system, the probabilities of both crop failure and low yield were generally higher during relatively dry seasons compared with relatively wet seasons. In addition, low yields and crop failures were more probable under tree canopy compared with open field conditions. This could be due to the fact that the facilitative effects of *Acacia* trees could be counterbalanced by the drought (dry spell), which is likely to intensify competition for moisture (Noumi *et al.*, 2011). In support of this, Rao *et al.* (1997) argued that the positive influence of scattered trees on crops may be offset by large competition of trees with crops for water, especially during dry seasons. Low yields and complete crop failures observed in our study could also be attributed to such competitions. Because tree shades can cause significant delay in the vegetative development of understorey crops (Page *et al.*, 2011), crops may fail due to shortage of moisture during the grain filling stage.

Similarly, the probability of low yield and crop failure was higher during drier seasons in *Grevillea*-maize systems. Under canopy grain yield was 55-58% less compared with grain yield

from the open field during relatively dry seasons (2015A and 2016B). The yield decline was more severe during relatively dry seasons (2015B and 2016A), where yield loss ranged from 63%-100%. This agrees with the findings of Ong *et al.* (2000), which showed crop failures in *Grevillea*-maize systems to be more prevalent in dry seasons. Other studies have suggested that competition poses consistently negative effects on grain formation in *Grevillea*-maize systems (Muthuri *et al.*, 2005), affirming the increased probability of crop failure could be due to competition.

Interestingly, the probability of low yield and crop failure varied with the N-P fertilization in tree-crop systems (Figure 3.3 and 3.4). In both *Acacia*-maize and *Grevillea*-maize systems, treatments that involved N fertilizer (i.e., N only and combined N-P) reduced the probability of low yield and crop failure. Moser *et al.* (2006) demonstrated that grain yield increases with an increasing N rate for maize exposed to pre-anthesis drought. While the existence of competition from trees may compound the interaction between drought and N, our analysis did not include the three-way interaction between tree, fertilizer and drought. This makes the exact N rate that leads to maximum grain yield for maize exposed to drought in tree-crop system difficult to determine. However, there is an evidence that increased rate of N reduced the probability of low yield and crop failure.

3.4.3. Tree presence modifies crop NUE and PUE

It has been established that combination of organic materials and mineral fertilizer can improve nutrient use efficiencies in crops (Goyal *et al.*, 1999; Han *et al.*, 2004). As trees add organic matter to the soil through N_2 fixation, litter fall and dead roots, nutrient use efficiencies could be higher for crops growing under their canopies. Our results confirmed this assertion for *Faidherbia*-wheat system, where NUE was larger for under canopy wheat. PUE was doubled for wheat under the canopy of *Faidherbia*. This *Faidherbia* effect is interesting, as inefficient P use has been a major constraint in agricultural systems across the tropics (Simpson *et al.*,

2011). In SSA, where limited availability of P is a critical limitation in cereal production, *Faidherbia*-based agroforestry systems could improve food security of the region.

However, the presence *Grevillea* and *Acacia* resulted in inferior nutrient use efficiencies in maize. N and P deficiencies, which are likely to happen because of competition from tree roots, could be one of the causes for low nutrient use efficiencies (Simpson *et al.*, 2011). The other explanation for the inefficiencies could be low radiation penetration resulting in low rates of photosynthesis in maize (Setter *et al.*, 2001). Although nutrient use efficiencies by maize are low and often negative in tree-crop systems, van Noordwijk and Brussaard (2014) argued that system level (for example, if the yield of *Grevillea* were included in the analysis) nutrient use efficiency may give a different perspective.

3.5. Conclusions

The current study demonstrated that the effect of N and P fertilizers in tree-crop interactions depended on tree species, crop types and seasonal effects. In *Faidherbia*-wheat agroforestry systems, N fertilizers could be saved, with localized application of P fertilizers close to tree crowns. In *Grevillea*-maize and *Acacia*-maize agroforestry systems, maize did not respond to N and P fertilizers applied at recommended rates. Further study is needed to identify fertilization rates that minimize tree-crop competition for *Grevillea*-maize and *Acacia*-maize systems, while further study is needed to identify the rates and timing of application that optimize *Faidherbia*-wheat facilitation.

Acknowledgement

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

Abstract

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

4.1. Introduction

Faidherbia albida (Del. A. Chev) trees are common features of the Sudano-Sahelian region of sub-Saharan Africa, forming 'parklands' (Bayala et al., 2014). 'Parklands', where scattered mature trees occur as an integral part of crop and livestock production landscapes, are one of the oldest agroforestry systems in Africa. They generate ecosystem services such as provisioning and regulation values (Sinare and Gordon, 2015), valuable assets in the economy of local communities (Mokgolodi *et al.*, 2011) and socio-cultural values (Wahl and Bland, 2013). *Faidherbia* trees improve soil fertility through ecological process of nitrogen fixation (Giller, 2001), nutrient recycling(Sileshi, 2016) and accumulated soil organic matter (Gelaw *et al.*, 2015). They improve water availability through different ecological processes such as hydraulic redistribution and improve water use efficiency of understorey crops (Bayala *et al.*, 2015). Agroforestry has been suggested as an option to adapt to climate change (Matocha *et al.*, 2012), which poses a serious threat to food security in smallholder agriculture (Mbow *et al.*, 2014). According to a study from the Sahel, the parklands buffer climate risk and sustain agricultural production (Bayala *et al.*, 2014), magnifying their importance under expected future climate change (Kassie *et al.*, 2014).

Despite these positive effects, trees in parkland systems also compete with crops for scarce resources (Bayala *et al.*, 2015). Thus, research into management practices that maximize facilitation and minimize competition is needed. In the central rift valley of Ethiopia, *Faidherbia* is the most common tree species, whereas wheat is the second most important crop after *teff* [*Eragrostis tef (Zucc.)* Trotter]. The current study focuses on unravelling the effects of interactions between *Faidherbia* and wheat. Frequent droughts and sparse use of fertilizer and improved seeds in the area cause extremely small crop yields (Van Halsema *et al.*, 2011). Wheat yields average 1.4 t ha^{-1}, far below the yields of close to 5 t ha^{-1} reported from experimental stations (Abate *et al.*, 2015). As crop yields are expected to fall further due to

expected climate variability and change in the region (Kassie *et al.*, 2014), these parkland systems could provide sustainable and affordable coping strategies for smallholder farmers with limited access to inputs (Lin, 2007).

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

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

4.2. Materials and Methods

4.2.1. Study area

The study area (Figure 4.1) is located in the Central Rift Valley of Ethiopia (8°30'33" N and 39°04'16" E) at an elevation of 1665 m above sea level and has a flat topography. The climate is semi-arid with a potential evapotranspiration of 1305 mm yr^{-1} and an average annual rainfall of 700 mm yr^{-1} over the last decade (RSO, 2003). The rainy season generally starts in June and ends in September. The long term average mean minimum daily temperature is 24.2°C and the mean maximum daily temperature is 31°C. However, the maximum daily temperature often exceeds 35°C during the cropping season (Van Halsema *et al.*, 2011).
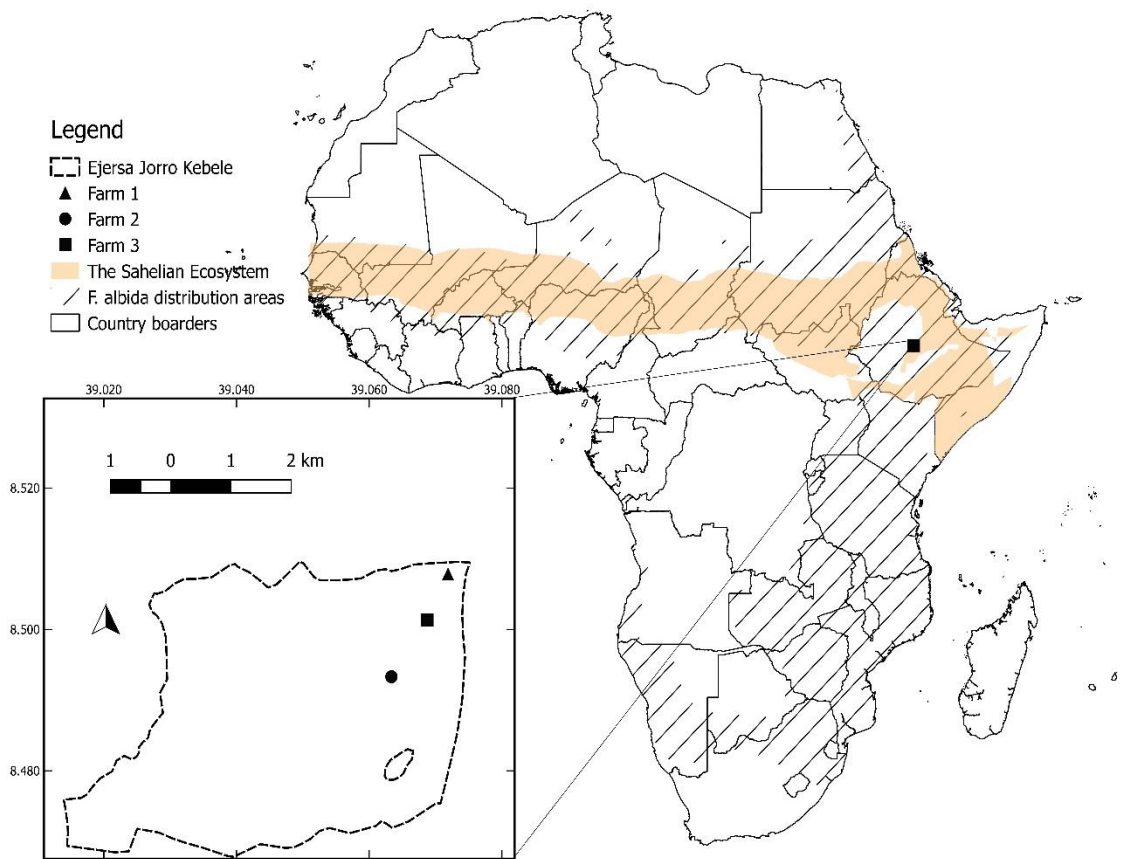
Figure 4.1 Location of the study area in relation to the Sahelian ecosystem and the distribution area for *F. albida*. Ejersa Jorro is an administrative boundary where the landscape under study was located.

Andosol is the dominant soil type (RSO, 2003). Except for strong phosphate fixation, andosols are generally fertile with good nutrient content, aggregate stability and high porosity (Matus *et al.*, 2014). The natural vegetation in the area is classified as woodland and savannah, where *Acacia* species are commonly incorporated into the rain-fed farming system, forming 'parkland' agroforestry. *F. albida* is the main agroforestry species in fields where teff [*Eragrostis tef* (Zucc.) Trotter] is the most important crop, while wheat (*Triticum aestivum* L. *var aestivum*) is the second most important. The density (mean ± sd) of *F. albida* on the selected farms was 5.6 ±1.3 trees ha^{-1}. The other dominant tree species in the area are: *Acacia tortilis*, *Acacia etbaica* and *Balanites aegyptiaca*, respectively (Iiyama et al., 2017). Wheat is generally planted early July and harvested late in October. In the study area, the 'reverse phenology' of *F. albida* is generally not observed. Heavy and frequent pruning of the trees towards the end of dry season (for fencing, charcoal and firewood production) apparently 'forces' the regeneration of green canopies during the crop growth period.

4.2.2. Experimental design and plot management

Tree-crop interaction was explored for wheat growing under crowns of scattered on-farm *F.albida*, replicated in three farms (Figure 4.1). Two mature *F. albida* trees per farm were selected for an on-farm experiment. Selected pairs of trees were located in a single field within a farm and had approximately similar crown structures and pruning history (Table 4.1). For each tree, plots measuring 10 x 10 m were established with trees at the centre. Within the same field, another plot of the same size was established in an open field, at least 70 m away from any tree. This made a total of three plots per farm. Wheat was grown under the crown of one of the trees and in the open filed. The plot under the crown of the other tree remained bare. Treatments were designated as: 'tree with wheat' – for wheat grown under the canopy of *F. albida,* 'sole wheat' – for wheat grown in the open, and 'sole tree' – for *F. albida* without wheat.

The experiment was replicated on three contrasting farms, creating a total of nine plots, and repeated for three seasons. Both trees and plots were managed following farmers' typical practices.

Table 4.2 Characteristics of *Faidherbia albida* trees under investigation. DBH = Diameter at breast height, DSH = Diameter at stump height, height = tree height to the tallest part of the canopy and CD = mean canopy diameter. Standard deviations from the means are given in the parenthesis.

	Tree Characteristics			
Treatment	DBH (cm)	DSH (cm)	Height (m)	CD (m)
Sole tree (n= 3)	43.8 (8.8)	46.2 (9.8)	10.7 (1.7)	11.8 (1.5)
Tree + Crop (n=3)	44.3 (8.5)	45.5 (9.1)	10.7 (2.5)	11.7 (1.3)

Wheat variety 'Ude', which is well-adapted to semi-arid conditions, was used. Plots were fertilized with 64 kg ha^{-1} N (split applied 50% at sowing and the remaining side dressed at tillering) and 30 kg ha^{-1} P broadcast at sowing. Seed was drilled at a spacing of 20 cm between rows at the rate of 150 kg ha^{-1}. All plots were kept weed free. The experiment was conducted over three seasons from 2013 to 2015. Seasons 2013 (1001 mm yr^{-1}) and 2014 (727 mm yr^{-1}) had good rainfall, while 2015 was an El Niño season with 578 mm yr^{-1}, below the long-term average of 700 mm yr^{-1} for the area.

4.2.3. Soil sampling and analysis

Soil was sampled from all plots at depths of 0-10 cm, 10-20 cm and 20-40 cm at wheat grain filling stage, in 2014. For each depth and treatments, the samples were composited from three cores, oven-dried for 48 hours at 60°C and sieved to 2 mm. The composite bulk samples were analysed for pH$_{(water)}$, organic C (Walkley-Black), total N (micro Kjeldahl), P (Olsen),

exchangeable K (Ammonium acetate method), and texture (hydrometric method) following procedures described in (Van Reeuwijk, 2008). Separate soil samples were collected using auger cores of known volume for bulk density determination. These samples were oven-dried at 105°C for 24 hours and weighed to determine bulk density. Soil nutrient contents were adjusted for bulk density during final mean comparison among treatments. Soil samples were also collected in the same manner at the end of dry season (May, 2015) and available Nitrogen (NO_3-N) was analysed using a fast nitrate test method (Reflectoquant®, EM Science) following a procedure outlined in (Schmidhalter, 2005), where $CaCl_2$ was used as extracting agent.

4.2.4. Climatic, microclimatic and soil water data

Soil moisture was measured using Delta-T© moisture probes (Delta-T-Devices, 2013) at depths of 10, 20, 30, 40, 60 and 100 cm within pre-installed access tubes. The access tubes were installed at three distances from the tree trunk: under the tree crown (at 0.7 m and 6.2 m from the tree trunk) and outside the canopy i.e. in the sole wheat treatment (minimum of 70 m from the trunk of any surrounding tree). Soil moisture was measured twice a week during the cropping season (July-October) and twice a month during off-season (October-June). Tinytag© temperature loggers (Gemini-Instruments, 2013) from Gemini© instruments were installed at a height of 60 cm above-ground (approximately at the height where floral initiation and anthesis is expected for the wheat variety used), 0.7 m away from the trunk in the TW treatment and in the centre of the plot for the W treatment. Temperatures were recorded every 30 minutes starting from two weeks after wheat emergence (July) to harvesting (October) for all seasons (2013-2015). Photosynthetically active radiation (PAR) sensors from SunScan© Canopy Analysis System (Webb *et al.*, 2013) were used to measure PAR above and under wheat canopy for both 'tree with wheat (TW)' and 'sole wheat (W)' treatments. Measurements were taken at

increasing distance from the tree trunk during mid-day at booting, anthesis and grain filling on cloudless days.

4.2.5. Crop parameters

In the 'tree with wheat' and 'sole wheat' treatments, days to 50% emergence, 50% tillering, 50% booting, 50% flowering, grain filling and physiological maturity were recorded. Leaf Area Index (LAI), number of tillers, plant height and number of senesced leaves were recorded weekly until physiological maturity. At harvest, plant height, number of fertile tillers per plant and number of grains per spike were recorded.

4.2.6. Data analysis and simulation modelling

Soil nutrient content and soil moisture content data were log-transformed for the data to follow normal distribution. For soil moisture, repeated measures ANOVA, also referred to as ANOVA for correlated samples, was used to analyse trends across treatments and depths at different days after planting. Tukey's HSD test was applied to find significant differences among treatments. We compared soil nutrient contents from under tree crowns and open fields using two-sample T-test. We carried out repeated measures ANOVA for air temperature logged between five days before 50% anthesis and end of milk stage. We made pairwise comparison for experiments with tree and without tree for 24 hours, to identify the time of the day when temperature variation is the most pronounced. The same procedure was used to measure variations in photosynthetically active radiation (PAR). For PAR, we limited our analysis to means of the three measurements made at booting, anthesis and start of grain filling.

We compared LAI, number of tillers, number of senesced leaves, plant height, number of fertile tillers, number of grains spike^{-1}, total aboveground biomass and dry grain yield using independent samples t-test. For all the analyses, a probability level of 5% was used to test for

significance. Only treatment means were collected during 2013 season, while data was disaggregated along distances from tree trunk for 2014 season. Thus, for trends across distance gradients, only the data from 2014 were used. Crop development was irregular and we included only the final yield and some environmental variables for season 2015, which was an El Niño season. Where complete data was available, it was presented over three seasons. All statistical analyses were conducted in R (R Core Team, 2015).

4.2.7 Sensitivity analysis using Agricultural Production Systems sIMulator (APSIM) wheat module

The wheat crop model in APSIM 7.8.2 was calibrated using sole wheat data from season 2013. Model validation was done using data from different treatments of season 2014. We used observed days to maturity, grains per g stem, maximum grain size, and potential grain filling rate in the calibration process, because the APSIM-wheat module was reported to be particularly sensitive to these parameters (Zhao *et al.*, 2014). We also included observed soil moisture across wheat development stages in calibration, as moisture stress could be the most important factor under the semi-arid condition of the current study area. In-season soil moisture and grain yield were used to validate the model. Validation showed reasonable fits for in-season soil moisture against predicted values with RMSE of 6.3 (mm) and r^2=0.61 (Appendix Figure 1), and RMSE of 204.4 (kg ha^{-1}) and r^2=0.75 for observed grain yield against its corresponding predicted values (Appendix Figure 4.2). We carried out sensitivity analysis with factorial combinations of three levels of radiation (-20%, -10% and observed), three levels of maximum temperature (-5 °C, observed and +2 °C), and three rates of N (0, 64 and 120 kg ha^{-1}). Graphs showing the sensitivity of wheat yield to factorial combinations of N, radiation, and temperature are presented as supplemental materials (Appendix Figure 4.3a-c).

4.3. Results

4.3.1. Impact of F. albida on understorey resources (soil moisture and soil nutrients)

At planting (Figure 4.2a), soil moisture in the topsoil did not show a clear trend across depth and treatments. For deeper profiles, there was a slightly larger moisture content for the sole tree (T) treatment compared with W and TW treatments. Towards the peak of wet season (Figure 4.2b), soil moisture increased for all treatments and across all depths without clear influence of the treatments.

At around peak grain filling (Figure 4.2c), moisture content in the subsoil (30-60 cm) started to diverge between treatments. There was no such divergence in soil moisture content in the top soil (10-30 cm). In the subsoil, the least moisture was available in the TW and the most in the W treatments, except for the exceptional dry season of 2015. At harvest (Figure 4.2d), there was relatively more soil moisture in the sole wheat treatment at greater depths, regardless of the general decline in moisture for all treatments.

At the end of 2013 cropping season, soil chemical parameters (soil organic C, total N, Olsen P and exchangeable K) and physical properties (bulk density and pH-H_2O) did not significantly differ in the soils under and outside the canopy of *F. albida* (Table 4.2). On the other hand, at the end of dry season (May, 2015) topsoil available NO_3-N decreased with increasing distance from the trunk of *F. albida* (Figure 4.3a). This contrasts with the result in Table 4.2, where total SOM did not significantly vary in relation to tree crowns. However, no similar trend was observed at depths of 30-60 cm (Figure 4.3a), where NO_3-N was more variable. In addition, NO_3-N did not change with distance at greater depths.

Another important localized resource – photosynthetically active radiation (PAR) – also varied due to shading by the trees. The recorded PAR was lower under the canopy than outside of *F. albida* (Figure 4.3b). The reduction in PAR was much more variable under than outside the canopy whose influence extended to about 3.5m from the tree trunk. Incident PAR close to

the maximum of 2200 µmol m^{-2}s^{-1} was found above the wheat canopy in the open field at most
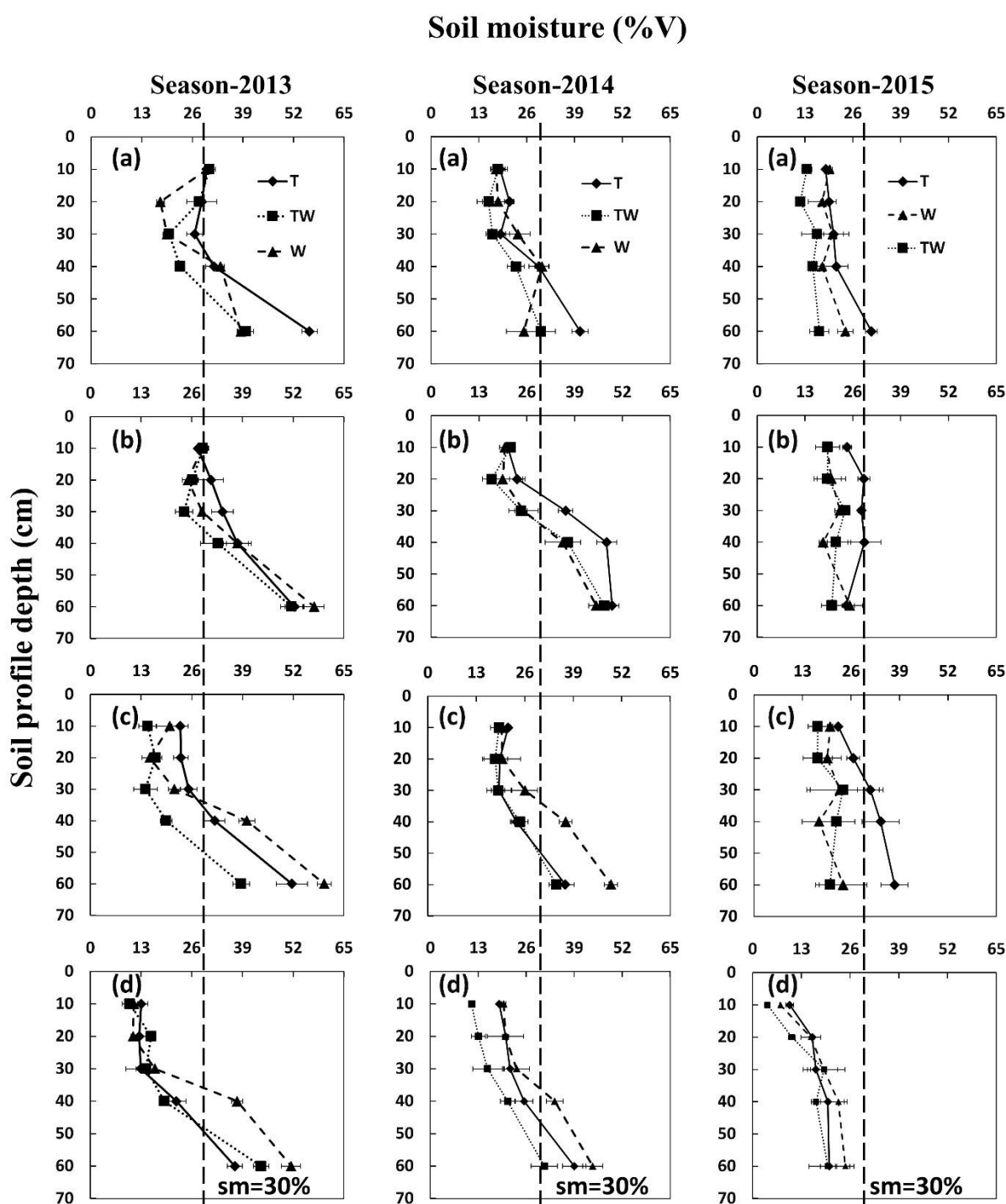
measurement times.

Figure 4.2 Volumetric soil moisture content with depth at planting (a), 45 days after planting (b), 80 days after planting (c) and at maturity (d) in 2013, 2014 and 2015 sole tree (T), wheat under tree crowns (TW) and sole wheat (W) treatments. 45 and 80 days represent vegetative and grain-filling stages, respectively of wheat. Broken vertical lines across the graph represent 30% by volume level of moisture content. Error bars are standard deviations.

4.3.2. Impact of F. albida on understorey microclimate (PAR and temperature)

Air temperature was lowered by up to 6°C at midday under compared to outside the canopy of *F. albida* (Figure 4.3c). Temperature reached 36°C and was highly variable in the open field, while it reached a maximum of 29°C and fluctuated less under the canopy. Temperature exceeded 28°C, for about six hours day^{-1} (i.e., from 10:00-16:00 GMT) in the open fields and for less than two hours (i.e., from 12:300-14:300 GMT) for under the canopy. For close to three hours around midday (i.e. from 10:40-13:30 GMT), temperature was significantly cooler under tree crowns than in open fields (*P<0.001*).
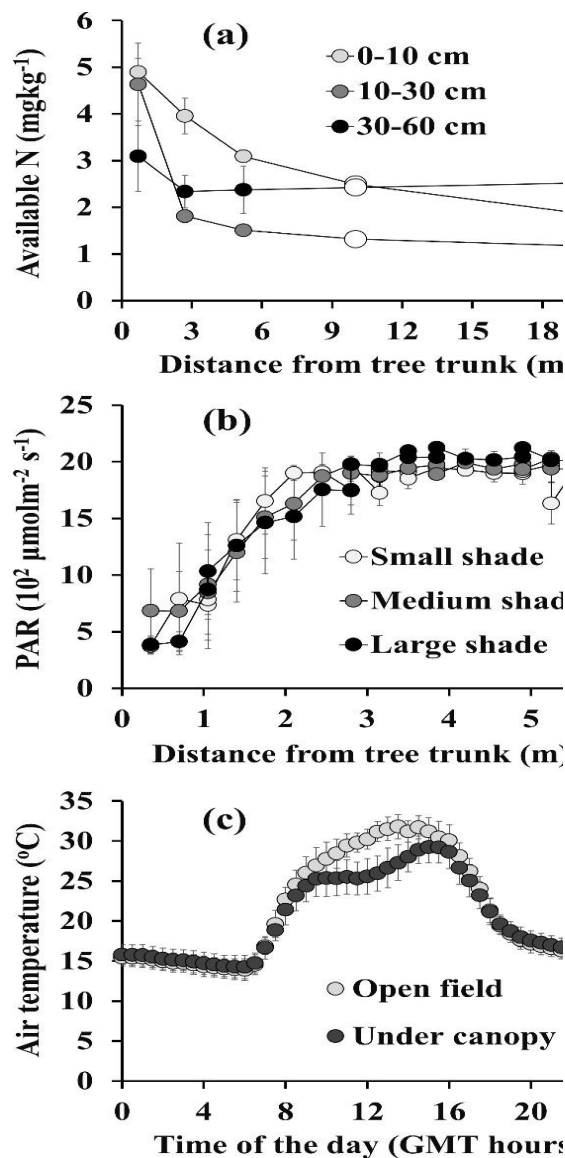

Figure 4.3 Localized microenvironment modification by *F. albida:* available nitrogen (a), photosynthetically active radiation (PAR) (b) as a function of distance from the trunk of trees and diurnal variation in air temperature under and outside the canopy of *F. albida* between anthesis and grain filling stages (c). Graphs were generated from the means of two seasons, except for available nitrogen. The error bars are standard deviations.

4.3.3. Crop development and productivity

Leaf senescence occurred earlier in wheat growing outside compared with under the canopy of *F. albida* (Table 4.3). Wheat under the canopy grew significantly more vigorously as illustrated by more tillers and larger LAI. Despite the significantly greater number of tillers under than outside tree crowns during vegetative stages, the number of fertile tillers at harvest was not significantly more (Table 4.3). Similarly, plants grew significantly taller under tree canopies than outside during earlier crop growth stages (Table 4.3), although height was not significantly different at maturity (Table 4.3).

Table 4.3 Crop growth parameters at different physiological stages for sole wheat and wheat under the canopy of *F. albida* in 2014. DAP = days after planting and LAI = Leaf area index, SL = Senesced leaves and No = number. Standard deviations from the mean are given in the parenthesis.

	Crop growth parameters			
	Tillers[1]	Plant height		SL
Treatments	(No plant $^{-1}$)	(cm)	LAI	(No plant $^{-1}$)
30 DAP				
Sole Wheat	2.55 (1.3)	26.59 (3.8)	1.9 (0.9)	-
Wheat + *Faidherbia*	2.77 (1.2)	28.94 (3.7)	2.4 (1.2)	-
P-values	0.087	**0.000**	**0.000**	-
40 DAP				
Sole Wheat	3.47 (1.9)	34.46 (5.3)	4.7 (1.6)	2.08 (0.09)
Wheat + *Faidherbia*		36.0 (4.2)	5.7 (2.3)	1.01(0.12)
P-values	*0.14*	***0.001***	***0.000***	*0.184*
60 DAP				
Sole Wheat	4.27 (2.7)	71.98 (6.4)	7.8 (2.5)	3.75 (0.96)
Wheat + *Faidherbia*		69.22 (8.3)	8.6 (3.4)	2.22 (0.70)
P-values	***0.000***	***0.000***	***0.012***	***0.007***
Harvest[2]				
Sole Wheat	4.0 (1.4)	70.3 (2.2)	-	-
Wheat + *Faidherbia*	4.2 (1.6)	73.4 (2.6)	-	-
P-values	*0.388*	*0.213*	-	-

[1] Tillers per plant at harvest represent the number of fertile tillers

[2] All values at harvest represent the mean values of the 2013 and 2014 seasons.

More grains per spike were recorded under compared with outside the canopy of *F. albida* (Table 4.4). Grain filling period was significantly longer under than outside the canopy of *F.*

albida (Table 4.4). Simulations using long-term weather data demonstrated that most of the longer period of grain filling was due to lower temperatures under the canopy (Table 4.4). The decrease in mean maximum daily temperature by 5 degrees slowed maturation of wheat (MDTM) by about 9 days. Almost all of the observed delay in duration to maturity (ODTM, also about 9 days) appeared to be attributed to the decrease in maximum temperature as a result of shading by *F. albida* crowns.

Table 4.4 Final yield and yield components for wheat grown under and outside canopy of *F. albida* for three consecutive seasons. ODTM = Observed duration to maturity and MDTM = Modeled duration to maturity. Standard deviations from the means are given in the parenthesis.

Treatments	Wheat yield and yield components				
	Grains (spike$^{-1)}$)	Total biomass (t/ha)	Grain yield (t/ha)	ODTM (days)	MDTM[1] (days)
2013 season					
Sole wheat	39.7 (1.7)	5.7 (1.2)	1.9 (0.3)	103	100
Wheat + *Faidherbia*	42.3 (2.5)	7.9 (0.7)	2.4 (0.2)	111	110
P-values	*0.021*	*0.002*	*0.002*	*0.000*	-
2014 season					
Sole wheat	40.5 (3.7)	7.4 (1.5)	2.6 (0.8)	101	96
Wheat + *Faidherbia*	42.8 (3.4)	8.9(1.6)	3.3 (0.7)	113	107
P-values	*0.000*	*0.000*	*0.000*	*0.000*	-
2015 season[2]					
Sole wheat	N/A	1.8 (1.0)	0.7 (0.4)	97	90
Wheat + *Faidherbia*	N/A	3.3 (1.3)	1.3 (0.6)	104	97
P-values		*0.000*	*0.000*	*0.000*	-

[1]MDTM for 'wheat + Faidherbia' was simulated by lowering daily mean maximum temperature 5 degrees, keeping all the other variables constant.

[2]2015 season was an El Nino season, where wheat yield was very low, but still better closer to tree canopies. Other parameters were not included in the analysis for this season.
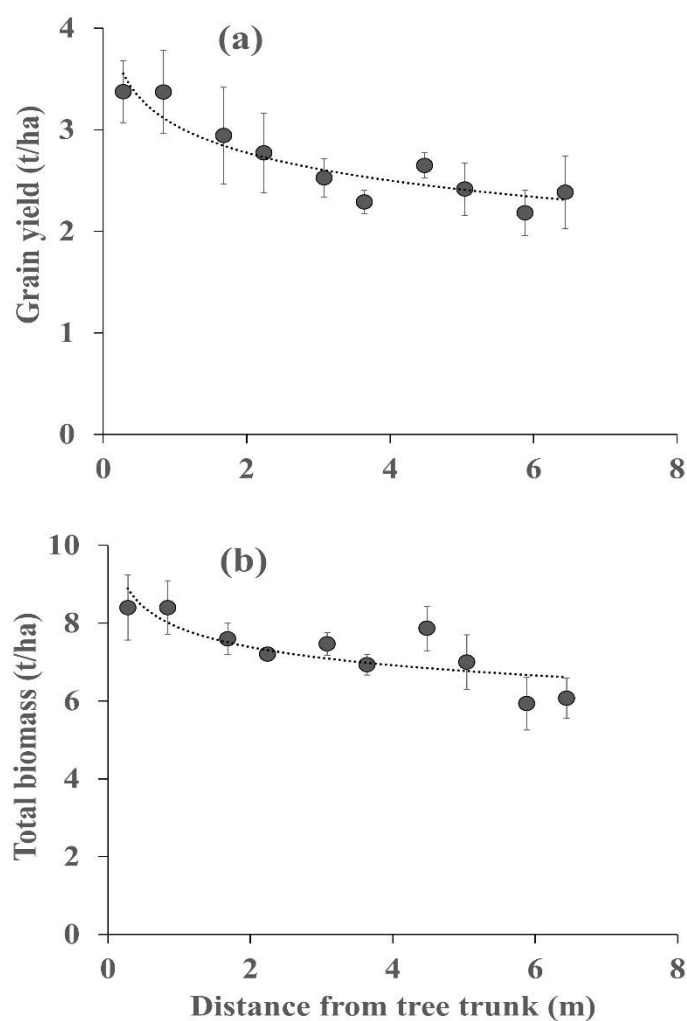
Figure 4.4 Grain yield (a) and total aboveground biomass (b) as a function of distance from the trunk of F. albida in 2014. The error bars represent the standard deviations.

An average increase of 23-26% in grain yield and 20-39% in aboveground biomass was found under compared with outside the canopy during normal seasons of 2013 and 2014 (Table 4.4). While both yields were low in 2015, an El Niño year, an average increase of up to 85% in grain yield and 83% in aboveground biomass was found under compared with outside of the canopy (Table 4). Wheat grain yield and straw yield decreased exponentially with increasing distance from the tree trunk up to a distance of about 5.5 m (Figure 4.4). Beyond this, yield of straw and grain was similar to that in the sole wheat.

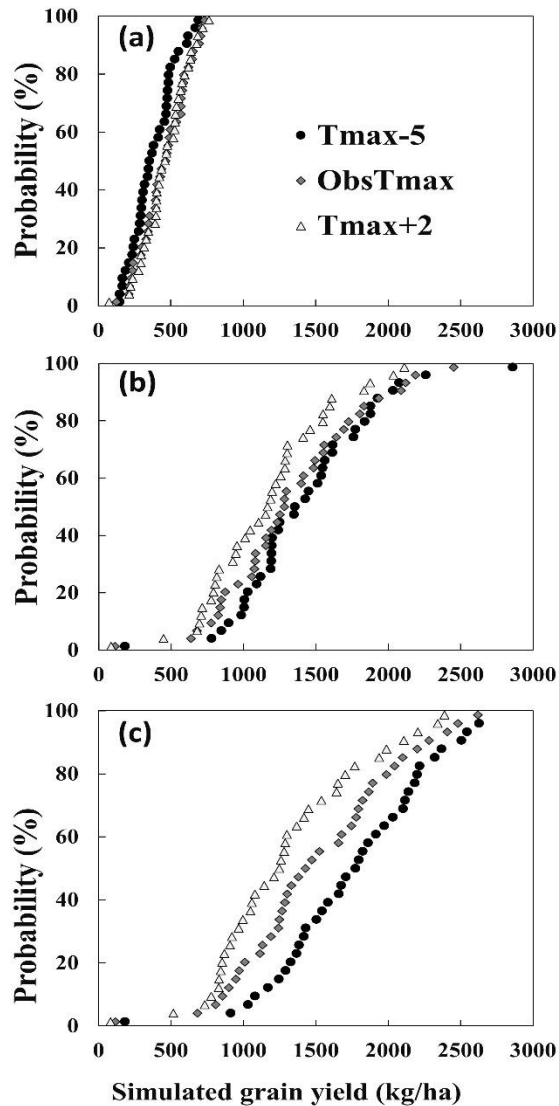### *4.3.4. Sensitivity of wheat productivity to microenvironment*

Figure 4.6 Cumulative probability distribution of simulated wheat yield (using APSIM) for three levels of maximum temperature (maximum temperature reduced by 5°C (Tmax-5), observed maximum temperature (ObsTmax) and maximum temperature increased by 2°C (Tmax+2)) and three nitrogen rates (0kg/ha (a), 69kg/ha (b) and 120kg/ha(c)) for 38 rainy seasons (from 1977 to 2015). Simulations with factorial combination of radiation, temperature and N rates are given in Figure S4.3 of supplemental material.

In general, simulated wheat grain yield was more sensitive to changes in nitrogen rates than to changes in radiation or maximum temperature (Figure 4.5). Without N added (0 kg ha⁻¹), simulated wheat grain yield was extremely small and showed no clear response to changes in temperature (Figure 4.5a). With a medium N rate (64 kg ha⁻¹), an increase in maximum temperature by 2°C resulted in an average yield decline of about 7% compared with yield simulated using observed maximum temperature (Figure 4.5b). With this rate of N, a 5°C reduction in maximum temperature had a positive impact on simulated wheat yield. Under this

scenario, yield increase of about 16% was observed compared to yield simulated using observed maximum temperature.

With the highest N rate (120 kg ha^{-1}), a decrease from +2 to -5°C in maximum temperature increased simulated grain yield by 36.9% in comparison to yield simulated for observed maximum temperature (Figure 4.5c). An increase in maximum temperature by 2°C resulted in about 12.5% decrease in yield compared with simulated yield using observed maximum temperature. Similarly, simulated yield was about 24.3% greater when the maximum temperature was decreased by 5°C from the observed maximum.

4.4. Discussion

4.4.1. Partitioning, not competition, prevails in the F. albida-wheat interaction

A key question in tree-crop interaction in moisture stressed areas is whether the trees could absorb moisture from deeper horizons leaving more available topsoil moisture for annual crops. We observed no variation in topsoil moisture content between treatments (Figure 4.2). Because wheat tends to utilize moisture preferentially in the topsoil (Ngigi *et al.*, 2006), a treatment with no wheat, i.e. sole tree, would be expected to exhibit extra moisture available in the topsoil. Both components (tree and wheat) can potentially extract moisture from the topsoil (Smith *et al.*, 1997; Van Noordwijk *et al.*, 2015). Thus, we expected the least moisture content in the topsoil would be found in treatments involving tree-crop interaction, which was not observed in the current study. While, this could suggest the absence of intensive competition for moisture in the topsoil, it could also be attributed to the reported reduction in evaporation from the soil surface under tree canopies, leading to greater soil moisture in the top soil (Lin, 2010).

On the other hand, at critical stage of grain filling (Figure 4.2c), there was less moisture in deeper soil horizons when trees were present, except for the 2015 El Niño season where the tree alone treatment had more water in the subsoil. The tree roots apparently derive more of their

moisture from deeper horizons hinting at 'niche differentiation' between tree and annual crop (García-Baquero *et al.*, 2016). The increasing gap in moisture contents (decreased under tree-wheat and increased for sole wheat) at greater depths in the soil indicates that the tree can extract more water from deeper layers. Trees extracted water from deeper soil profiles, while millet extracted water from the topsoil, especially during moisture stress periods.

In addition, sole trees had more moisture in deeper soil horizons and later in the seasons compared with tree-wheat treatments, supporting the notion that niche differentiation could be driven by competition for moisture (García-Baquero *et al.*, 2016). Late in the season when ground water table recedes and competition for soil moisture is likely to intensify between tree and crop roots, deep-penetrating roots of *F albida* can capture moisture from deeper soil horizons (Canham *et al.*, 2012). This would enable the shallow-rooted wheat to extract soil moisture in the top soil with minimal competition from tree roots. Thus, the association of the two species utilized more water than any of the two species in isolation, implying that systems that involve trees have increased water use efficiency. This corroborates previous reports from other systems, where presence of trees increased resource capture in maze systems (Lott *et al.*, 2009).

Although soil fertility improvement effects of parkland trees are well established (Boffa, 1999; Kho *et al.*, 2001; Gelaw *et al.*, 2015; Sileshi, 2016), we found no evidence of enhanced soil organic matter under the canopy of *F. albida.* Yet, we did measure increased concentrations of available mineral N under the tree crowns (Figure 4.3a). Yengwe *et al.* (2017) also found faster rates of N mineralization close to F. *albida* crowns. However, it has been contested whether trees actually increase soil fertility or redistribute it (Bayala *et al.*, 2014), although N2-fixing trees such as *F. albida* undoubtedly add N to the production system (Giller, 2001).

4.4.2. F. albida buffers wheat against extreme temperatures and radiations

Our conclusion that resource partitioning may improve the productivity of understorey annuals concurs with studies from savannah (Ludwig *et al.*, 2004), the Sahelian parklands (Kho *et al.*, 2001) and other tropical agricultural systems (Black and Ong, 2000). Whether the improved nitrogen and soil moisture under crowns lead to enhanced productivity depends on the impact of trees on the understorey microenvironment. *F. albida* buffered wheat against heat stress at critical reproductive stages (anthesis-grain filling). Peak temperatures above 28°C for consecutive days can slow development in wheat, especially during reproductive stages (Fischer, 2011; Lobell *et al.*, 2012). Such temperatures, which are common in the study area, could result in heat stress that reduces spike length and the number of seeds per spike (Acreche and Slafer, 2009), leading to significantly less grain yield (Zhao *et al.*, 2014). In addition, reduced heat stress optimizes photosynthetic rates (Al-Karaki, 2012). Under projected climate change scenario, temperature in the area is expected to increase in the range of 1.4-4.1°C by 2080 (Kassie *et al.*, 2014). Such variation in temperature was reported to cause about 50% reduction in wheat grain yield (Asseng *et al.*, 2011), magnifying the importance of *F. albida* trees as an affordable and locally available adaptation strategy (Lin, 2007; Mbow *et al.*, 2014).

Simulation results suggest the lower temperature also explains the longer grain filling period for wheat under the canopy of *F. albida* compared with sole wheat (Table 4). High temperatures shorten the duration of the pre-anthesis period in wheat (Al-Karaki, 2012). Shortening of the growing season, resulting in more rapid crop maturity and reduction in yield, is one of the challenges from climate change on agricultural production (Anwar *et al.*, 2015). *F. albida* shade moderates wheat against such heat extremes, increasing the duration of these period, hence increased productivity in wheat.

F. albida moderated wheat against the excessive radiation in this semi-arid area (Figure 4.3b). A PAR up to 2200µmol m^{-2}s^{-1} measured from outside *F. albida* shade for most of the season is above the optimum for wheat (Motzo *et al.*, 2013). Such intense radiation causes photo-inhibition during biomass accumulation in wheat (Acreche and Slafer, 2009), causing decreased aboveground biomass. Similarly, improved maize yield as a result of microclimate modification was reported from other tree-based systems (Black and Ong, 2000).

4.4.3. *F. albida delays wheat senescence and lengthens grain filling*

Slower leaf senescence was observed when wheat was grown under tree compared with wheat in full sun (Table 4.3). Leaf senescence in wheat is a physiological adaptation to moisture and heat stress (Motzo *et al.*, 2013). Delayed senescence, perhaps as a result of shade, increases rate and duration of photosynthesis, enhancing assimilation and dry matter accumulation (Al-Karaki, 2012; Sanou *et al.*, 2012). In turn, a lengthened grain filling period (Table 4.4) allows wheat to use more resources (water and nutrients) and produce heavier grains (Lobell *et al.*, 2012). Although delayed grain filling may have a negative impact on productivity when soil moisture (Fischer, 2011; Lobell *et al.*, 2012) or other resources (Anwar *et al.*, 2015) are limiting, it can be beneficial when sufficient water and nutrients are available to utilize.

4.4.4. *F. albida improves overall productivity of wheat*

A larger leaf area of wheat under the canopy of *F. albida* (Table 4.3) could result in more wheat aboveground biomass (Guendouz *et al.*, 2016). Although there were significantly more tillers during the vegetative stage under crowns (Table 4.3), we did not observe significantly more fertile tillers at harvest. Perhaps more abortion occurred under than outside the canopy, which is common for wheat under terminal stress (Al-Karaki, 2012). However, infertile tillers still contribute to more biomass. While Fischer (2011) reported that the number of grains per spike is negatively related to the number of tillers, our result suggested that wheat under *F.*

albida shade apparently overcame this by reducing its spike fertility index i.e a greater proportion of infertile tillers compared with wheat in the open. Grain development is strongly affected by moisture and heat stress during anthesis and pre-anthesis (Fischer, 2011; Al-Karaki, 2012). The buffering effects of *F. albida*, increasing moisture availability and limiting heat stress during these stages, could have facilitation effects for wheat under the canopy.

The yield reduction we observed with increasing distance up to about 5 m from tree trunk contradicts previous studies, which found maximum yield close to the canopy edge for millet (Boffa, 1999; Kho *et al.*, 2001; Sanou *et al.*, 2012). This difference could probably be attributed to three main reasons. First, the heavy pruning of *F. albida* in the study area might reduce the effect of shading on crop growth, contrasting with the large canopy of unpruned trees in other regions (Boffa, 1999). Second, compared with millet, the C3 wheat could tolerate shade better, leading to better performance closer to tree trunk. Third, the inherently porous soil of the current study area may enhance better infiltration under tree canopies, leading to higher infiltration around the canopy edges than in open fields, compared with soils with poor structures common in the other drylands (Bargués Tobella *et al.*, 2014).

4.4.5. *Wheat yield is highly sensitive to N and slightly sensitive to reduced temperature*

Without applied N (Figure 4.5a), simulated wheat grain yield was extremely small and did not respond to changes in temperature regimes. While increasing N rate strongly increased yield, reduced temperature, which is observed under *F. albida* shade, has a positive impact on wheat yield. An extended grain filling stage (Table 4.4) is one of the ways that lowered temperature improves yield (Craufurd and Wheeler, 2009). However, delayed phenology could potentially reduce wheat yield where resources (soil water and nutrients) are limited (Fischer, 2011; Lobell *et al.*, 2012; Kassie *et al.*, 2014; Anwar *et al.*, 2015). By contrast, *F. albida* delays

the phenology of wheat, whilst providing it with more resources (water and available nitrogen) under the tree.

4.4.6. F. albida in the context of sustainable intensification and adaptation to climate change

In the Central Rift Valley of Ethiopia, temperature is predicted to increase at the rate of 0.12–0.54°C per decade and crop growing season will be shortened to about 76 days (Kassie *et al.*, 2014). At this rate, temperature in the year 2100 would be about 4.1°C higher compared with 1980. Similar predictions exist for sub-Saharan Africa and the Sahel (New *et al.*, 2011). With climate change impact of such magnitude, most farming systems in the region are predicted to collapse, unless they undergo transformational adaptation (New *et al.*, 2011; Rickards and Howden, 2012). While Challinor *et al.* (2014) classified crop-level adaptations of existing cropping systems, such as changes in varieties, planting times, irrigation and residue management as typically 'incremental', shifting from sole cereals to farm forestry, leading to a relatively profound change in the system could offer a transformational adaptation option (Rickards and Howden, 2012). Major and purposeful action at national level, such as the plan by the government of Ethiopia to incorporate 100 million *F. albida* trees into smallholder farming systems (Mekonnen *et al.*, 2013) has a potential to achieve this. *F. albida* based systems could provide a triple benefit of climate change mitigation (Bayala *et al.*, 2006), ecosystem based-adaptation (Matocha *et al.*, 2012) and improved food security (Mokgolodi *et al.*, 2011; Mbow *et al.*, 2014).

4.5. Conclusion

Scattered *F. albida* trees improve wheat productivity significantly by buffering the crop against extreme temperature and by facilitating increased water use efficiency. With heat and moisture stress likely to be more prevalent in the face of climate change, these trees provide a

starting point to design more resilient and climate smart farming systems. The facilitative impacts were found to be localized close to the tree trunk and were more pronounced during extremely dry season. In addition to its positive impact on wheat productivity, trees at the same time would provide more feed, fuel and construction material, as well as other ecosystem services (carbon sequestration, reduced soil erosion, habitat, etc.). This is a rare triple win for climate smart agriculture, providing enhanced productivity and adaptation while contributing to mitigation in the face of climate change.

Acknowledgement

Over-harvesting and limited regeneration: Population decline in *Faidherbia albida* (Del. A. Chev) threatens environmental sustainability in the Rift Valley of Ethiopia

Abstract

Scattered *Faidherbia albida* trees provide multiple ecological, biodiversity and production benefits across the Sahel. Its population possibly faces degradation challenges from intensive use and blocked regeneration. We explored bottlenecks for regeneration and modeled its population dynamics. A 100 treated seeds were planted on experimental plots and exposed to combinations of grazing and plowing treatments. In addition, population survival and age-class distributions were investigated within 100 permanent plots scattered over the landscape. A dynamic model was used to predict future trends in population. On experimental plots, exposure to the first two months of dry season resulted in a quarter of seedling mortality. Exposure to season-long aftermath grazing caused significantly greater seedling mortality. Results from the permanent plots showed that adult population density was only 4.2 trees ha^{-1} and dominated by old age classes. 65% of the total population were older than 30 years. The density for juveniles was 1.4 individuals ha^{-1}. The annual rates of decline were 1.2%, 51.3%, and 63.2% for adults, seedlings, and saplings, respectively. We predicted *F. albida* population will start to decline within 1-2 decades to eventually fall below one tree per hectare within 60 years, under current scenario. The modelling highlighted that limited seed source, caused by intensive use, was the main constraint for the degradation of *F. albida* parkland. As the population decline leads to land degradation and threatens the capacity of the system to adapt to climate change, appropriate land management policy that ensure seed production would avert current trends in population decline.

5.1. Introduction

Parkland agroforestry systems, mainly dominated by scattered *Faidherbia albida* (Delile. A. Chev) trees, are integral part of farming systems across the Sudano-Sahelian zone, a region that expands from the Atlantic coast to the Red Sea coast. These parklands provide various ecological and production benefits. *F. albida* sequestrates carbon in the form of soil organic matter (Gelaw, Singh & Lal 2014) and accumulated woody material (Breman & Kessler 2012). It increases microbial biodiversity in the fragile ecosystems (Willems *et al.* 2000), maintains overall agrobiodiversity (Khumalo *et al.* 2012) and improves primary productivity in the drylands (Sileshi 2016). It was reported to harbour an invertebrate-rich foraging habitat for birds (Stoate, Morris & Wilson 2001). In the tree-scarce landscapes of the Rift Valley of Ethiopia, where millions of smallholder farmers maintain *F. albida* on crop and pasture fields, it could serve as a keystone species (Manning, Fischer & Lindenmayer 2006). Sileshi (2016) found that the presence of *F. albida* trees tended to increase cropping systems diversity and crop yields in sub-Saharan Africa (SSA), improving food security in the region (Mokgolodi *et al.* 2011).

F. albida improves soil fertility by fixing atmospheric nitrogen (Giller 2001), recycling nutrients from deep soil horizons (Canham *et al.* 2012) and protecting soil nutrients against erosion through root anchorage (Van Noordwijk *et al.* 2015). As a result, soil organic matter (Gelaw, Singh & Lal 2014) and exchangeable cations (Umar, Aune & Lungu 2013) were higher under its canopies. *F. albida* parklands improve soil moisture availability through increased infiltration (Sileshi 2016) and reduced evaporation from the soil surface (Bayala & Ouedraogo 2008). Bayala *et al* (2014) reported that parklands reduce the risk of climate change to smallholders in SSA. These parklands also buffer crops against extreme heat and provide an affordable climate-smart production option (Sida *et al.* In press). Various other studies reported that trees maintained in croplands sustain cereal yields (Bayala & Ouedraogo 2008) and

improve household food and nutritional security (Akinnifesi *et al.* 2011). Ludwig *et al.* (2004) suggested that *F. albida* parklands in savannah ecosystems play significant role in understory microclimate amelioration.

The multiple benefits that *F. albida* brings in these fragile ecosystems begs the question whether the current management practices ensure sustainability of its population? This tree is rarely planted, although farmers might assist natural regeneration from sprouts and coppices. Farmer-Managed Natural Regeneration (FMNR) has widely been advocated for its contribution to re-greening and rebuilding resilience in the Sahel (Sendzimir, Reij & Magnuszewski 2011). FMNR may facilitate the adoption of evergreen agriculture (Garrity *et al.* 2010), improving livelihoods for millions of smallholder households (Akinnifesi *et al.* 2011).

Although there are various indications that the parklands are degrading (Mbow *et al.* 2015), neither the current population status nor the impact of FMNR on *F.albida* has been explored. It was, thus, hypothesized that intensive pruning of branches practiced in the study area may cause limited seed production, reducing the chance of recruitment from seed. High dry season seedling mortality, ploughing, aftermath grazing and browsing may limit juvenile survival. Whereas ungulate browsing reduces woody seedling survival in savannah tree species (Moe *et al.* 2009), aftermath grazing from domestic animals may threaten seedling survival in on-farm species (Marcora *et al.* 2013). Because of the importance of *F.albida* in environmental sustainability and agrobiodiversity of the system, its conservation requires comprehensive assessment of the current status and trends in population. Thus, this study aimed to: (i) explore the current population status, (ii) identify major regeneration bottlenecks and (iii) model future trends in population under different scenarios.

5.2. Materials and Methods

5.2.1. Study area

The study area is located in the Central Rift Valley of Ethiopia (8.509° N, 39.071 E), at an elevation of 1665 m above sea level within the Ethiopian part of the Sudano-Sahelian ecosystem (Figure 5.1). The climate is semi-arid with average annual rainfall of 700 mm yr^{-1} falling mainly between June and October (RSO 2003). The long-term mean minimum daily temperature is 24.2°C and the mean maximum daily temperature is 31°C (Kassie *et al.* 2013).
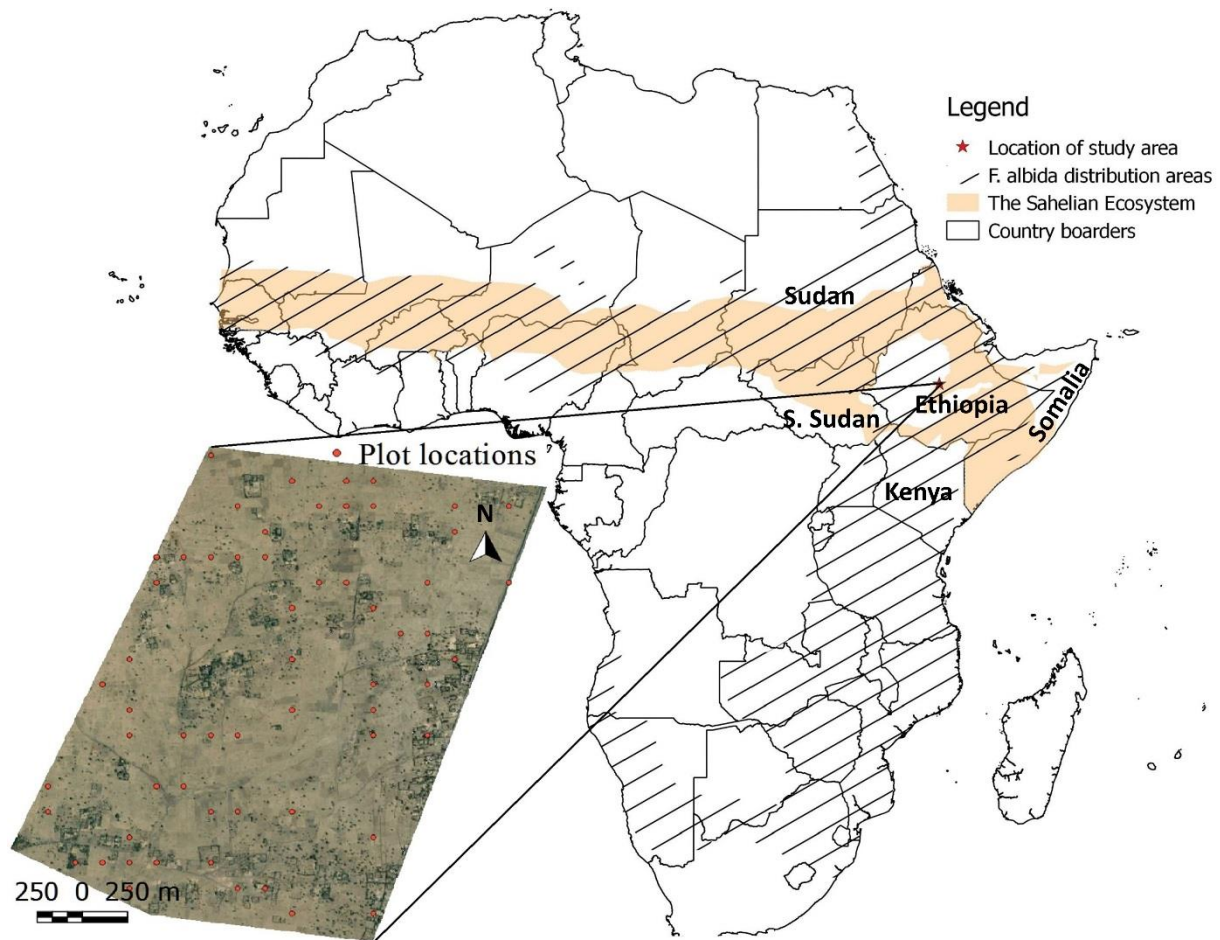

Figure 5.1 Map showing the location of the study area in relation to the Sahelian Ecosystem and major distribution areas for *Faidherbia albida*. The circular dots overlaid the aerial photo of the study area (bottom left) show the sampling locations within the landscape.

Andosol is the dominant soil type (RSO 2003). Sparsely distributed *Faidherbia albida* (Delile. A. Chev) is the main agroforestry species on wheat (*Triticum aestivum* L. var *aestivum*) and *tef* [*Eragrostis tef* (Zucc.) Trotter] fields. The smallholder farming systems is characterized as tree-crop-livestock system (Sida *et al.* 2013). All livestock are limited to pasture lands during the rainy season to avoid crop damage. After harvest, livestock roam freely in agricultural fields.

5.2.2. Seed production and germination

We selected eight *F. albida* trees at random with a diameter at breast height (DBH) ranging from 16-77 cm, to quantify seed production (Experiment 1). As pruning intensity and frequency affect seed production (Schumann *et al.* 2010), we intentionally included three unpruned, three partially pruned and two completely pruned trees (Figure 5.2).
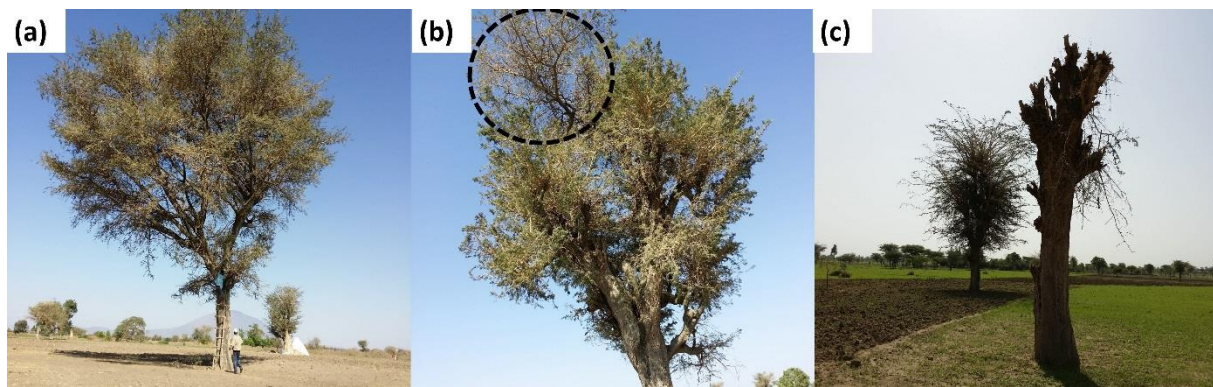

Figure 5.2 *Faidherbia albida* trees (a) unpruned within the last six years, (b) partially pruned within the last three years (part of the branch encircled at the top of the canopy was unpruned over the last six years, while the lower part was pruned four years ago) and (c) completely pruned recently (the tree in the background of figure c was pruned three years ago and did not produce any seed).

We considered a tree to be completely pruned, if all of its branches had been removed at least once within the last six years; partially pruned, if part of its branches had been left unpruned within the last six years; and unpruned, if it had not been pruned in the last six years. We used randomized branch sampling to quantify seed production per tree (Chirici *et al.* 2014). We conducted germination test (Experiment 2) with healthy seeds following Koech *et al.* (2014).

We treated seeds by mechanical scarification with metal clippers to allow imbibition (Teketay 1996). We conducted Experiment 2 only to generate rates for model inputs and did not presented results (we presented these and similar results not included as main findings in the manuscript only as supplemental material).

5.2.3. Regeneration and survival

5.2.3.1 Seedling emergence and survival

In addition to the laboratory germination test, we set an experiment under field condition with treated seeds (Experiment 3) in a split plot design with grazing as a main plot (i.e. open-grazed vs exclosure) and plowing as a sub-plot (i.e. plowed vs unplowed). The treatments were: no plowing-open-grazed, no plowing-exclosure, plowing-open-grazed, and plowing-exclosure. Plots exposed to plowing treatment were oxen-plowed four times following local practice. We used wooden fences to create exclosures. We set the experiment on plots of 4 m by 4 m in four replications and over two seasons (2014 and 2015). We recorded seedling survival at (1) two weeks after planting, (2) two months after the end of rainy season and (3) the end of dry season. We analyzed seedling survival data through repeated measure ANOVA in R (R Core Team 2015). In the model (Equation 5.1), we treated exclosure (i.e. fenced vs open-grazed) as main plot factor. Plowing (i.e. plowed vs unplowed) as sub-plot factor.

$$Y_{ijk} = \alpha + \beta GR_i + \gamma TL_j + \lambda(GR_i * TL_j) + R \qquad (5.1)$$

where, Y_{ijk} seedling survival at different periods, GR_i is the ith grazing exposure, TL_j is the jth tillage treatment, and where, α, β, and λ represented regression coefficients for the main and interaction effects. R was the residual of the regression. As survival data was either count or proportions, we fitted the models following a Poisson distribution.

5.2.3.2. Tree survival and natural regeneration

We explored other mechanisms of regeneration by marking 100 permanent plots within farmers' fields for two seasons (2014 and 2015) (Experiment 4). We used QGIS mapping tool (Westra 2014) to generate geographic grids of 150 m by 150 m overlaid the whole study landscape (i.e., covering a total area 562.5 ha). We created a total of 237 grid points across the focus landscape, out of which we selected a 100 systematically randomized plots (i.e., covering a sampling area of 78.5 ha). We marked circular sampling plots with radii of 50 m at the center of the selected grids. No experimental manipulation was made on the plots in order to represent seedling emergence, survival and population dynamics under farmers' settings. We investigated all *F. albida* trees (adults, saplings, seedlings, root suckers) rooted within the plots over two seasons (2014 and 2015). We classified individuals into seedlings, saplings and adults based on Groenendijk *et al.* (2012). We recorded data (1) at the end of the cropping season, (2) two months after the end of rainy season, (3) at the end of dry season and (4) after seedbed preparation for planting crops was complete, which followed intensive plowing. We assumed data from the first sampling period to represent survival under limited exposure to dry period, no grazing pressure, and without ploughing disturbance; data from the second sampling period to represent survival under some exposure to dry period, high grazing (and browsing) intensity, and no ploughing disturbance; data from the third sampling period to represent survival under exposure to season-long dry period and high grazing pressure and data from the fourth sampling period to represent survival after intensive ploughing disturbance, in addition to season-long grazing pressure and season-long dry period.

In addition, we conducted questionnaires with 60 randomly selected households on how farmers assist regeneration of new individuals, use values of tree prunes and the main reasons underlying the current management. We used the outcomes from this household survey to inform rate variations in scenario modelling. Hence, we did not present it as a separate result.

5.2.4. Growth-ring formation and population age composition

We analyzed discs from six purposively selected *F. albida* trees, from varying DBH ranges, to verify formation of incremental growth rings. We used a standard dendrochronological method for sample preparation and description of growth ring boundaries (Tolera *et al.* 2013). Although a study elsewhere reported that *F. albida* did not show distinct growth-rings (Gourlay 1995), our samples showed the presence of marginal parenchyma bands verifying the formation of growth ring boundaries. We included the outcome of this experiment only in supplemental material, as it was conducted only to verify the existence of growth ring boundaries and decide whether to use ring analysis to estimate age of *F. albida* trees.

Following the verification of growth ring boundaries, we collected increment wood cores from 60 trees at 0.3 m above soil surface. We collected core samples from opposite directions, making a total increment core samples of 120 (Experiment 5). We collected the increment samples purposively from different diameter classes representing the population. We measured height, diameter at breast height (DBH) and diameter at stem base, called 'diameter at stump height (DSH)'. We used core-microtome to estimate the age of sampled trees. We developed a regression equation relating tree ages to the allometric parameters. For all adults rooted in the plots (described above), we measured height, diameter at breast height (DBH) and diameter at stamp height (DSH). We predicted ages of all trees within these plots using the equation developed from increment cores.

5.2.5. Modelling population and regeneration status of F. albida

We modelled the population dynamics of *F. albida,* using the software package SIMILE (Version 6.7) (Muetzelfeldt & Massheder 2003). We explored implications of current management practices (especially FMNR) under different scenarios. We considered seed production scenarios of current practice and increased seed production. Under the current practice, intensive pruning of branches limits seed production (Fig. 2c). Under increased seed

production scenario, trees were left unpruned for at least six years (Fig. 5.2a) or underwent partial pruning (Fig. 5.2b) to allow some seed production. The model assumed natural regeneration as a dynamic process where new individuals are recruited into the mature population, compensating the losses due to mortalities induced by several biotic and abiotic factors. Factors affecting seedling and sapling mortality rates were the main focus. Figure 5.3 represented the model architecture in SIMILE, while Figure S5.1 showed our conceptual approach involving three interrelated submodules.
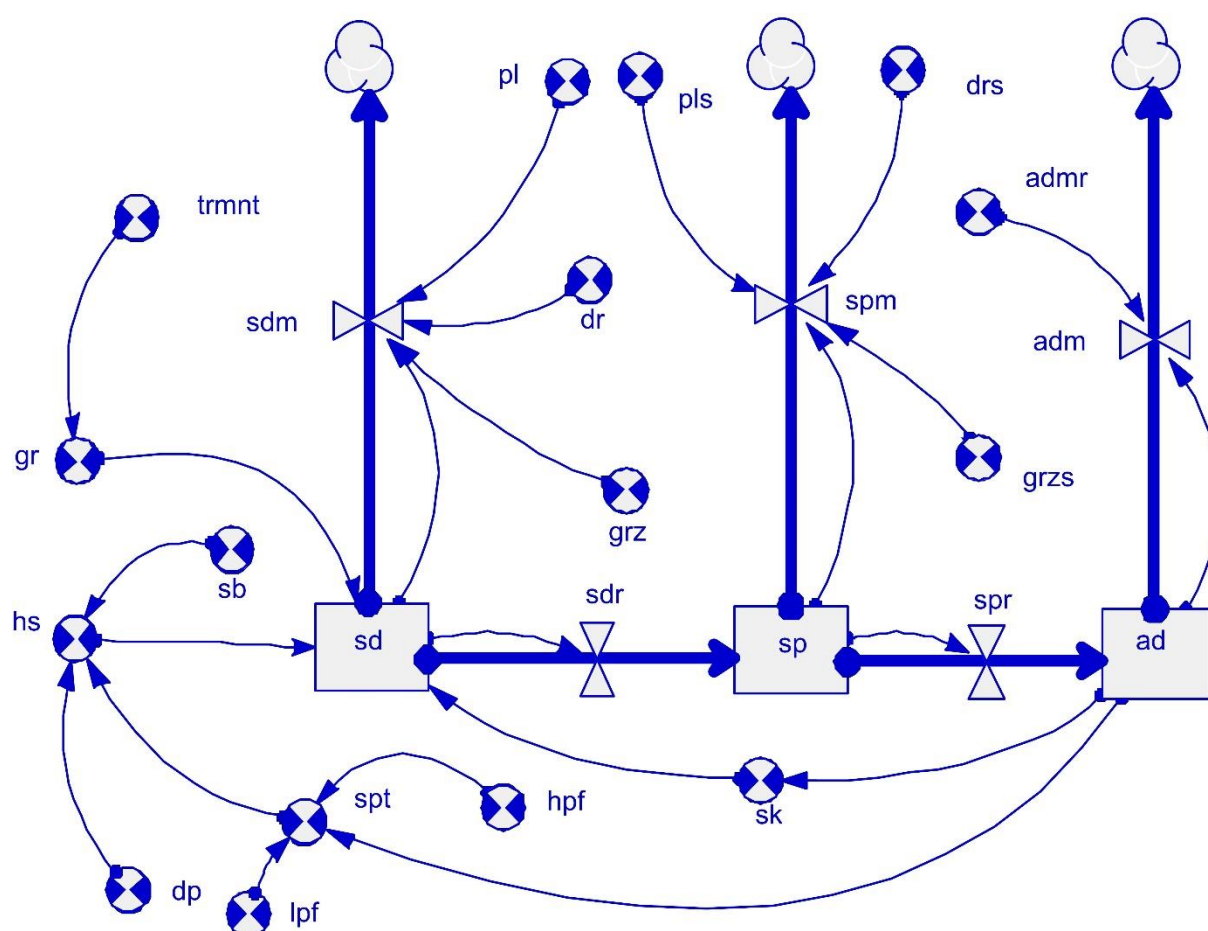

Figure 5.3 Model components for quantitative modelling of the population and regeneration status of *F. albida*. spt = seed production per tree, hpf = high pruning frequency, lpf = low pruning frequency, dp = disease and pest attack on seeds, hs = healthy seeds, sb = seeds from seed bank, gr = germination rate, trmnt = seed treatment, sd = seedling population, sdm = seedling mortality, pl = ploughing impact on seedlings, dr = drought impact on seedlings, grz

= grazing impact on seedlings, sk = seedlings from root suckers, sdr = seedling survival in time, sp = sapling population, spm = sapling mortality, pls = ploughing impact on saplings, drs = drought impact on saplings, grzs = grazing impact on saplings, spr = sapling survival in time, ad = adult population, adm = adult mortality, admr = adult mortality rate.

We presented measured, derived and assumed values of variables used in the equations of the model in the Table S1. We assumed that population drivers in this model affect the transition from seeds to adults and the adult population change depended on natural mortality or removal by farmers. We used model estimated output from two season's data in Experiment 5 to initialize the natural adult mortality. We used Eulers' integration – a time-step integration function – to transport individuals from younger to older adult population age class (Fig. S1). In the model, we used 110 years as a rotation age limit, which was a recorded maximum age from Experiment 5. Rates as inputs for this function were measured mortality rates within each age group and time needed to the next class.

5.3. Results

5.3.1. Current population status, seed production and seedling survival in F. albida

Current density of *F. albida* was sparse for all population stages (Table 5.1). Adult tree density was only 4.2 trees ha^{-1}. The densities for juveniles (seedlings, suckers and saplings) were even lower at 1.4 individuals ha^{-1}. We found 1.9, 0.4 and 0.1 individuals ha^{-1} for seedlings, root suckers and saplings, respectively. The annual rates of decline were 1.2%, 51.3%, and 63.2% for adults, seedlings, and saplings, respectively.

Table 5.1 Stage-wise population density, amount of seeds produced under different pruning regimes and allometric characteristics of *F. albida*.

PP=Partial pruning, NP=No pruning, DBH = Diameter at breast height and DSH = Diameter at stump height. Trees that underwent complete

pruning within the last six years did not produce any seed (zero seeds tree $^{-1}$) and were not included in this Table.

Values	Stage-wise population density (n=256)				Amount of seed produced (n=8)		Biometric parameters (n=256)			
	Adults	Saplings	Seedlings	Suckers	PP	NP	DBH	DSH	Height	Age
	(ha^{-1})	(ha^{-1})	(ha^{-1})	(ha^{-1})	(tree^{-1})	(tree^{-1})	(cm)	(cm)	(m)	(years)
Max	36.9	9.8	12.7	10.2	3478	5190	103.5	118.0	20.0	110
Mean	4.2	0.3	1.9	0.4	2416	4355	29.5	32.2	6.0	42.7
Min	0.0	0.0	0.0	0.0	1869	3620	5.0	6.0	1.8	11.0
SD	6.1	1.4	3.2	1.4	1818	1786	18.0	20.0	3.1	19.6

Faidherbia albida trees did not produce any seed within six years of complete pruning (Table 5.1). Trees that were never pruned within the last

six years produced the largest amount of seeds (4355 ±1786) followed by trees that underwent partial pruning within this period (2416 ±1818).

Immediately after emergence, seedling survival was neither affected by grazing nor plowing (Table 5.2). The trend did not change within the first

two months of dry period, where more than 75% of the emerged seedlings survived.

Table 5.2 Summary of the results of GLMM models for explaining the effect of exclosure and tillage treatments on seedling survival in *F. albida*. Seedling survival 1, 2 and 3 represent seedling survivals at two weeks after emergence, two months after the end of rainy season and at the end of dry season, respectively.

Effects	Estimate	Std. Error	Z-value	P-Value
Seedling survival 1				
Intercept	0.43	0.06	7.63	**0.0000**
Grazing (Exclosed)	0.04	0.08	0.48	0.6320
Tillage (Unplowed)	0.10	0.08	1.22	0.2230
Grazing*Tillage	-0.05	0.11	-0.42	0.6710
Seedling survival 2				
Intercept	0.43	0.06	7.4	**0.0000**
Grazing (Exclosed)	-0.01	0.08	-0.04	0.9670
Tillage (Unplowed)	0.03	0.08	0.37	0.7130
Grazing*Tillage	-0.02	0.12	-0.17	0.8640
Seedling survival 3				
Intercept	0.32	0.10	3.20	**0.0030**
Grazing (Exclosed)	0.48	0.13	3.71	**0.0002**
Tillage (Unplowed)	0.06	0.14	0.42	0.6730
Grazing*Tillage	-0.07	0.18	-0.36	0.7153

After 10 months (i.e. at the end of dry season), grazing started to show a significant negative effect on seedling survival (*P < 0.001*). After this period, seedlings on exclosed plots were 48% more likely to survive than seedlings on open-grazed plots (Table 5.2). On exclosed plots, 32.3% of the seedlings survived after full dry season. On open-grazed plots, the survival was even lowered to 21% (i.e. seedling survival was about 53% higher on exclosed plots compared

to open plots), indicating that grazing had significant impact on survival when persisted for longer than 10 months. By contrast, plowing manifested only a non-significant negative effect on seedling survival within this period.

5.3.2. Tree age-size distribution and allometric relationships in F. albida

Tree age was significantly correlated to DBH ($R^2 = 0.82$, $P < 0.001$), DSH ($R^2 = 0.81$, $P < 0.01$) and height ($R^2 = 0.56$, $P < 0.001$). However, the combination of the three parameters predicted tree ages with a slightly improved accuracy ($R^2 = 0.83$, $P < 0.001$, $RMSE = 6.6$) (Figure 5.4).
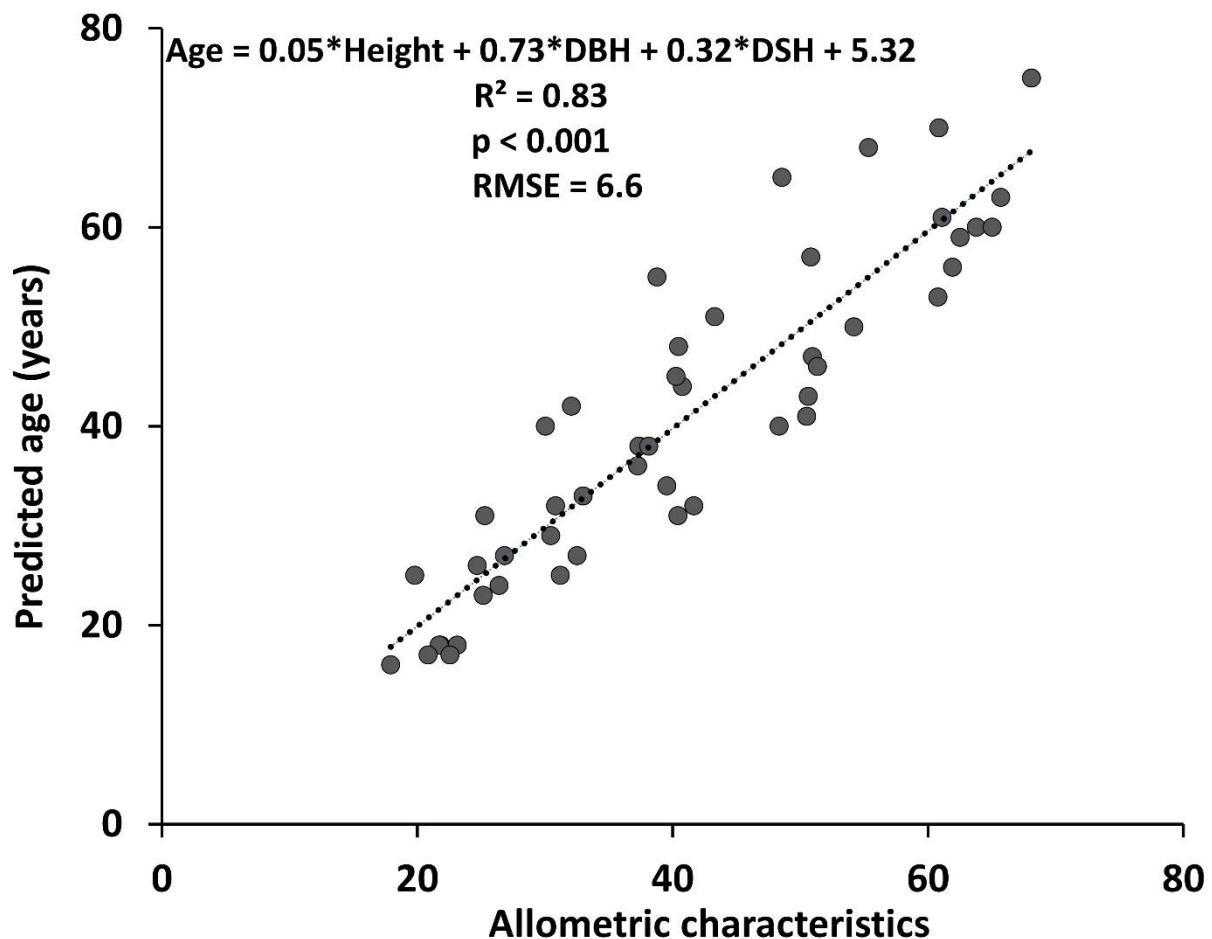

Figure 5.4 Relationship between tree age and tree allometric characteristics (DBH = diameter at breast height [cm], DSH = diameter at stump height [cm], and height [m]) for *F. albida* in Mojo, Ethiopia.

Figure 5.5 presented the DBH class (a) and age class (b) distribution for the population, computed using the regression equation in Figure 5.4. Figure 5.5b showed that the majority of trees (65% of the total population) were older than 30 years. Only 48 % of the population is younger than the current average age of 42 years. The maximum age recorded from the current study area was 110 years, although less than 3% survived beyond 75 years. There are hardly any adult trees younger than 10 years and only 9.4% of the trees were younger than 25 years, indicating little recruitment happened within the last 2-3 decades.
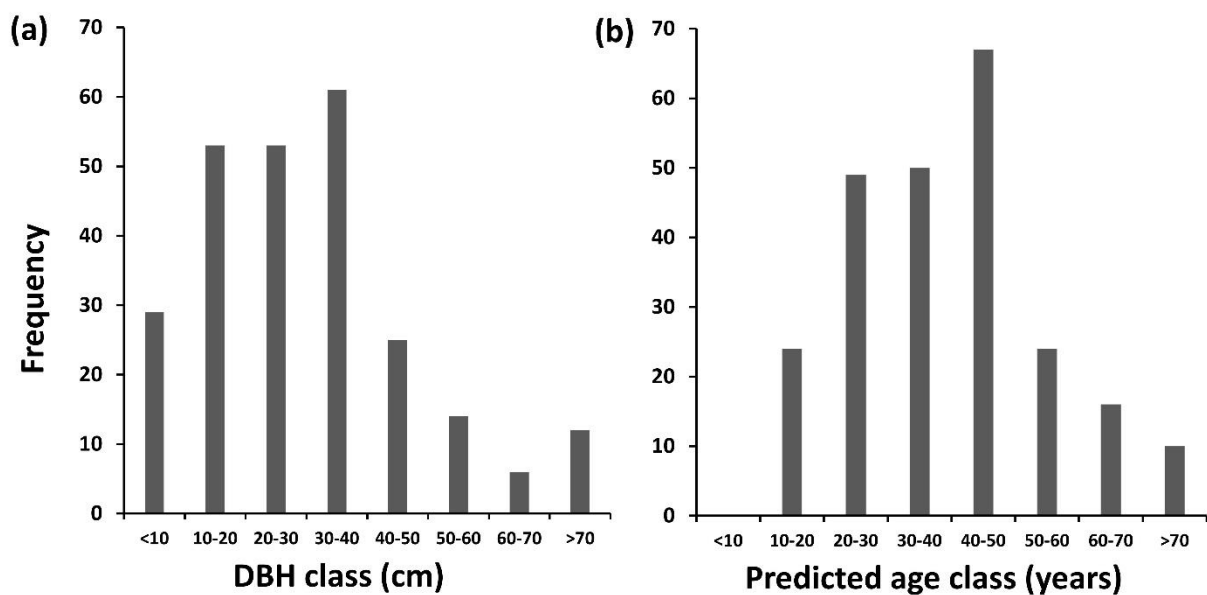
Figure 5.5 Measured diameter at breast height (DBH) class (a), and predicted age class (b) for *F. albida* population in mojo, Ethiopia

5.3.3. Modeling F. albida population status

Under current tree management, pruning intensity is the most important factor in affecting the future population status (Figure 5.6). The current practice pruned trees completely every 2-3 years (Figure 5.6, left), limiting seed production (Table 5.1). If the current trend continues (Figure 5.6, left), population will start to decline within 1-2 decades, depending on seedling and sampling survival rates. It would eventually fall below one tree per hectare within the next 60 years. With management practices that lower both seedling and sapling mortality rates (Figure

5.6c, left), tree density would increase to 6.9 trees ha⁻¹ in the next decade. However, that

increase would only delay the on-set of population decline, which would fall below the base

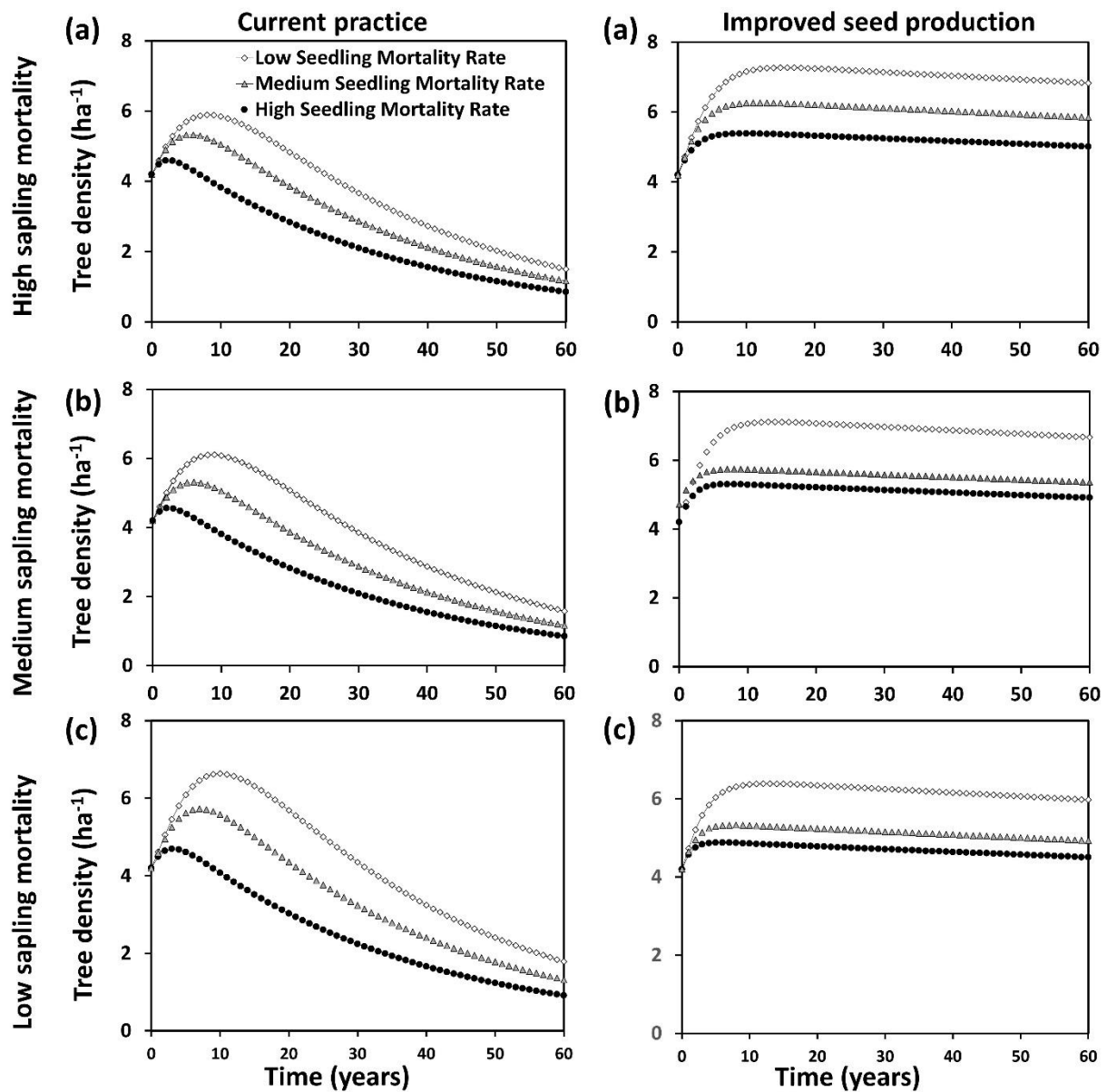level within a little over two decades (Figure 5.6c, left).

Figure 5.6 Simulated population status of *F. albida* for different seedling mortality rates and

under low (a), medium (b), and high (c) sapling survival rate for the current management (left)

and under improved seed production (right). Low, medium and high survival rates were 0.2,

0.5 and 0.8 respectively. The difference in input between 'current practice' and 'improved seed

production' is only the amount of seeds produced per tree.

While there is a clear decline in tree densities for all scenarios under current management practices (Figure 5.6a-c, left), the rate of decline is generally more sensitive to seedling mortality than sapling mortality. For example, increasing sapling survival by 50% with the current practice (Figure 5.6a-c) resulted in less than 5% increase in tree density. By contrast, increase in seedling survival rate by the same rate resulted in an increase of more than 15% density after 60 years.

5.4. Discussions

5.4.1. Dry season seedling survival in F. albida was low

Our results showed that more than a quarter of emerged seedlings did not survive the first two months of dry season, regardless of exclosure and plowing treatments (Table 5.2). Such early seedling mortality had been attributed to moisture limitation starting from early in the season (Stave *et al.* 2005), damages from invertebrates (Shaw, Keesing & Ostfeld 2002) and rodent attacks (Goheen *et al.* 2004). Ten months after planting, a third of these seedlings survived in the enclosures compared with only 21% in the open plots, indicating that damage by other factors than grazing contributed to seedling mortality. Enclosures from livestock improved seedling survival significantly (seedling survival was about 53% higher on exclosed plots compared with open plots). This result contrasts with Moe *et al.* (2009) who found seedling survival to be as high as 78% in enclosures compared with only 32% in open plots. However, the current findings corroborate the detrimental effect of open grazing on seedling survival of Oak parklands (Tyler, Davis & Mahall 2008), paddy fields (Hocking & Islam 1995) and woody patches (Wassie *et al.* 2009). As a result, open grazing has been a strong land management policy debate in Ethiopia (Baudron *et al.* 2015).

Although a study from the Mediterranean reported that tractor plowing lowered seedling survival in Oak (Pulido *et al.* 2010), the current study found no effect of plowing on seedling survival. The contrast could be due to two possible reasons. First, in the current study,

intensive plowing was done only at the beginning of the subsequent season, where data was not included in the analysis. Second, tractor plowing is likely to be more damaging to seedlings than the oxen-drawn plough of the current study.

5.4.2. Faidherbia albida tree age is linearly related to combinations of DBH, DSH and height

Understanding population structure and pattern enables the design of appropriate parkland tree management (Pulido, Díaz & de Trucios 2001), whereas methods to assess population age-size distribution are complex and costly (Tolera *et al.* 2013). Regression equations to estimate population age-class distributions from simple allometric measurements could be effective. Such approach has rarely been used for parkland species. We found a good fit for regression curve relating DBH, DSH and tree height to tree ages. This corroborates the findings of several studies that reported DBH as a good estimator of age in forest trees (Hunter *et al.* 2013) and savannah species (Mbow *et al.* 2013). Our results indicated that allometric approaches can also be used to estimate tree age structure accurately for tree species with reverse phenology concurring with the findings of Gebrekirstos *et al.* (2014).

5.4.3. Current F. albida population is sparse and declining

In addition to low overall population density, the ratio of juveniles to adults was very low – about 0.3 young individuals for every adult. Low juvenile to adult ratio is a manifestation of a population facing extremely high juvenile mortality risk (Gonzalez, Tucker & Sy 2012). Although adult mortality rate was not significantly high in *F. albida*, new recruitment was very limited, making population decline inevitable (Lykke 1998).

From our study, the maximum age of *F. albida* was 110 years (Table 5.1 and Figure 5.5b) agreeing with previous findings that reported a maximum age of 100 years (Barnes & Fagg 2003). *F. albida* trees as old as 150 years had been reported from southern Africa (Wood 1989).

A small juvenile population, such as found in this study, is a characteristic of fast-growing species with an even population growth and high survival rate (Lykke 1998). By contrast, *F. albida* showed uneven population growth and high mortality risk (Figure 5.4 and 5.6). A special case where small juvenile population may not necessarily indicate population decline happens for long-lived parkland species with very low mortality, such as Baobab (Venter & Witkowski 2010). *F. albida* does not fall under such demographic groups as it is comparatively short-lived. In thriving populations, the size-class distribution graph (Figure 5.5) normally follows an 'inverted-J' shape – large number of individuals with younger size classes and small number of older individuals – (Tolera *et al.* 2013). Bell-shaped population distribution, similar to Figure 5.5b, indicates a declining population (Pulido, Díaz & de Trucios 2001), except where juvenile survival rate is very high. As juvenile survival for *F. albida* is extremely low, the bell-shaped population distribution (Figure 5.5) clearly indicated that its population is declining.

The abundance of individuals established after the last 35 years was clearly low (Figure 5.5b). The population distribution of trees older than 40-50 years followed the 'inverse-J' shape characteristic of a thriving population, hinting that population decline started about half a century ago. A study from the same area reported that adult *F. albida* was 4.7 trees ha^{-1} (Poschen 1986). We found 4.2 trees ha^{-1}, indicating only a minor decline (about 11%) occurred over the last three decades. In contrast, population modelling from the current study revealed that the rate of population decline over the next three decades would be faster than the corresponding period in the past. Thus, the fast population decline rate appeared to be a relatively recent phenomenon with the possibility to intensify in the future. Similar trends of population decline were reported for parkland trees within several human dominated landscapes in the Sahel (Venter & Witkowski 2010), North Ethiopian savannah (Tolera *et al.* 2013), West African savannah (Lykke 1998), the Mediterranean (Pulido, Díaz & de Trucios 2001) and the Kalahari (Steenkamp *et al.* 2008). Although the causes of population decline ranged from angulate

browsing (Moe *et al.* 2009) to suspected climate change (Gonzalez, Tucker & Sy 2012), it has long become a hot discussion topic in environmental conservation (Sendzimir, Reij & Magnuszewski 2011).

5.4.4. Limited recruitment due to lack of seed source caused population decline in F. albida

Both observation and population structure study pointed to a population decline in *F. albida*. However, disentangling the main factors driving this decline requires a systems dynamic modelling approach (Muetzelfeldt & Massheder 2003). Although seedling and sapling mortality affected the rate of population decline (Figure 5.6), lack of seed source appeared to be the most threatening factor for population decline. Several previous studies have reported grazing and low dry season survival as common bottlenecks for parkland tree regeneration (Stave *et al.* 2005; Pulido *et al.* 2010; Venter & Witkowski 2010). While the current study corroborated these findings on the impact of dry season survival and grazing, it underlined low seed production as the most important bottleneck. While improved seedling and sapling survival through management practices, such as fencing, may improve short-term population status, lack of seed source would be the most important constraint for population sustainability in *F. albida* (Figure 5.6a–c, right). Even under high sapling and seedling mortality rates (Figure 5.6a, right), population can be maintained at least at its current level, only if seed availability could be improved. Although seed dormancy (Barnes & Fagg 2003), seed herbivory (Shaw, Keesing & Ostfeld 2002), and diseases and pests (Moe *et al.* 2009) may constrain seed availability, inhibited seed production in the current study area arose from pruning practices – complete removal of all branches – mainly done for provisioning services. A payment for ecosystem services (PES) scheme that rewards farmers to change their management practices by compensating the foregone value of fencing and fuel material – to ensure seed multiplication

– could prevent tree population decline. Such policies have been successfully implemented elsewhere to change farmers practices (Smith *et al.* 2013).

5.6. Conclusions

In general, within season survival of *F. albida* seedlings was affected by dry season browsing and drought but not by ploughing. Even if current tree and regeneration management practices were changed to improve recruitment, the population would still continue to decline to a critical density of less than a tree per hectare within half a century from now. Unless seed production is increased – by decreasing pruning frequency and/or intensity – the density of *F. albida* will start to fall within a decade. As the population decline threatens agrobiodiversity and the capacity of the system to adapt to climate change, payment for ecosystem services that would encourage farmers to change their pruning frequency and/or intensity would ensure seed production, hence averting the population decline.

Acknowledgement

General discussion and conclusions: Sustainable intensification of smallholder farming systems in Ethiopia – What roles can scattered trees play?

Chapter 6

In this Chapter, I look back to the previous chapters and synthesize the main findings. I demonstrate how the results of each chapter are interlinked, what they imply for smallholder agricultural systems and what potential exists for tree-based sustainable intensification pathways. I address the main question as to whether trees within crop fields can play a role in sustainable intensification of smallholder faming systems. For an affirmative answer, I further try to answer the question: what actions maximize overall benefits from scattered trees? For non-affirmative answer, I will explore ways that possibly minimize negative trade-offs.

Chapter 2 showed the prevalence of trade-offs in most tree-crop systems. The economic gains from trees were not large enough to compensate for tree-induced crop yield penalties. Trees in tree-crop mixed systems are retained for their direct values and income stabilization. Importantly, this chapter found an evidence that the application of certain agronomic practices could minimize tree-crop trade-offs. In Chapter 3, I showed that the effect of N and P fertilizers on tree-crop interactions depends on tree species, crop species and agroecological conditions. In scattered *F. albida*-wheat systems of semi-arid Ethiopia, N fertilizers could be saved, with localized application of P fertilizer close to tree crowns. In *G. robusta*-maize systems of semi-arid Rwanda and *A. tortilis*-maize systems in semi-arid Ethiopia, under canopy maize did not respond to N and P fertilizers applied at recommended rates. Chapter 4 explored the exceptionally positive effect of *F.albida* for wheat productivity. This chapter revealed a potential rare triple win (productivity, mitigation and adaptation) role scattered trees could play in smallholder farming systems. Chapter 5 followed on from Chapter 4, and explored the status and future trend in the population of 'the good one' – *F. albida* – among the studied tree species scattered within crop fields.

In the following sections, I explore the potential and actual roles of scattered trees in smallholder systems. I focus on the direct economic gains from these trees in light of the

implication of tree and/or crop management. Using the results in previous chapters as a backdrop, I discuss the contribution of scattered trees to the sustainable intensification of smallholder systems from the concepts of multifunctional agriculture, agroforestry, crop agronomy, landscape ecology and socio-ecological systems.

6.1. The role of scattered trees in smallholder farming systems

This section is limited to the discussion of the roles of scattered trees in line with the current findings. Based on my findings, farmers maintain scattered trees for different reasons and under different management approaches. As indicated in Chapter 2, scattered trees are maintained and managed for their direct contribution to household income diversity and stability. This chapter also showed that tree-crop trade-offs are prevalent at farm scale, whereas certain agronomic practices can be followed to reduce them at field scale. Chapter 4 showed that selected tree species could boost crop productivity in addition to those roles, especially through buffering wheat against climate variability and change. In the following sections, I will discuss the effects of scattered trees on crop productivity and direct utilization values.

6.1.1. Productivity effects

The results in Chapter 2, Chapter 3 and Chapter 4 revealed that only one out of the five investigated scattered tree species had a positive effect on crop productivity. As shown in Chapter 2, *Cordia africana* resulted in up to 78% reduction in maize yield compared with open field. The reduction improved, but remained 20% under 'good agronomic practices' with this tree species. In Chapter 3, *Grevillea robusta* and *Acacia tortilis* resulted in maize yield reduction of up to 100% (i.e., complete failure), depending on the amount of seasonal rainfall. These two species caused severe crop yield penalty during severe dry seasons. The yield penalties could not be avoided under various combinations of recommended N and P fertilizers under tree canopies. Results in Chapter 4 are the exception, where *Faidherbia albida* resulted

in up to 75% increase in wheat yield under its crowns compared with open field wheat, during the unusually dry season. Contrasting with the main established hypothesis that scattered trees could improve crop productivity, the current findings showed that maize did not benefit from any facilitation effects of tree canopies when grown under *A. tortilis, C. africana, C. macrostachyus* and *G. robusta*. The mechanisms underlying the negative outcomes from tree-maize interaction could vary for each of the scattered tree species. In this section, I will explore some plausible ecological, physiological and agronomic principles that may lead to the negative outcomes from the interaction of each tree species with maize.

A. tortilis is a nitrogen fixing tree that was repeatedly reported to improve soil nutrient contents beneath its crowns (Hagos & Smit 2005; Noumi *et al.* 2011). However, the nutrient enrichment associated with the tree crowns did not translate into higher yields for maize growing under its canopy compared with maize growing in the open. Noumi *et al.* (2011) similarly reported that higher nutrient content under the crowns of *A. tortilis* did not lead to superior yields in barley. The renowned hydraulic redistribution of soil moisture by this tree species in the Savannah ecosystem (Ward, Wiegand & Getzin 2013) did not translate into tree-maize facilitation. Moisture stress usually results in reduced nutrient use efficiency in maize (Waraich *et al.* 2011), leading to yield penalties.

Tree-crop interaction in *Cordia africana* and *Croton macrostacyus* are studied under sub-humid conditions, with the mean annual rainfall of 1280 mm (Yadessa *et al.* 2001). Competition for moisture is less likely to determine the outcome of the interaction. Figure 6.1 shows that soil moisture during maize growth period did not differ for under canopy and outside canopy plots for *Cordia africana* (a) and *Croton macrostachyus* (b). For these species, soil moisture stress cannot be the major cause of reduced maize yield presented in Chapter 2.
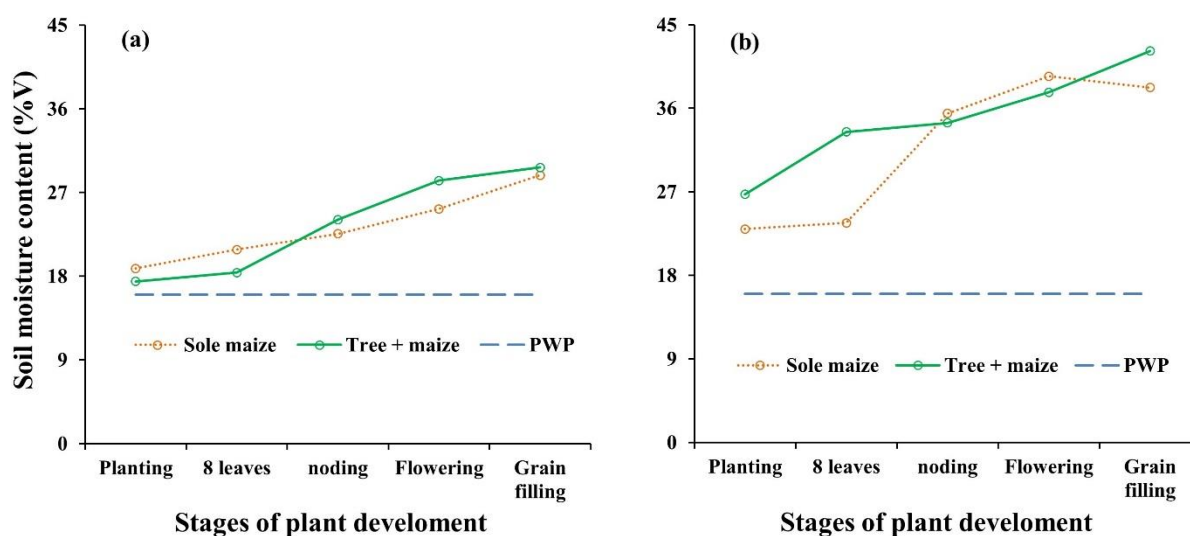
Figure 6.1 under canopy and open field volumetric soil moisture content for *Cordia africana* (a) and *Croton macrostachyus* (b) in 2014 for Bako, Oromia, Ethiopia. The broken horizontal line represents the permanent wilting point (PWP) for the soils in the area.
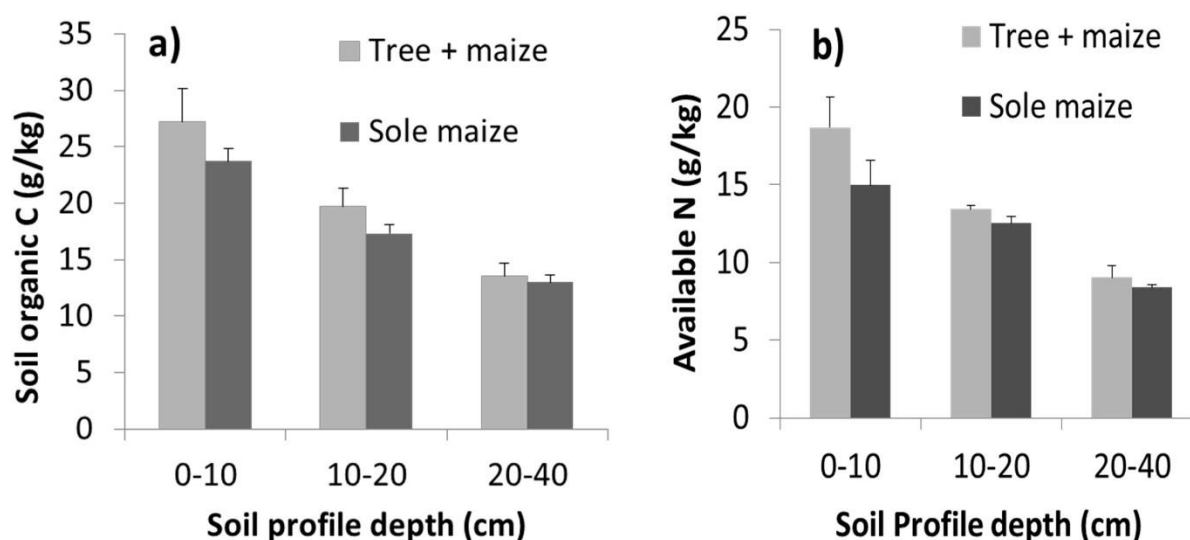

Figure 6.2 Soil organic carbon (b) and available Nitrogen outside and under the canopy of C. africana along soil profile depth. Error bars represent the standard deviations.

However, these tree species are broadleaved with heavy branching. They may impose heavy shade during the crop growing season. Even with canopy pruning, the fast regenerating branches can create dense canopies that may block photosynthetically active radiation (PAR), especially during the maize reproductive stages of anthesis and grain filling. Shade reduces dry

matter assimilation rate, transpiration rate, stomatal conductance and water use efficiency in maize (Ding & Su 2010; Dufour *et al.* 2013). Reduction in temperature because of tree shades could also reduce yields in C4 maize (Lobell *et al.* 2011; Challinor *et al.* 2014), unlike a C3 wheat, which could benefit from reduced temperature (Chapter 4).

The other 'usual suspect' for yield reduction in tree-crop interaction is tree-crop competition for soil nutrients. It has been widely established that soils under the canopies of *C. africana* and *C. macrostachyus* are more fertile than soils in the open fields in their vicinity (Yadessa *et al.* 2001; Zebene 2003; Gindaba *et al.* 2004; Gindaba *et al.* 2005; Yadessa *et al.* 2009; Moges *et al.* 2013). The analysis of organic carbon and available nitrogen conforms with these findings for *C. africana* (Figure 6.2). Similar trends were observed for P and K (Sida *et. al.* 2015, unpublished data). Although both *C. africana* and *C. macrostachyus* are not nitrogen fixers, the higher soil nutrients under their crowns can be caused by *in situ* processes such as litter fall, root activities and nutrient (re)cycling (Gindaba *et al.* 2005). External factors such as bird/wildlife droppings, weeds, cow dung and urine may also contribute to the improved soil fertility under tree crowns (Schroth & Sinclair 2003). Their roots may protect soil nutrient loss from erosion and leaching through anchorage (Reubens *et al.* 2007). Regardless of such improvements in soil fertility, the current study showed that there is no improvement in under canopy crop yield for most scattered tree species.

Maize biomass and grain yield were reduced under the canopy of *G. robusta* compared with outside its canopy. This results contrast with Sanchez (1995) who regarded this tree to be non-competitive, and hence, recommended for its high potential benefit in tree-crop mixed systems. By contrast, Ong *et al.* (2000) reported that maize yield was up to 50% lower under mature *G. robusta* trees, similar to the current finding. They concluded that the reduction in yield was mainly a result of belowground competition for moisture rather than aboveground competition

for light. This could be mainly because of concentration of *G. robusta* roots in the topsoil, coinciding with maize roots (Smith *et al.* 1999). As results in Chapter 3 showed, the negative effect from *G. robusta* on maize was significantly less with the addition of N and omission of P than the addition of P and omission of N fertilizers. This is perhaps because of proteoid roots of *G. robusta* that are known to assist in P uptake (Skene *et al.* 1996). Such enhanced P uptake, may improve P use efficiency of the tree, allowing the maize to utilize the remaining P.

Chapter 4 dealt with the exceptional case of *Faidherbia albida*, where its scattered presence enhanced wheat productivity under the semi-arid conditions. The reverse phenology (i.e., shedding leaves during wet season and remaining green during dry season) was not observed in the current study area. Reduced temperature because of its shade benefited wheat growth and development. Recently, *F. albida* has become the sole 'saviour' in almost all problems threatening stallholder farming systems in SSA. It has been hailed for its role as an agro-ecological solution for intensification of agricultural systems (Breman 2011) by making agriculture evergreen (Garrity *et al.* 2010). It has been trusted to save Africa's soils (Glover *et al.* 2012), helping smallholders in SSA to achieve food and nutritional security (Mokgolodi et al. 2011) and improved livelihoods (Faye et al. 2010). It has been considered instrumental to buffer smallholder farming systems against climate risk (Bayala et al. 2014), protect loss of biodiversity (El Tahir *et al.* 2010) and help smallholders adapt to climate change (Garrity 2012). Results in Chapter 4 explored some of the mechanisms whereby *F. albida* buffers smallholders against the risk of climate change and offer an affordable adaptation and mitigation option without compromising crop productivity.

While these scattered tree species can be a good starting point for sustainable intensification of smallholder farming systems in SSA, viewing a single species as the 'holy saviour' for smallholders against all their problems must be handled with caution. It could lead to over-

simplification of a complex problem that, perhaps, cannot be solved through any single intervention.

6.1.2. Roles in direct income generation

As discussed in the above section (6.1.1), only the exceptional *F. albida*-wheat resulted in crop yield gains. Thus, the main question is 'why do farmers still maintain scattered trees, regardless of the trade-offs?' This question was the central theme of Chapter 2. In this section, I explore the 'why' and 'why not' of farmers' decision to integrate trees into crop fields under smallholder conditions, especially when these trees have clear negative effects on crop yields.

To make a point that high Gross National Product (GNP) alone does not guarantee welfare for citizens, and hence cannot be a good measure of economic prosperity, Davidson (2001) wrote a book with a title 'You can't eat GNP'. Similarly, a Nobel laurate and renowned agriculturalist, Norman Borlaug said 'farmers can't eat potential' to emphasize that anything that cannot be translated to utilization under smallholder conditions remains useless. Analogous to these arguments, it can be said that 'farmers can't eat soil organic matter', which scattered trees are confirmed to improve. Neither can they eat agrobiodiversity. Thus, most of the 'ecological benefits' of scattered trees should be weighed against the practical and immediate benefits that local farmers earn from their presence. In fact, scattered trees can save soils from erosion and leaching loses by providing soil cover and root anchorage (Gessesse *et al.* 2015). They improve soil fertility through improved soil organic matter (Yadessa *et al.* 2009). They may improve soil moisture content through reduced surface evaporation and hydraulic lift (Bargués Tobella et al. 2014). In general, the combinations of these ecological processes enhance overall land health (Frizzo & Vasconcelos 2013). Hypothetically, these trees could help to reconcile the often conflicting goals of ecological restoration and conservation with agricultural production (Benayas *et al.* 2008). Thus, they potentially provide a balancing strategy and facilitate adaptive

responses to climate change in human modified landscapes (Manning *et al.* 2009). Farmers may understand and acknowledge the ecological roles of scattered trees (Palmer & Wadley 2007; Meijer *et al.* 2015), although their decision to integrate trees into crop fields may not arise from this knowledge. Chapter 2 showed that tree-crop trade-offs are pervasive. However, trees provide utilities such as firewood, fencing material and charcoal that otherwise cannot be affordable to smallholders. These utilities can be traded locally, providing smallholders with stable income unlike the fluctuating incomes from maize and other annual crops. The immediate decision on whether to integrate trees with crops appears to depend highly on these direct utilities rather than higher overall farm scale returns. While it is not contested that scattered trees can improve landscape functions and long-term sustainability of the production system (Tscharntke *et al.* 2011), my findings suggest that these functionalities are not the main drivers for tree-crop integration in smallholder systems.

The economic rationality theory strongly emphasizes that preference and decision behaviour of smallholders is strongly determined by their consistent preference for more income over less (Timmer 1988). Smallholders are, thus, assumed to apply their capital, labour and land resources in such a way as to maximize outcomes (Kremer & Lock 1993). Contrasting with this, findings in Chapter 3 and Chapter 4 showed that the decision behaviour in smallholders is not necessarily according to economic rationality theory. This could suggest that the main objectives of poor rural households, especially under remote locations where markets are imperfect, may not necessarily follow economic rationale and optimization behaviour (Klapwijk *et al.* 2014). A 2017 Nobel laureate Richard Thaler called such a behaviour a 'limited rationality', where people simplify decision-making by focusing on the narrow impact of each individual decision rather than its overall effect (Thaler 2010). Under the current study setting, where smallholders are constrained by various institutional and environmental factors (Stahl 1990; Gebreselassie, 2006), these trees could provide a 'safety net' against volatility in grain

prices, which is a common characteristic of many countries in SSA (Minot 2014). Scattered trees additionally provide households with income 'safety net' and are used as relatively stable source of household income when annual crops fail (Cadisch *et al.* 2004). Although small compared with income from annual crops, income from scattered trees could provide a diversified income option. Such rationale, whereby smallholders managed risk through the practice of economies of scope (i.e., preference of small but low risk incomes over higher, but more risky incomes) rather than economies of scale that could be achieved through specialization, were also reported elsewhere (Chavas and Di Falco 2012). The current findings may conform to the arguments by Rasmussen and Reenberg (2012) that not just economic rationality influences decision in smallholder farmers. They challenged the assumption of smallholder farmers as either economically irrational or economically rational and argued that smallholders prefer to manage resources in such a way as to minimize risk for the household.

6.1.3. Role in mitigation and adaptation to climate change

Both the causes and consequences of climate change are global. However, it has been continuously emphasized that poor and smallholders farmers in the developing world will suffer the most from the consequences of climate change (Bohle *et al.* 1994; Downing *et al.* 1997; Jones & Thornton 2003; Morton 2007; Harvey *et al.* 2014; Cohn *et al.* 2017). Mitigation of climate change, which involves reduction of the emission of greenhouse gases, was the first response to climate change-related problems. Mitigation largely relies on elaborate commitments and related institutional and financial mechanisms that often involve complex political negotiations, to ensure the main emitting countries took actions to reduce their emissions (Huq & Reid 2004). Such interventions are usually made through state-sponsored, donor-funded, and NGO-operated projects. It is vulnerable not only to donor policy, but to changes in government, to markets incentives, to public sector financial constraints and

inefficient management (Altieri *et al.* 2012). Predictably, the smallholder farmers in many developing countries are not part of the negotiations.

Chapter 2 and Chapter 3 showed that scattered trees negatively affect food crop production, although the magnitude of the effect can be reduced through management. Despite the dominance of negative trade-offs, scattered trees remain an integral part of the smallholders systems in Ethiopia and beyond. Some of farmers' main non-yield rationale for tolerating trade-offs with crop productivity and maintain these trees were discussed in sections 6.1.2. In this section, I discuss the (potential) role of scattered trees in climate change mitigation and adaptation.

Factors that cause climate change are mostly globally derived, but mitigation strategies will be difficult to attain globally. We then need to focus on locally specific mitigation (or at least adaptation) strategies. Scattered trees sequester carbon (Nair *et al.* 2010) and protect soil organic carbon from being released to the atmosphere (Gindaba *et al.* 2005; Atangana *et al.* 2014), hence providing climate mitigation options that are within the reaches of poor smallholders. In addition to their roles in mitigation, scattered trees help to sustain many ecosystem services such as increasing species diversity (Brussaard *et al.* 2010; Kalaba *et al.* 2010), enhancing wildlife habitats (Lovell *et al.* 2010), fostering natural food webs (Maas *et al.* 2013), fostering water infiltration and improving soil and ecosystem health (Garrity *et al.* 2010; Nair *et al.* 2010). Such functionalities enhance the biological efficiency of smallholder systems, where the sustainability of the system is attained through internal processes and recycling of materials (Altieri *et al.* 2012). Such biologically efficient systems are more likely to be resilient to climate change than systems that are just economically efficient (i.e., systems where profit maximization is the goal). Scattered trees in landscapes, patches of trees, social fencing (farm enclosures etc.) are some promising adaptation alternatives. In that regard, even those trees that

lead to negative crop productivity can help to ameliorate local climates for understory flora and fauna. Small and affordable steps that are locally popular, such as the retention of centuries-old scattered trees within agricultural fields, could provide viable adaptation options for smallholders.

Chapter 4 presented the case of a special scattered tree species – *F. albida*. This species lowered water stress in wheat during critical stages of development, leading to superior yields under its crowns. Under the climate change scenario in the central rift valley region of Ethiopia, precipitation will be lower and irregular (Kassie *et al.* 2015), increasing the importance of systems that improve water use efficiency. While temperature in the region is already above optimum for wheat production, predictions show that temperature could be about 4°C higher (compared to the 1980 base temperature) before the end of this century (Kassie et al. 2015). The buffering effect of these trees would, thus, becomes even stronger. While not all trees explored showed positive effects on understorey crop under the current climate, their buffering role could be more significant under temperature increases projected for climate change scenarios of the future.

6.2. Rationale for tree-crop integration in smallholder farming systems

The main scientific hypothesis that underlies integration of perennials (i.e., scattered trees) and annual crops mixed in a single field stems from an ecological concept of 'niche partitioning', whereby the roots of scattered trees capture resources from deeper soil horizons that annual crop would not reach to absorb (Cannell *et al.* 1996). This has been the main ecological and production basis on which most tree-crop mixed systems have been promoted (Sanchez 1995), although results for enhanced productivity have been unconvincing (Ndoli *et al.* 2017). In this section, I will discuss this scientific rationale, which is mainly based on the ecological principle of coexistence, and the rationale of smallholders, which is mainly based on their real life

realities and experiences of managing complex systems. I mainly discuss how promotion based on solely ecological concepts could be mythicized, especially when viewed in light of the realities of smallholders by taking examples from Chapter 2 and Chapter 3. I will then attempt to link how the mismatch between the myths and the existing realities could affect the future of scattered trees.

6.2.1. Smallholder realities and the myth of scattered trees in crop fields

Scattered trees within crop fields may have countless ecological benefits within the farming systems (Lovell *et al.* 2010; Tscharntke *et al.* 2011). However, their presence cannot be considered as a 'free lunch' (Van Noordwijk *et al*. 2015). Trees have well established root systems, while annual crops usually have shallow roots that are often limited to a few centimeters in the topsoil. If trees and crops compete, trees almost always win. From their recent extensive review of the importance of trees in rural landscapes, Percival *et al.* (2014) rightly emphasized that scattered trees are 'underrated environmental resources'. However, results in Chapter 2 and Chapter 3 indicated that scattered trees within agricultural landscapes might not be so underrated. Their overall effect on crop performance was negative, with the exception of *F. albida* presented in Chapter 4. In a review of the influence of single-trees in agricultural systems, Rhoades (1996) summarized that only *F. albida* had a positive effect, whereas all the other scattered trees showed negative effects on the crops growing under their crowns compared with those growing in the open fields. This was true even where the presence of those trees resulted in a positive role for soil nutrients and soil structure, creating patches of fertile spots within landscapes. Rhoades (1996) concluded that the conditions that generated the positive yield effects under *F. albida* are rather unique combination of increased soil fertility without the associated limitation in light or water. Thus, efforts that attempt to capitalize on the positive ecological roles of single trees within farms for the positive productivity in crops need to

differentiate (1) where tree effects can be aggregated to have positive outcomes and (2) where species-specific effects can be managed to reduce negative outcomes.

One of the central questions in my study was 'do scattered trees improve crop yield?' From Chapter 2 and Chapter 3, the answer to this question is emphatically '*no*'. Since Rhoades (1996) concluded the effect of scattered trees on crop yield to be negative, with the exceptional *F. albida*, more than 50 studies exploring the effect of scattered trees within farming systems were published from SSA. I explored the findings reported in 21 of these publications, which were directly focused on the impacts of scattered trees on crop productivity. In this section, I attempt to summarize some of the findings of these studies and discuss them in light of my own findings.

Almost all of the studies reported mainly positive effects on soil nutrients, soil carbon and soil water contents under the canopies of scattered trees. Only a few studies reported neutral effects and no study reported a negative effect. The positive effects make scattered trees very important from an ecological perspective. However, the main objective for the farmers is possibly crop productivity, rather than maintained ecological integrity. In this regard, most of the studies reported negative effects of scattered trees on crop yields (Wilson, Brook & Tomlinson 1998; Rao et al. 1999; Boffa et al. 2000; Samba 2001; Fadl & Gebauer 2004; Coulibaly et al. 2014; Hussain et al. 2015; Ndoli et al. 2017). The findings in Chapter 2 and Chapter 3 also mirror the predominance of negative effects of trees on crop yields. This shows improved crop yield is not one of the strong benefits of scattered trees within crop fields, regardless of the improved soil conditions underneath their canopies.

Jonsson *et al.* (1999) reported neutral effects of scattered trees on crops, suggesting that combined beneficial effects of temperature modifications and soil fertility improvement could neutralize the negative effects from belowground competition and tree shade. Other studies showed that the outcome of tree-crop interaction is negative, neutral or positive depending on

crop type (Pouliot *et al.* 2012; Dossa *et al.* 2013; Sinare & Gordon 2015), crop management (Tilander & Ong 1999; Bazié *et al.* 2012; Dossa et al. 2013), the amount of seasonal rainfall (Pouliot *et al.* 2012), tree species (Bazié et al. 2012; Sinare & Gordon 2015) and tree management (Rao *et al.* 1999; Tilander & Ong 1999; Bayala *et al.* 2002; Bazié *et al.* 2012). For example, Bayala *et al.* (2012) showed that scattered trees generally had a negative impact on maize yield under high potential areas compared with low potential areas. They reported that trees almost always had a negative effect on maize in areas where maize grain yield exceeded 2 t ha^{-1}. The probability of tree presence to increase crop yield declined with the potential productivity of the crops in the open fields. A similar trend was observed for sorghum and millet. Such findings underline the importance of approaching tree-based interventions on specific 'option by context' basis, rather than a 'wholesale' approach.

A few other studies reported positive effects of scattered trees on crop yield (Payne *et al.* 1998; Kho *et al.* 2001; Garrity 2012). Interestingly, those positive effects on yield from scattered trees were mostly reported from *F. albida*. In Chapter 4, I explored the physiological and ecological mechanisms by which *F. albida* exceptionally improves wheat yield. The chapter showed that most of the increase in productivity improvement was due to microclimate amelioration and improved resource use efficiency of wheat growing under the crowns of this tree. Contrasting with this finding, Kho *et al.* (2001) attributed about 40% of the yield advantage to improved soil nitrogen and phosphorus. They found the effect of microclimate modification on yield increase negligible. While the crop yield improvement effect of *F. albida* is only an exception, and 'exceptions don't make the rule', the insistent promotion of scattered trees for their 'food security' role is paradoxical. Paradoxical in the sense that promoting these trees for the wrong reasons may threaten their sustainability. In the next section, I discuss how this paradoxical promotion of scattered trees for 'what they are not' rather than for 'what they are' could affect the future of scattered trees.

6.2.2. The future of scattered trees: Doomed or bright?

In the previous section (6.2.1), I demonstrated that improved productivity alone cannot be the ultimate goal to promote scattered trees. Evidences show that scattered trees usually affect crops negatively, with few exceptions. This remains true at least in the short-term. Their potential contribution in the long-term sustainability and resilience of the system could be different. While the ecological importance of trees, which is also acknowledged by smallholders, is not contested, there is remarkable advocacy for these trees as contributors to food security (Section 6.1.2). On the other hand, farmers maintain scattered trees for income stability and direct use values as presented in Chapter 2. Now, the question is 'what will happen to these trees when there would be a possibility to substitute them by other goods?'

I argue that, once smallholders start to access and afford industrial products, such as iron fencing material; scattered trees may become obsolete and removed from agricultural fields. Such land use transition, where substitution of utilization values by industrial products caused land degradation was reported from elsewhere (Lambin & Meyfroidt 2010). Here, I am not arguing that smallholders should not access industrial products. I rather highlight the assumption that the conservation of scattered trees driven by their current utilization roles alone could be misleading, as these roles could be substituted. Chapter 5 showed that scattered trees could be endangered even when they play a rare triple win-win-win role of climate change mitigation, improved productivity and adaptation to climate change.

F. albida, presented in Chapter 4, is a special scattered tree species. It buffers wheat under its crowns against extreme temperature. It extends crop growth duration, providing enough water and nutrients to utilize. In addition to its established ecological roles (Payne *et al.* 1998; Kho *et al.* 2001; Mokgolodi *et al.* 2011), it provides a significant source of energy, construction material and livestock forage (Gebreegziabher *et al.*; Mokgolodi *et al.* 2011; Haile *et al.* 2014;

Luvanda *et al.* 2016). Regardless of the multiple benefits that *Faidherbia* provides, Chapter 5 showed that its population faces the risk of decline under current management. Undoubtedly, the ecosystem services and crop yield enhancement values provided by these scattered trees in the smallholder agricultural landscapes would wane following the tree population decline. This suggests the notion I discussed above that importance in use values, ecological, cultural or productivity roles, may not guarantee the management that lead to sustainability. The findings indicated in Chapter 5 conform to previous studies spanning over four continents by Gibbons *et al.* (2008) who predicted a decline in the population of scattered mature trees under the current management. They suggested an integrated management approach that embraces trade-offs between meeting short-term human needs and maintaining long-term ecosystem services rather than managing scattered trees solely for their contributions to improved landscape functions. Thus, scattered trees should neither be advocated in the 'food first' (Jerneck & Olsson 2014) nor 'conservation first' (Karp *et al.* 2012) manor. In the next section, I will explore how scattered trees can be managed in the context of multifunctional agriculture that maintains agricultural productivity without jeopardizing the conservation roles of these trees.

6.3. Scattered trees and multifunctional agriculture

Recently, Zomer *et al.* (2014) estimated 43% of agricultural land, sustaining almost one-third of the global rural population, has at least 10% tree cover. These scattered 'trees on farms' dominate the vast majority of smallholder agricultural systems. It is almost impossible to ignore 'trees on farms' in attempts that aim to improve the sustainability and productivity of these systems. These trees can be integrated with crop production, creating a multifunctional production system. Wilson (2007) described multifunctional agriculture as an agricultural activity that extends beyond its usual food production emphasis and embraces other functions such as the conservation of natural resources, landscapes, biodiversity and contribution to the

socio-economic viability of production systems. Such definitions appear to give much emphasis on what agricultural systems should provide and less emphasis on what smallholder farmers may prefer. That seems why Renting *et al.* (2009) argued that expressions of multifunctionality should be made, not only in terms of what agricultural systems supply, but also in terms of the demands of the smallholders, the wider society and the political-institutional frameworks in which they operate at specific time and place. As I argued in Sections 6.2.1 and 6.2.2, the rationale of promoting scattered trees in interventions that aim to improve smallholder farming systems need cautious contextualization of the processes and features under which smallholder farmers operate. In this section, I discuss the importance and need of a more pragmatic and less dogmatic approach. In light of the results in Chapter 2, Chapter 3 and Chapter 4, I explore the potential contribution of agronomic practices in enhancing the facilitative effects of scattered trees on crop production. I finally comment on the obsession of the conservation community with the importance of trees within crop fields.

6.3.1. The need for a pragmatic approach

In an inaugural address of his special professorship of agroforestry at Wageningen University, van Noordwijk (2014) stressed that 'agroforestry still doesn't have many silver bullets'. He was adamant that most advocates keep reinventing the wheel and proclaiming that trees with specific properties solve all problems for all farmers. He concluded that only rarely they do solve many problems. Scattered trees have been advocated for a pivotal contribution in multifunctional agriculture (Tscharntke *et al.* 2011), evergreen agriculture (Garrity *et al.* 2010), and sustainable agriculture (Mbow *et al.* 2014). They have been promoted as a basic component for climate-smart agriculture (Scherr *et al.* 2012), sustainable development (Mbow *et al.* 2014a) and sustainable intensification of smallholder farming systems (Smith *et al.* 2012). From the field of planning and policy, Markusen (1999) blamed such concepts as 'fuzzy concepts with

scanty evidences', making them difficult to operationalize. Although such blames maybe very harsh for scattered trees, Faludi (2001) complained rightly about similar concepts that have a "generative capacity" to be created and (re)created in different ways without practical changes on how to operate under real-world circumstances. In most cases, advocates of such regenerative concepts devote much of their arguments on what these concepts are: the definitions. Less often, they include 'how' and 'why' these concepts are useful. The question 'how to operationalize?' has been consistently missing. From conservation science, Reed *et al.* (2017) recently compiled evidences where landscape approaches have been successfully applied and arrived at a similar conclusion about the applicability of these approaches. In their extensive review, Reed *et al.* (2017) could not find a single applied example of a landscape approach in the tropics that adequately demonstrated effective balancing of social and environmental trade-offs.

Van Noordwijk (2014) pragmatically enlisted why and why not farmers may be willing to integrate trees on their farms. Trees compete with crops and reduce yields. Managing trees with crops need extra labour. Trees consume the space that could be used to produce crops or pastures. Benefits may be communal, while externalities can be individual. Refining agroforestry systems that meet local conditions is hard work, which cannot be met by promoting trees on the grounds of their importance at conceptual level. It was emphasized that only the basic concepts of how tree–soil–crop interactions relate to local biophysical environment, market access and labour availability can be extrapolated (van Noordwijk, 2014).

Even where scattered trees have positive all-round effects, their scaled up/out applications require a more pragmatic approach. For example, improved water use efficiency, temperature and radiation regulations, and improved productivity are highly localized about 5 m from tree trunk of *F. albida,* as shown in Chapter 5. Full utilization of the potential of this species, which

could be achieved at full canopy closure, needs increasing its on-farm density from the current 4.2 trees ha^{-1} to about 100 trees ha^{-1}. On the other hand, high on-farm tree density may impair mechanization, consume more space and create within field heterogeneity in resources. Such heterogeneities may lead to the need for heterogeneous crop management, varying fertilizer applications and heterogeneous maturity dates in crops. Rather than a dogmatic promotion of scattered trees, a more pragmatic approach that explores alternative and operational pathways may help to harness the multifunctional potential of these trees, especially under smallholder farmers where alternatives are scarce. In the next section, I explore and discuss how alteration in everyday agronomy may enhance tree-crop facilitation.

6.3.2. Can agronomy enhance tree-crop facilitation?

Until recently, researchers, donors and policy makers pleaded for the equivalent of the 'green revolution' for Africa (Mosley 2002; Annan 2008; Denning *et al.* 2009; Sanchez *et al.* 2009; Nziguheba *et al.* 2010). They sought after the African equivalents of the big leaps in fertilizer use and crop breeding research that performed miracles in Asia. Most often, these efforts of an 'African green revolution' have failed (Vanlauwe *et al.* 2014), leading to a realization that the 'African green revolution need not be a mirage' (Ejeta 2010). The main reasons for the failures of these efforts were partly attributed to the heterogeneity of farming systems in SSA. Tree-based systems are among the main sources of within field heterogeneity. Application of the 'green revolution technologies' to such heterogeneous systems becomes difficult in practice. Simple manipulations of the existing management practices maybe equally or more effective. Chapter 2 and Chapter 3 explored the potential impact of combining certain agronomic practices with scattered trees within crop fields. The main question was 'can agronomic managements reduce trade-offs in tree-crop interactions?'

Agronomic practices recommended under conventional open field conditions did not prove to reduce tree-crop competition and enhance facilitation (Chapter 3). The exception was *Faidherbia*-wheat interaction, where localized use of phosphorus fertilizer could enhance facilitation. By contrast, results in Chapter 2 from farmers' fields hinted that certain agronomic practices can reduce tree-induced trade-offs. In this section, I will draw on results from N management, tillage frequency, rate of herbicide from chapter 2 to discuss how agronomic practices may enhance facilitation in tree-crop interaction. For example, Figure 6.3a shows under canopy maize did not respond to any rate of urea below the recommended rate for open field (i.e., 46 kg ha^{-1} N). Maize under the canopy started to respond to N rates larger than 58 kg ha^{-1}. For under canopy, the response did not plateau even for rates in excess of 138 kg ha^{-1} N, indicating that marginal rate of return from additional N did not start to decline. On the other hand, maize in the open field responded positively starting with N rates as low as 12 kg ha^{-1}, suggesting that under canopy maize has lower NUE. Similarly, Batish *et al.* (2007) reported low nitrogen-use efficiency for wheat under temperate alley cropping system. They attributed the low response of under canopy crops to mineral fertilizer to the higher likelihood of trees to dominate interspecific competition for nutrient uptake. The result in Figure 6.3a conforms to this argument as under canopy and open field maize almost had the same response to higher rates of urea. From an old experiment on nutrient uptake in tree-crop interaction, Palm (1995) calculated that crops growing under tree canopies captured less than 16% of the available nutrients, demonstrating a low nutrient-use efficiency. On the other hand, Pouliot *et al.* (2012) affirmed that crops growing under shade condition exhibit low nutrient use efficiencies because of slower growth and development accompanying low photosynthetic rates. However, the nutrient-use efficiencies were improved for rates of urea beyond what is currently recommended under open field conditions. Although the rate of urea at which crop yield became comparable with the open field is extremely high (i.e., 300 kg ha^{-1} vs the recommended

100 kg ha^{-1}), the trend of improved facilitation in tree-crop interaction under such fertilizer rates itself is interesting. While such rates have enormous economic implications under smallholder conditions, it highlights the untapped potential of crop management to enhance facilitation in tree-crop interactions.

Figure 6.3b shows tillage had a marginal but positive effect on maize grain yield under tree canopy. This contrasted with grain yield in the open fields, which tended to decline with tillage frequencies in excess of two times. Ploughing more than four times during seed bed preparation resulted in better grain yields for under canopy maize compared with open fields. This is not surprising, because tillage possibly damages lateral roots of trees in the top soil (Van Noordwijk *et al.* 2015; Ndoli *et al.* Submitted), minimizing competition with maize roots. However, this result is at odds with the notion that conservation agriculture with trees (CAWT) may improve crop productivity in agroforestry systems (Bayala *et al.* 2011).
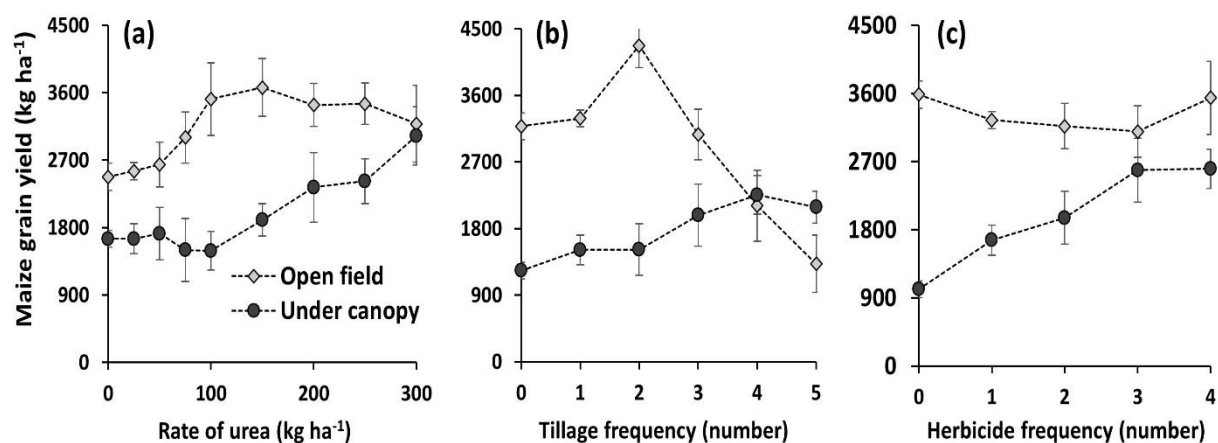

Figure 6.3 Open field and under canopy maize grain yields (kg/ha) as affected by rate of urea (a), tillage frequency (b) and herbicide application frequency (c). Error bars denote standard deviations.

In Figure 6.3c, maize grain yield under the canopy of trees responded positively to higher frequencies of herbicide. Maize in the open field did not respond much to higher rates of

herbicide. While it has been reported that trees can suppress weed, it did not cause yield benefits in annual crops (Pumariño *et al.* 2015). By contrast, the current results hinted that higher frequencies of herbicide might reduce competition from weeds for under canopy maize.

In general, the current study has hinted that simple tweaks in crop management practices may reduce trade-offs in tree-crop interaction. For example, Chapter 2 presented the pervasiveness of trade-offs between economic benefits from annual crops and direct tree products. Figure 6.4 is the conceptual representation of how manipulation of agronomic practices may reduce the trade-offs and shift the concave shape of tree-crop trade-off curve to straight line and eventually to convex trade-off curve. This could lead to a potentially efficient interaction, where trade-off curves between benefits from annual crops and benefits from on-farm trees convex outwards (van Noordwijk *et al.* 2012).

Figure 6.4 attempts to show the hypothetical shapes of trade-off curves under tree-crop systems. When two components compete for the same resource (in this case, land allocation for trees vs crops), trade-offs are inevitable. To achieve certain benefits from scattered trees, a farmer must give up certain benefits from annual crops. Region A in Figure 6.4 is a representation of an inefficient combination and/or management forming a trade-off curve that concaves towards the origin. It closely resembles the current system, which was presented in Chapter 2. Under such conditions, managing scattered trees with crops causes a disproportionally high trade-off between the benefits gained from annual crops and scattered trees. Region B represents a hypothetical situation where minor changes on crop or tree management straighten the trade-off curve, creating a linear trade-off curve. From the results in Chapter 2, there is an indication that changes in crop management practices such as selection of varieties, modification of planting dates, adjustment of fertilizer and herbicide rates, tillage frequencies and choice of tree species could lead to reduced trade-offs between scattered trees and annual crops. It represents

a reasonably achievable target without undertaking big changes in inputs or redesigning the system as a whole.
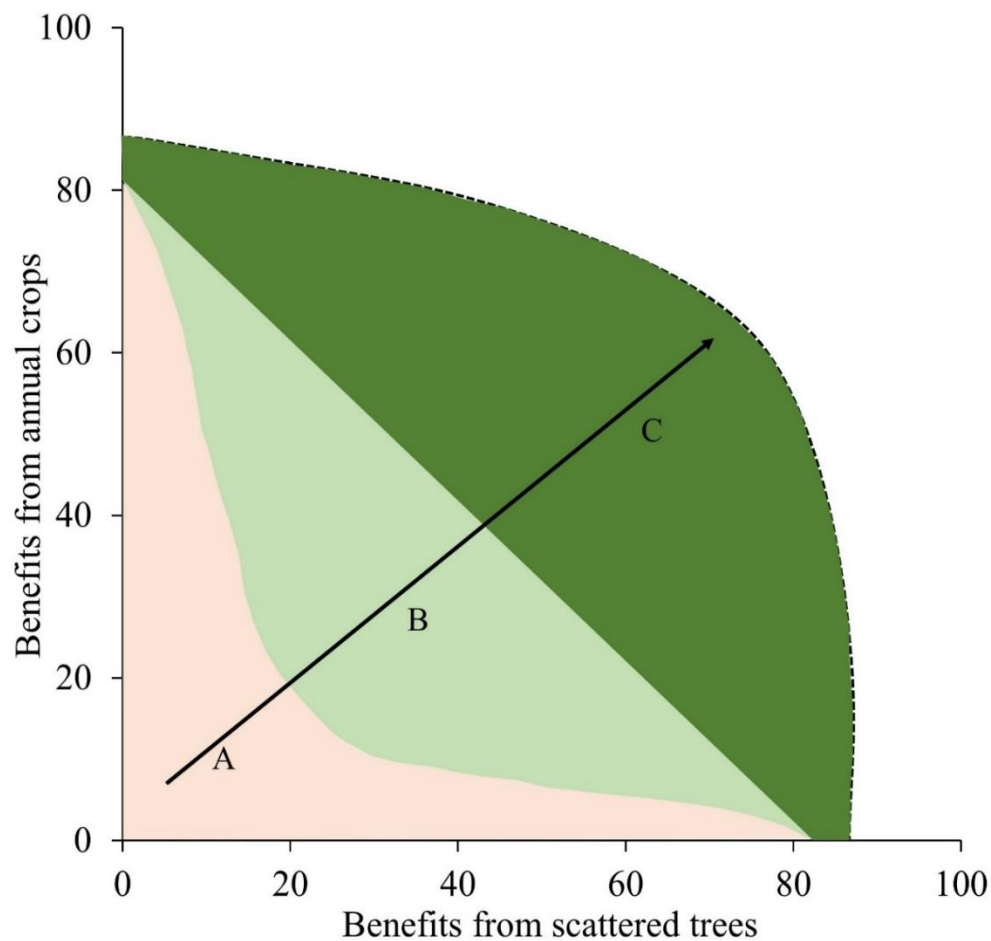

Figure 6.4 A schematic representation of trade-offs between benefits from scattered trees and annual crops [adapted from van Noordwijk *et al.* (1995)]. Region A denotes a trade-off curve concaving towards the origin, B denotes hypothetical management that pushes the trade-off curve towards straight line and C denotes an optimum management and/or arrangement combination creating a convex trade-off curve. The arrow represents the direction of pathways for change.

Region C represents tree-crop management, choice or arrangement that maximizes benefits from both components. While it could be achievable, it may require great changes in the way trees and crops are arranged within the landscapes. Multiple pathways could lead to such

optimization. It may require a landscape level decision rather than a farm/field based decision at individual farmer level. For example, segregating the trees from crop fields might be proposed (Lefroy & Hobbs 1998; Fischer *et al.* 2008; Phalan *et al.* 2011). Fischer *et al.* (2008) argued that whether to favour segregation or integration is mainly driven by how the role of agriculture is viewed within the system. For production-centred views, the scattered trees deter crop production. Thus, they should be segregated to capture their other benefits within the system. Conservation-centred approaches consider agriculture and trees as integral components. The reality on the ground may not be so simple. This is especially so, where trees are not only used for their conservation values but for their additional contribution in community livelihoods.

On the other hand, the current arrangement, where trees are scattered within crop fields does not lead to intensive interspecific competition between trees. Segregation may intensify interspecific competition, which demands more spacing. Most of the challenges that surround integration of trees into farming systems arise from how they are framed. One of the most common views is that trees are good. The other view, also closely related to this, is that they can somehow be managed to enhance the positive roles. Such a model totally ignores the crop component. The findings discussed in Chapter 2 indicate that crop management can play a significant role in enhancing facilitation in tree-crop interaction. In the next section, I will discuss how too much focus on scattered trees, and too little focus on crops may threaten the whole system, possibly jeopardizing both conservation and production goals in the long run.

6.3.3. Over-romanticizing trees in crop fields?

About two decades ago, an environmental historian William Cronon published a sarcastic critique against the First World environmentalists on 'over-romanticization' of the wilderness and conservation of the environment. He highlighted the excessive emphasis on the

environment as a place where nature thrives but not where people inhabit and make a living (Cronon 1998). While his accusations were harsh on the western environmentalists, there are some points that could be applied to how environmentalists and conservation scientists perceive and advocate the role of scattered trees within crop fields. The environmentalists have strengthened their grounds ever, assisted by the climate change crisis, although there are still strong arguments that the implementation of the nature-centred concepts for development is causing serious deprivation of livelihoods in the Third World (Erazo 2016). Whereas there is no argument that trees are vital component of many smallholder farming systems, I argue that there is a large mismatch between why trees are promoted and why farmers maintain them. Stiff proponents of scattered trees within crop fields tend to 'over-romanticize their roles. As discussed in Chapter 2 and Section 6.2.1, scattered trees are often promoted for reasons that are distant from the realities of smallholders.

It is clear that the outcomes of tree-crop interaction are not often positive from a 'productionist' perspective, whereas reports often 'over-romanticize' the role of scattered trees. Reed *et al.* (2017) also suspected the prevalence of 'selective reporting' and unnecessary emphasis on positive cases, ignoring cases of failure or negative outcomes. A meta-analysis of the contribution of temperate agroforestry trees to ecosystem services also reported a similar bias towards 'desirable outcomes', although actual results were heterogeneous (Torralba *et al.* 2016). They found the ecosystem regulation and biodiversity conservation roles of scattered trees to be significant, while effects on provisioning services and biomass production were either unclear or negative.

At system level, the scattered trees can have an overall positive effect. However, the positive effects, especially on the productivity of annual crops, are mainly context dependent. Thus, knowing what did not work with scattered trees can help to understand what could work. That

seems why Reed *et al.* (2017) emphasized the importance of focusing not only on the successes, but also on the failures of approaches that aim to achieve sustainability. In the following section, I explore and discuss the socio-ecological and biophysical contexts under which scattered trees could be used as a starting point in sustainable intensification of smallholder farming systems in Ethiopia.

6.4. Scattered trees as a starting point for sustainable intensification (SI)

The main theme of this thesis surrounds the question – what roles can scattered trees play in the sustainable intensification of smallholder farming systems in Ethiopia? This question is important because: (1) both from the conceptual and practical points of views, sustainable intensification appears to be a promising framework on which smallholder farming systems can be improved, (2) scattered trees dominate smallholder farming systems in SSA, making it difficult to imagine productivity a boost that ignores them and (3) tree-crop interactions usually involve trade-offs that need appropriate understanding in order to maximize positive outcomes from the interaction. According to Mbow *et al.* (2014) scattered trees within crop fields could provide a viable option as a starting point in sustainable intensification of the smallholder farming systems because they provide valuable assets, opportunities for climate change mitigation, enable adaptation to climate change, promote sustainable production and enhance agroecosystem diversity, leading to resilient production systems. In this section, I explore the positive functionalities of scattered trees that can be harnessed in SI and the negative trade-offs that need to be managed to achieve that.

Trees are good but not all trees are equally good. As I highlighted in the introduction of this thesis, the SI approach attempts to increase production of food, fuel and fibre without threatening environmental sustainability. Production and environmental sustainability are two objectives, often contradictory, that the smallholders need to address. There could be multiple

pathways to achieve these goals (Baulcombe *et al.* 2009; Pretty *et al.* 2011; Garnett *et al.* 2013; Mekonnen *et al.* 2013; Godfray & Garnett 2014; Pretty & Bharucha 2014). Environmental sustainability is only one of the two central variables in the SI equation. This focus differentiates SI from other production intensification concepts and/or practices. The role of scattered trees within crop fields in environmental sustainability has been unambiguously established and discussed in earlier sections. These trees were reported to enhance almost all components of environmental sustainability such as biodiversity and soil conservation (van Noordwijk *et al.* 1995; Atangana *et al.* 2014). None of the results in Chapter 2, Chapter 3 and Chapter 4 reported negative effects of scattered trees on these variables of 'ecological sustainability'. Trees outside crop fields may be managed and protected for the goal of environmental sustainability alone. However, improved resilience capacity and long-term sustainability is not the only goal for SI. Neither are they the only priority for the smallholders. Thus, scattered trees can certainly fulfil the 'sustainability' component of the 'sustainable intensification (SI)' concept. But, what role do they play in the 'intensification' part of SI?

In Chapter 2 and Chapter 3 the main effects of scattered trees on crop productivity (i.e., intensification) are dominantly negative. These results imply that improvements in environmental resources such as enhanced soil moisture and nutrient content associated with scattered trees may not automatically lead to improved crop productivity. Most of the negative effects have been attributed to tree-crop competition for nutrients (Tilander & Ong 1999; Bazié *et al.* 2012; Hussain *et al.* 2015), light (Bazié *et al.* 2012; Dufour *et al.* 2013) and soil moisture (Tilander & Ong 1999; Ong *et al.* 2000). Allelopathy can also suppress crop growth under canopies of scattered trees (Noumi *et al.* 2010; Noumi & Chaieb 2011; Girrna & Wolka 2012). On the other hand, there were some positive interactions observed in tree-crop mixed systems.

Some trees are always good, while most trees can become good under certain circumstances. In Chapter 2, the negative effects of scattered trees on crops were minimized through certain crop management practices. This could be an indication that the positive contribution of scattered trees in environmental sustainability can be harnessed, if crops are managed in ways that minimize the negative effects of these trees on crops. While these could hint the potential role of scattered trees in SI, it must be weighed against the additional costs incurred (e.g., for higher rates of fertilizer and herbicides), peak season labour demand (e.g., for increased frequencies of ploughing and weeding) and extra space occupied by the trees. Results in Chapter 3 also highlighted that only a simple manipulation of agronomic practices, without additional cost could enhance positive effects in tree-crop interaction, although those are rare instances. Chapter 4 presented a rare case. If only all scattered trees had similar positive effects on mitigation of climate change, adaptation to climate change and enhanced crop productivity, scattered trees would be 'the silver bullet'. Unfortunately, a 'silver bullet' solution to development and environmental challenges has been elusive to discover and may remain only an obsession (Vira & Adams 2009), frequently leading to a 'meaningless puff' (Buncle 2015).

So, can scattered trees play a role in sustainable intensification of smallholder farming systems in East Africa? The answer may range from 'yes, but…' to 'it depends on…' This shifts the question to 'under what conditions can scattered trees play a role in SI?' The negative effect of trees on crop yield is mainly as a result of competition for resources between the trees and the annual crops, thus depends on the availability of those resources. Results of Chapters 2, 3 and 4 showed that the outcome of tree-crop interaction depend on crop management, tree species, ecological conditions, amount of rainfall and the type of crop used. Chapter 2 emphasized specifically that small holder farmers may capitalize on processes that lead to positive interaction by following certain agronomic practices. Chapter 3 highlighted the possibility of

certain scattered tree species as resources saving agents by improving the nutrient use efficiencies of crops. This chapter also stressed that not all trees have positive impacts on crops.

In general, scattered trees can be considered as a starting point for sustainable intensification of smallholder farming systems under certain, but not all, conditions. Understanding the processes by which trees such as *F. albida* lead to all-round positive interaction outcomes may help in the selection of suitable trees, the design of tree-crop management that reduces trade-offs and the identification of the socio-ecological settings under which tree-based sustainable intensification attempts may succeed. More importantly, such understanding will help to identify and avoid what does not work. One of the most important emphasis in this thesis is the inevitability of trade-offs when trees are managed scattered within crop fields, initiating the doubt that if such a system is worth considering at all rather than looking for other alternatives. However, there are multiple reasons why scattered trees can be a promising starting point for sustainable intensification of smallholder farming systems.

First, scattered trees within crop fields have been managed with crops for centuries in this region. Smallholder farmers have accumulated knowledge on managing/tolerating tree-induced trade-offs. Interventions that use such systems as a starting point are more likely to succeed than coming up with a completely new 'technology', because scattered trees are locally available, affordable and socially acceptable. Second, incremental changes that start from pre-existing conditions are more sustainable than externally driven transformational changes (Borel-Saladin & Turok 2013). This is especially important where smallholders are reluctant to take up new 'technologies' because of their risk aversion. Third, smallholder farming systems are heterogeneous and externally derived approaches of SI tend to be 'blanket recommendations'. Designing a single 'best bet' path for sustainable intensification of these systems is difficult. Tree-crop trade-offs can be managed effectively at lower scales, i.e., field

scale trade-off management is more effective than, for example, landscape level trade-off management. Thus, scattered trees offer a great potential as a starting point for sustainable intensification of smallholder farming systems, but 'process-based' rather than 'technology-based' recommendations are required.

6.5. Concluding remarks

This thesis showed that four out of five tree species scattered within crop fields posed economic trade-offs. Although the current analysis was mainly at field scale, a case study hinted the existence of trade-offs between crop production and overall benefits from scattered trees at farm scale. Nevertheless, this does not disregard the precious importance of these trees in biodiversity conservation and environmental sustainability. Neither does this diminish their significance in local livelihoods as direct source of income, energy and construction material. However, these evidences can trigger questions about 'the wholesale' approach towards promoting scattered trees. Promoting trees solely for their environmental value could be futile. So is advocating them on the sole basis of 'trees for food security'. Over-romanticizing and mythicizing scattered trees for what they are not, rather than for what they are, requires extra caution. Such obsession is to the determent of the scattered trees in the long-run. While evidences in this thesis asserted that scattered trees buffer crops against climate change, improve water availability and nutrient use efficiencies in crops, trade-offs are conspicuous. Utilization of these facilitative effects of scattered trees necessitates a pragmatic approach that considers crop choice and management, in addition to tree choice and management. Thus, 'process-based' rather than 'technology-based' approaches are required when promoting scattered trees.

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Many countries in sub-Saharan Africa (SSA) face daunting challenges from environmental degradation, food insecurity and climate change. These challenges are compounded by fast population growth. Sustainable intensification (SI), where more food and fibre can be produced without endangering the environment, has been suggested as one of the solutions. This thesis explored the potential of scattered trees within crop fields as a pathway for sustainable intensification of smallholder farming systems in Ethiopia and Rwanda. Scattered trees dominate smallholder agricultural landscapes in Ethiopia, as in large parts of SSA. While the inclusion of scattered trees can provide products (fodder and fuelwood) and may enhance crop production, they also lead to trade-offs. Both trade-off minimization and benefit maximization from these trees in the system require the processes that underlie tree-crop interaction to be unravelled. To understand tree-crop interactions, series of on-farm experiments were conducted in different agroecologies. Four tree species (*Cordia africana, Croton macrostachyus, Faidherbia albida* and *Acacia tortilis*) from Ethiopia and one tree species (*Grevillea robusta*) from Rwanda were selected for the study. The interaction of these trees with maize and wheat, the major cereal crops, was investigated over 2-4 seasons.

Chapter 2 investigated the reason why farmers maintain trees on their farms and explored the impact of agronomic practices on the outcome of tree-crop interactions. The chapter showed that farmers maintained on-farm trees because of their direct timber, fencing, fuelwood, and charcoal production values. Under farmers' practices, trees generally had a significant negative effect on maize yield. Mean maize grain yields were 59%, 42% and 26% less under the canopies of *Cordia africana, Croton macrostachyus* and *Acacia tortilis,* respectively, compared with their corresponding open field yields. The yield reductions dropped to as low as 5% under 'good

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agronomic practices', such as early planting, variety selection, improved weed management, fine seedbed preparation and higher rates of nitrogen fertilizer. A further trade-off analysis at farm scale showed that higher incomes from trees were usually accompanied by lower incomes from maize. Interestingly, farmers who owned smaller land areas tended to maintain higher densities of trees, implying the increased importance of trees for land-constrained households.

Following the promising effects of farmers' agronomic practices in reducing trade-offs in tree-crop systems, an on-farm controlled experiment was conducted to explore tree-crop-fertilizer interactions (Chapter 3). This experiment hypothesized that facilitative and competitive interactions are affected by the use of mineral fertilizers in tree-crop systems. The results showed that *Grevillea robusta* and *Acacia tortilis* resulted in maize yield reduction of up to 100% (i.e., complete failure), depending on the amount of seasonal rainfall. These two species caused more severe yield penalty during dry seasons than relatively wetter seasons. By contrast, presence of *Faidherbia albida* improved nitrogen and phosphorus use efficiencies, leading to significantly higher yields in wheat. This tree apparently contributed as much as 64 kg ha^{-1} yr^{-1} mineral N. In addition, it doubled the phosphorus use efficiency of under canopy wheat compared with open field wheat. Although application of no fertilizer, P alone, N alone and combined N-P fertilizers resulted in significantly progressive increase in maize yields in the presence both *Grevillea* and *Acacia* trees, nutrient use efficiencies were lower, leading to significantly smaller maize yields. Probabilities of critically low crop yields and complete crop failures were significantly larger because of these trees.

Chapter 4 explored the ecological and physiological processes underlying the exceptionally positive effects of *Faidherbia albida* on wheat. A three season on-farm experiment revealed that tree roots extracted most of its water from the sub-soil, while wheat used more water from the top soil, minimizing tree-crop competition for soil water. In addition, available N was 35-

55% larger close to tree crowns compared with open fields. *Faidherbia* trees reduced photosynthetically active radiation (PAR) reaching the canopy of wheat growing underneath to optimum levels. Midday air temperature was about 6°C less under the trees than in the open fields, magnifying the importance of these trees in buffering crops against current and projected climate change. Model-based sensitivity analysis showed that under moderate to high rates of N, wheat yield responded positively to a decrease in temperature caused by *Faidherbia* shade. These results indicated that *Faidherbia* trees increase soil mineral N, wheat water use efficiency and reduce heat stress, hence, increasing yield.

Most of the scattered trees studied had negative effects on crop yield, except for *Faidherbia*. Furthermore, this agroforestry species is known to provide multiple ecological, biodiversity and production benefits across the Sahel. Chapter 5 investigated the current status of its population. Combination of data from tree population and household survey, permanent plots, experimental plots and simulation modeling revealed that Farmers' Managed Natural Regeneration (FMNR) has been the chief practice to maintain the tree population. On experimental plots, exposure to the first two months of dry season resulted in mortality of a quarter of the seedlings. Exposure to season-long aftermath grazing caused significantly greater seedling mortality. Results from the permanent plots showed that adult population density was only 4.2 trees ha^{-1} and dominated by old age classes. Two-thirds of the total population were older than 30 years. The annual rates of decline were 1.2%, 51.3%, and 63.2% for adults, seedlings, and saplings, respectively. Using a simulation model, I predicted that the *Faidherbia* population will start to decline within 1-2 decades to eventually fall below one tree per hectare within 60 years, under current practice. The modelling study highlighted that the limited seed source, caused by intensive use, was the main constraint for the degradation of *Faidherbia* parkland.

Summary

The current results clearly indicated that most scattered trees reduce crop yields, with the exception of *Faidherbia.* However, certain agronomic practices can minimize trade-offs (Chapter 2 and Chapter 3), emphasizing the importance of managing the crop component, not just the tree, in agroforestry. Although scattered trees will likely remain an integral part of these systems, especially with the expected decline in per capita land size, there was evidence that over-utilization may threaten the population of these trees. The threat of decline in population even of *Faidherbia*, which showed all-round positive effects, is particularly worrying. My results suggest that promoting trees based on biodiversity or direct economic values alone may not be enough. Ways to enhance the facilitative effects of trees on crops seems paramount, both for environmental conservation and for improved system productivity.

Exploring 'good agronomic practices' is vital to minimize tree-crop trade-offs in tree-based sustainable intensification pathways of smallholder farming systems. With heat and moisture stress likely to be more prevalent in the face of climate change, the microclimate modification effects of trees could be useful in the design of more resilient and climate-smart farming systems.

Veel landen in Afrika suid van de Sahara (ASS) gezicht intimiderend uitdagingen van aantasting van het milieu en de voedselvoorziening en klimaatverandering. Deze uitdagingen worden vergroot door een snelle bevolkingsgroei. Duurzame intensivering (DI), waar meer voedsel en vezels kunnen worden geproduceerd zonder het milieu in gevaar is voorgesteld als een van de oplossingen. Dit proefschrift onderzocht de mogelijkheden van verspreid staande bomen binnen akkers als alternatief voor duurzame intensivering van cooeperatieve landbouwsystemen in Ethiopië. Verspreid staande bomen domineren handelstechnieken landbouwlandschappen in Ethiopië, zoals in grote delen van de ASS. Terwijl de opneming van verspreid staande bomen kon een levensvatbare traject voor duurzame intensivering van deze landbouwsystemen, ze geven ook aanleiding negatieve balans. Beide negatieve balans minimalisering en uitkering maximering van deze bomen in het systeem vereist het ontrafelen van de processen die ten grondslag liggen aan de boom gewas interactie. Om te begrijpen wat werkt en wat niet werkt in tree-crop interactie, reeks op de boerderij experimenten zijn uitgevoerd in verschillende agroecologies. Vier boomsoorten (*Cordia africana*, *Croton macrostachyus, Faidherbia albida* en *Acacia tortilis*) uit Ethiopië en één boomsoort (*Grevillea robusta*) uit Rwanda werden geselecteerd voor het onderzoek. De interactie van deze bomen met gewassen (maïs en tarwe) werd onderzocht via 2-4 seizoenen.

Hoofdstuk 2 geanalyseerd beyond opbrengst motivering van landbouwers om op de boerderij bomen en de botsing onderzocht van landbouwkundige praktijken op de uitkomst van de boom-gewas interactie. Het hoofdstuk is gebleken dat landbouwers gehandhaafd op het landbouwbedrijf bomen vanwege hun directe hout, omheiningen, brandhout en houtskool productie. Onder boeren' praktijken, bomen had een ongunstige invloed op de opbrengst aan maïs. Gemiddelde korrelmaïs opbrengsten 59%, 42% en 26% minder onder de luifels van

Cordia africana, *Croton macrostachyus* en *Acacia tortilis*, respectievelijk, vergeleken met hun bijbehorende open veld opbrengsten. De opbrengst kortingen gedaald tot maximaal 5% onder 'goede landbouwpraktijken', zoals vroegtijdige aanplant, ras selectie, verbeterde weed management, fijne zaaibedvoorbereiding en hogere tarieven van stikstofmest. Een verdere negatieve balans analyse op boerderij schaal bleek dat hogere inkomens uit bomen waren meestal gepaard met lagere inkomens uit maïs. Interessant is dat boeren die eigendom kleiner land onderhouden met hogere dichtheden van bomen, hetgeen het toegenomen belang van bomen voor resource-beperkt huishoudens.

Na de veelbelovende effecten van boeren landbouwpraktijken in het verminderen van negatieve balans in boom-gewas systemen, een bedrijf beheerst experiment werd uitgevoerd om boom-gewas-meststof interactie (hoofdstuk 3). Dit experiment verondersteld dat faciliterende en concurrentiële interactie wordt beïnvloed door het gebruik van minerale meststoffen in tree-gewas-systemen. Uit de resultaten bleek dat *Grevillea robusta* en *Acacia tortilis* resulteerde in maïs opbrengst vermindering tot 100% (i.e., volledige uitval), afhankelijk van de hoeveelheid seizoensgebonden regenval. Deze twee soorten veroorzaakt ernstiger opbrengst boete tijdens droge seizoenen dan relatief regenrijke seizoenen. Door contrast, aanwezigheid van *Faidherbia albida* verbeterde stikstof en fosfor gebruik efficiëntieverbeteringen die leiden tot aanzienlijk hogere opbrengsten in tarwe. Deze boom schijnbaar bijgedragen minerale N in de orde van grootte van 64 kg ha^{-1} jr^{-1}. Bovendien verdubbeld de fosfor gebruik efficiëntie van onder het kronendak tarwe vergeleken met open veld tarwe. Hoewel toepassing van nee, P, N en gecombineerde N-P-meststoffen leidde tot aanzienlijke progressieve toename van maïs opbrengst voor beide *Grevillea* en *Acacia*-maïs systemen, aanwezigheid van deze bomen neergelaten nutriënten gebruik efficiëntieverbeteringen die leiden tot aanzienlijk kleinere mais. Waarschijnlijkheden van kritiek laag gewasopbrengsten en complete mislukkingen waren beduidend groter, want van deze bomen.

Hoofdstuk 4 verkenden de ecologische en fysiologische processen die ten grondslag liggen aan de uitzonderlijk positieve effecten van Faidherbia albida op tarwe. Een drie seizoen on-farm experiment bleek dat boomwortels gewonnen het merendeel van haar water uit de onderliggende bodem, terwijl tarwe gebruikt meer water uit de grond, waardoor de boom-crop wedstrijd voor bodem water. Bovendien bleek uit de beschikbare n was 35-55% grotere dicht bij boom kronen vergeleken met open velden. Faidherbia bomen verminderd photosynthetically active straling (PAS) bereiken van de omkasting van het tarweareaal onder tot het optimale niveau. 12:00 lucht temperatuur ongeveer 6°C groter onder de bomen dan in de open velden, vergrotende het belang van deze bomen in buffering gewassen tegen huidige en toekomstige klimaatverandering. Model gebaseerde sensitiviteitsanalyse toonde aan dat bij matige tot hoge tarieven van N, tarwe opbrengst positief gereageerd op een daling in temperatuur veroorzaakt door Faidherbia schaduw. Deze resultaten wijzen erop dat Faidherbia bomen verhogen bodem minerale N, tarwe watergebruik efficiency en lagere hittebelasting, vandaar, toenemende opbrengst.

Het merendeel van de verspreid staande bomen onder het huidige onderzoek had negatieve gevolgen voor gewasopbrengst, behalve voor *Faidherbia*. Bovendien heeft deze agrobosbouw soort bekend om meerdere ecologische, biodiversiteit en productie uitkeringen in de Sahel. Hoofdstuk 5 onderzocht de huidige status van zijn bevolking. Combinatie van gegevens van bomen en enquête onder permanente waarnemingspunten aanwijzen, experimentele plots en simulatie modellen bleek dat boeren beheerde natuurlijke regeneratie (FMNR) is de voornaamste praktijk te handhaven bomen. Op experimentele plots, blootstelling aan de eerste twee maanden van droge seizoen resulteerde in een kwart van de zaailingen sterfte. Blootstelling aan seizoen lange nasleep begrazing veroorzaakt aanzienlijk groter zaailing sterfte. Resultaten van de permanente waarnemingspunten is gebleken dat volwassen bevolkingsdichtheid was slechts 4.2 bomen ha^{-1} en gedomineerd door ouderdom klassen.

Samenvatting

Tweederde van de totale bevolking ouder dan 30 jaar. De jaarlijkse daling 1,2%, 51,3% en 63,2% voor volwassenen, plantgoed en kiemplanten, respectievelijk. Simulatiemodel voorspelde Faidherbia bevolking zal afnemen binnen 1-2 decennia om uiteindelijk onder één boom per hectare binnen 60 jaar, onder huidig scenario. De modellering bleek dat beperkte zaadbron, veroorzaakt door intensief gebruik, was de belangrijkste belemmering voor de afbraak van Faidherbia parklandschap.

De huidige resultaten duidelijk aangegeven dat de meeste verspreid staande bomen reduceren gewasopbrengsten, met uitzondering van *Faidherbia*. Echter, deze bevindingen ook gesuggereerd dat bepaalde landbouwpraktijken kunnen minimaliseren negatieve balans (Hoofdstuk 2 en Hoofdstuk 3), waarbij de nadruk wordt gelegd op het belang van het beheren van het gewas onderdeel, niet alleen de boom onderdeel in agrobosbouw. Hoewel verspreid staande bomen zal waarschijnlijk blijven integraal deel uitmaken van deze systemen, met name de verwachte daling in per capita land grootte, er is een bewijs dat de overbelasting dreigt de populatie van deze bomen. Dit wordt gestaafd door de afnemende bevolking bedreiging, zelfs in bomen zoals Faidherbia, waaruit bleek all-round positief effect. Dit zijn aanwijzingen dat de bevordering van deze bomen op basis van biodiversiteit van directe economische waarden alleen zijn niet voldoende. Manieren om hun faciliterende invloed op teelten lijkt enorme, zowel voor de milieubescherming en voor verbeterde productiviteit van het systeem.

Hoewel deze bomen bleek een veelbelovende potentiële als uitgangspunt, het verkennen van 'goede landbouwpraktijken' kan van levensbelang om boom-gewas negatieve balans in boom gebaseerde duurzame intensivering trajecten van cooeperatieve landbouwsystemen. Met warmte en vocht stress waarschijnlijk meer voorkomt op het gezicht van klimaatverandering, sommige van deze bomen met hun impact op microklimaat wijziging kan bijdragen aan meer robuuste en klimaat-smart farming systems. Echter, deze verspreid staande bomen aan de hand van de instandhouding of bijdrage in voedselveiligheid moet een toetsing.

Biyyoonni Afriikaa Saaraa-gadii (ASG) baay'een rakkoolee suukkanneessoo barbadaa'ina naannoo, hanqina nyaataa fi jijjiirama qilleensaatiin wal-qabatee uumamu keessatti argamu. Saffisaan dabaluun baay'ina ummataa ammoo rakkooleen kannneen daran akka hammatan godhaa dhufe. Rakkoolee kanneenif falli ammoo omish-guddisa waaraa (sustainable intensification) akka ta'e akeekamaa jira. Omish-guddisa waaraan (OW) odoo qabeenya naannoo hin gaaga'in meeshaa, nyaata fi anniisni gahaan mala ittiin omishamu dha. Qo'annoon ammaa kunis mukeen midhaan wajjin walmakanii ooyruu qonnaa keessatti argaman fayyadammun akkaataa omish-guddisa waaraa fiduun itti danda'amu sakatta'uuf yoo ta'u, qonnaanbultoota xixiqqoo Oromiyaa keessatti argaman irratti xiyyeefatetu hojjetame. Mukeen ooyruu qonnaa keessatti argaman qonnaanbultoota kana biratti beekamoo dha. Akkuma biyyoota ASG warra kaanii, mukeen kunneen Itoophiyaa keessattis baay'inaan ni argamu. Mukeen midhaanin wal-makanii argaman kunneen gama tokkoon omish-guddisa waaraa fiduuf carraa banuu malu. Gama biraatin ammoo omisha midhaanii hir'isuu malu. Miidhaa isaanii xiqqeessanii faayidaa ol'aantessuuf, wal-nyaatinsawwan fi adeemsota uumamaa muk-midhaan jidduutti uumaman gad-fageessanii beekuu barbaachisa. Walmakiinsa muk-midhaanii kana keessatti waan gaari fi yaraa baruuf gosa qilleensaa adda addaa Oromiyaa keessatti argaman saditu filatame. Sanyiiwwan muka afuritu qo'anno kana keessati hammatame. Itoophiyaa keessaa sanyiiwwan mukaa Waddeessa (*Cordia africana)*, Bakkanniisa (*Croton macrostachyus*), Xaddacha (*Acacia tortilis*) fi Garbii (*Faidherbia albida*) fa'atu filatame. Ruwaandaa irraammo Muka qawweetu (*Grevillea robusta*) filatame. Faayidaa fi miidhaa waliin jireenya mukeen kanneeni fi midhaanto (qamadii fi boqqoolloo) jidduutti ummu waggoota 2-4 irra deddeebi'amuun qoratame.

Boqonnaan 2, miidhaa fi faayidaa mukeen kanneen midhaanota haafa isaanii jala faca'an irraatti fidan sakatta'e. Miidhaawaan kana hir'issuuf maloonni qonnaan-bultoonni fayyadamaa jiranis laalameera. Akka boqonnaan kuni argisiisetti, sababni guddaan mukeen kanneen ooyruu irraatti dhiifamaniif faayidaa isaanii kan kallattii ti. Mukeen kunneen xaawulaa, ijaarsa, qoraan fi cileedhaf bakka bu'oo hin qaban. Kanaan achi, hedduun mukeen kanneenii omisha midhaanii ni hir'isu. Fakkeenyaaf, boqqoolloo ooyruu duwwaarra faca'e wajjin yoo madaalame, Waddeessi, Bakkanniisni fi Xaddachi omisha gara 59%, 42% fi 26%, wal-duraa duuban, ni hir'isu. Qonnaan-bultoonni bulleessanii qotan, sanyii filatamaa fayyadaman, dursanii facaasan,

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itti deddeebi'anii araman fi xaa'oo adii baay'isanii baay'inaan fayyadaman hir'ina sababa mukkeen kaneenitiin dhufu gara 5% qofatti gadi xiqqeessuu danda'anii jiru. Madaallin miidh-faayidaa (trade-off) mukkeni fi omisha midhaanii akka agarsiisetti, faayidaalee mukeen irraa argaman ol-kaasun faayidaalee omisha midhaaniirraa argaman gadi buusa. Argannoon nama hawwatu tokkommoo, ooyruuwwan warra lafa qonnaa xixiqqoo qabaniirraatti rukkunni mukken kanneenii ol-ka'aa ta'uu isaa ti. Kana jechuun, qabiyyeen lafaa yoo xiqqaatu, barbaachisuummaan mukeen kanneenii waan dabalu fakkata.

Milkii gaarii fayyadamni mala qonnaa adda addaa miidhaa mukeen omisharratti qaban hir'isuurraatti agarsiise irraa ka'uun, qo'annoon too'atamaan xaa'oowwan gosa addaa addaa mukeen wajjin fayyadamuun miidh-faayidaa mul'ate akkamitti akka jijjiiru sakatta'u gaggeeffame (Boqonnaa 3). Yaalin kuni, xaa'oo nam-tolchee fayyadamuun miidhaa fi faayidaa mukeen midhaanota haafa isaanii jala facaafaman irratti qaban jijjiiruu danda'inaa laata mamii jedhurratti hundaa'e. Yaalichi kuni muka qawwee fi Xaddacha qofarratti fuullefate. Miidhaan mukeen kunneen omisharraatti geessisan haaala roobaa irraatti akka hundaa'u hubatame. Miidhaan isaan boqqoolloo irraan gahan bara rooba ga'aan roobe caalaa bara hongeetti hammaate. Faallaa mukeen kaaniitti, Garbiin ittti-fayyadamina (efficiency) naayitrojiinii fi foosfarasii qamadiidhaf ni dabale. Kunimmoo omishni qamadii haafa Garbii jalaa isa alaa akka caalu godhe. Garbim naayitirojiinii heektaara tokkotti gara kiiloo 64 (kg ha^{-1} yr^{-}1) dabaluu akka danda'us mul'atee jira. Itti dabalees, mukni kuni itt-fayyadama foosfarasii qamadii dachaa taasisee argame. Kanaafuu, xaa'oo nam-tolchee foosfarasii qofa qabu qamadii haafa Garbii jala faca'etti dabaluun omisha midhaanichaa sirriitti ol-guddise. Dhiibban Mukni qawwee fi Xaddachi boqqoolloratti qabanimmoo kan Garbiin qamadiirratti qabuun wal-falleesse. Boqqoolloo haafa mukeen kanneenii jala faca'etti xaa'oo nam-tolchee naayitirojiinii, foosfarasii fi makaa jara lamaanii fayyadamuun omisha homaayyuu hin daballe. Ta'uyyuu garuu, xaa'oo malee, foosfarasii qofa, naayitirojiinii qofaa fi lamaan erga tokko dbaluun omisha boqqoolloo haafa mukeen kannneenii jalaa tartiiban ittuma fooyyessaa deeme. Haafa Xaddachaa fi muka qawwee jala boqqoolloon yoo faca'e, carraa oomishichi boqqoolloo gar-malee xiqqaachuu, akkasumas, guutumaatti baduu ol-kaase.

Boqonnaan 4 ammoo adeemsota xin-naannawaa (ecological) fi xin-qaamawaa (physiological) kan Garbii faayida-qabeessa taasisuu malan gadi fageenyan qoraqte. Qo'annichi qoteebultoota waliin ganna sadiif godhame kuni akka mul'isetti, hiddi garbii bishaan biyyee lafa jala gadi fagaatee harkifata. Qamadiin immoo bishaan biyyoo gara gubbaarraa waan xuuxxatuuf, wal-saamicha jiidhinsa biyyee Garbbii fi qamadii jidduutti uumamuu danda'u waan xiqqeesse

fakkata. Kana malees, biyyeen jirma Garbiitti dhiyaattee argamtu kan haafa Garbiirraa fagaattee aragamturra naayitirojiinii xuux-qophii (available nitrogen) harka 35-55% olaantummaa agarsiisee jira. Haafni Garbii calaqqee footooseentesisiif oolu (photosynthetically active radiation) hir'isuudhan guddinaa fi dagaagina qamadiitif akka mijaa'u taasisee jira. Gaaddisni muka kanaa hoo'insa qillensa guyyaa saafaa kan haafan ala jirurraa gara $^{\circ}C$ 6 gadi xiqqeeseera. Qilleensi madaalawaan akkanatti uumamu kuni ammo jiijjiirama qilleensaa amma mul'atu fi fuundurattis eegamaa jirurraa midhaanota ni dandamachiisa. Modelli si'aawummaa xiinxalu (sensitivity analysis) akka mul'isetti, naayitirojiinii gahaan jiraannan, hir'achuun hoo'insa qilleensaa omisha qamadii haalan olkaasee mul'ate. Walumaagalatti, Garbiin naayitirojiinii biyyee keessaa dabaluun, itt-fayyadamina bishaanii (water use efficiency) olkaasun fi gaaga'amina qilleensa oo'aarra dhufu ittisuun omisha qamadi ni guddisuu akka danda'amu hubatamee jira.

Garbiin xin-naannoo, lubbu-heddummii (biodiversity) fi omistummaa guddisuuf faayidaa guddaa akka qabutu mul'ate. Ta'ullee haala baay'inni muka kanaa irra jiru hin beekamu. Boqonnaan 5 haala baay'inni muka akanaa amma irra jiru sakatta'e. Itti-fufiinsi baayi'na muka kanaa biqiltuu offiin margitu qofa kunuunsanii guddisuurratti hirkata. Haaraa dhaabun hin baramne. Modelli, daataa fi yaalin dhiibutti gadhame akka agarsiisanitti, baay'inni Garbii haala yaachisaarra jira. Biqiltuu Garbii reefu margite waggaa tokko keessatti loon itti gadi dhiisun lakkoofsa isaanii haalan xiqqeesse. Hongeen ji'a lamaaf turemmoo biqiltuuwwan kurmaanan gadi buuse. Ammaan tana Garbii 4.2 ha^{-1} qofatu argama. Isaanis garri caalan dulloomtota. Garbii amma jiru harka sadi keessaa lama umuriin isaanii 30 oli. Hoggaa hoggaadhanis lakkoofsi Garbii hi'rachaatuma deemuusaa modeliin agarsiiseera. Waggaatti mukeen ga'eeyyin hark 1.2%, guddattoonni 51.3% fi biqiltuullen 63.2% gadi bu'aa deemu. Tilmaamni modelii raagaa (simulation modelling) akka agarsiisetti baay'inni garbii waggoota 10-20 dhufan jidduutti kan ammaa kanarraa gadi bu'uu ni jalqaba. Haalli aamma jiru fooyya'uu bananan, waggoota 60 dhufan keessatti baay'inni muka kanaa gara heektaaratti muka tokkoo gadiitti bu'uu danda'a. Kanaafimmoo sababni guddaan dhabamuu sanyii Garbii akka ta'e modelichi agarsiisee jira. Kanas kan fide ciccirama haafa garbii kan barabaraan godhamurraa ka'uun garbiin firii godhachuu waan dadhabeefi dha.

Mukeen amma qo'ataman harki caalu midhaanota haafa isaanii jala facaafaman akka miidhan hubanna. Garbii qofatau kanaan adda ta'ee argame. Gara biraan ammoo, midhaan seeran kunuunsun miidhaa mukeen kunneen fidan hir'isuu akka danda'u mallattoon nul'ate jira. Kunis, qon-bosona (agroforestry) keessatti gartuu mukeenii qofa odoo hin taane, gartuu midhaanotaas

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hordofanii kunuunsun faayidaa sirna qonna kanaa akka fooyyessu agarsiise. Xiqqaachaa deemun qabiyyee lafaa sirni makaan midhaan fi mukootaa kuni itti fufuu akka danda'u mul'iseera. Haa ta'u malee, akkaatan itt-fayyadamina mukeen kanaa itti-fufiinsa isaanitiif gaaga'ama ta'uu akka danda'us wanti mul'ate jira. Kunimmoo warra faayidaa heddummataa kennan kan akka Garbii fa'arrattiillee mul'atee jira. Kana jechuun, faayidaa kallattii mukeen kunneen kennanis ta'ee faayidaa isaan al-kallattiin lubbu-heddummii eeguf gumaachan qofarratti cichuun kunuunsa naannoo waaraa fiduuf gaahaa akka hin taane mul'isa. Fayyummaa naanno fi fooyya'ina sirna omishaa mukeen kanneenirraa argamuu malan fayyadamuuf, dirqama miidhaa isaanii xiqqeessinee faayidaa issan midhaanif kennanimmoo babali'isuu barbaachisa.

Akka walii galaatti, mukeen kunneen omish-guddisa waaraaf akka jalqabaatti fayyaduu danda'u. Haa ta'u malee, midhaanota haafa isaanii jala margan kununsun dirqama ta'a. Keessawuu, qonnaanbultoonni xixiqqoon filannoowwan hedduu waan hin qabneef, filannoowan akkasii kan harka isaanirra jiranirraa calqabuun faayidaa guddaa fiduu mala. Caalattimmoo, bara jijjiiramni qilleensaa qonnaanbultoota xixiqqoo gaaga'aa jiru kana, wantoonni dandamachiison akkasii filannoo hin qaban. Tilmaamni jiru akka agarsiisutti, hoo'inni dabalaa deema. Roobnimmoo hir'achaa dhufa. Haala akkanaa keessatti, qilleensi mijaa'an haafonni mukeen kanaa uuman omisha midhaanii fooyyesuudhan qoteebultoota hiyyeeyyii gaaga'ama jijjiirama haala qilleensatiin walqabtee dhufuu danda'urraa ni dandamachiisa. Wanti dagatamuu hin qabne tokko garuu jira. Mukeen kunnneen wabii midhaan nyaataa mirkaneessu jedhamanii qofa dhaadheffamuun hin qaban. Faayidaawwan isaanii kaan argachuuf dhiibbaawan isaan omistummaarratti qaban xiqqeesun hojii of'eeggannoo guddaa gaafatu dha.

My first heart-felt gratitude goes to my father, Obbo Shiferaw Sida and mother, Adde Letu W/Hanna. While this journey was started four years ago, mom and dad believed in my achievements long in advance. I thank mom for instilling that unflinching hope during difficult times. I will hold dear dad's insistence on hard work and perseverance, not only for this project, but also at every step along my journey in life.

I am grateful to Dr. Frédéric Baudron for trusting my capacity to carry out two projects: the PhD and the formal project at the same time. I thank you for not only assisting me navigate through the complex systems analysis, but also for sharing your personal experiences of how to deal with day-to-day project activities and a PhD. You were not only a supervisor, but also a friend and counsellor, especially during the emotionally draining political events across Oromia. I feel, indeed, fortunate to have you as a mentor. Your approach in making me progress without putting me under unmanageable stress, even at times when my performances were substandard for my level, will remain treasured with me. Starting with the conception of the initial project on which my PhD was grafted, you were the engine of ideas behind every activity I accomplished since. I hope I will be fortunate enough to work with you on bigger projects in times to come, which is a nice way of wishing for more time to 'steal into' your precious mind. This PhD would not have been imagined without you introducing me to Prof. Ken Giller of Wageningen University.

I am also indebted to Ken for agreeing to be my promotor and accepting me as his student. Ken, to have you as a mentor, is a boundless blessing. Your passion to understand the diversity in smallholder farming systems and use that to make a difference in the livelihoods of these farmers is enduring, extraordinary and inspirational. I will never forget how you put 'flesh' on

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also in other topics. Your comments on the draft of every one of my papers greatly enriched their contents. I thank you for making sense of my drafts, which were closer to Afan Oromo than they were to English. The occasional beer evenings were pivotal in rebooting and washing stress out of my brain. I hope we will work on similar and bigger projects in the future.

Behind all of my on-farm experiments, were the farmers in Bako, Mojo and Meki, where I conducted the field work. I am ceaselessly indebted for the confidence that they intrusted on me with the small plots that were the prime source of their livelihoods. I cannot not imagine the amount of kindness required to own only a quarter of a hectare land and allow an experiment on half of it. Above all, I will never forget your enthusiasm to share your lifelong experiences. Your passion to share those insights with me, repeatedly, was the source of most of my understanding about the system. For that, I can only say I will remain determined to work for the betterment of smallholder systems more in the future.

My brothers, Seboka Shiferaw, Mesfin Shiferaw, Chala Shiferaw and sisters, Lalise Shiferaw, Jitu Shiferaw, Gadise Shiferaw and Derartu Shiferaw, played decisive, albeit invisible, roles throughout this journey. Your boundless expectations about my success were energizing, stirring and reinforcing, especially at times when I ran out of the reason and drive to carry on. I thank Seboka, specifically, for shouldering all the family responsibilities that would take some of my efforts away from this PhD.

Last, but not least, is my beautiful wife Birtukan Endebu, who joined my journey at a messy stage. Haadha manaa, your warmth, understanding and love were pivotal for the completion of the journey. I am thankful for tolerating my late working hours and encouraging words every time you recognise my frowning face.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)
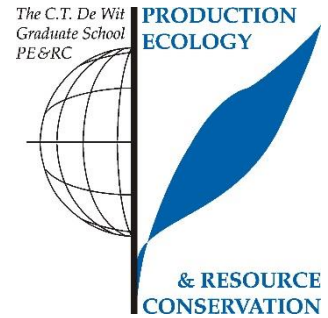
1. **Review of literature (5 ECTS)**
   - Tree-crop interaction in smallholder farming systems: can facilitation and complementarity benefits overweigh competitive disadvantages?

2. **Writing of project proposal (5.5 ECTS)**
   - The role of scattered trees in sustainable intensification of smallholder farming systems

3. **Post-graduate courses (6 ECTS)**
   - Farming systems and rural livelihoods; WGS (2013)
   - Geostatistics; WGS (2015)
   - Structural equation modelling; WGS (2015)

4. **Deficiency, refresh, brush-up courses (6 ECTS)**
   - Analysing sustainability of farming systems; WGS/PPS (2014)

5. **Competence strengthening / skills courses (3 ECTS)**
   - The essentials of scientific writing and presenting; WGS (2016)
   - Dynamic programing in R; WGS (2017)

6. **PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)**
   - PE&RC weekend – first year's edition (2014)
   - PhD Workshop carousel (2017)

7. **Discussion groups / local seminars / other scientific meetings (4.8 ECTS)**
   - Local seminars and meetings at CIMMYT-Ethiopia (2013-2017)
   - Sustainable Intensification discussion group (2017)

8. **International symposia, workshops and conferences (3.5 ECTS)**
   - Agroecology and sustainability conference, Antananarivo, Madagascar (2014)
   - Adaptation Futures: international conference, Rotterdam, the Netherlands (2016)

9. **Supervision of MSc students (9 ECTS)**
   - Impact of agronomic practice in tree crop facilitation on maize (Zea mays l.) In central rift valley of Ethiopia
   - Age structure and management of scattered on-farm Faidherbia albida in Lume, Ethiopian central rift valley
   - Determination of critical yield limiting factors and on-farm evaluation of maize yield gap in Bako Tibe district, west Shoa zone, Oromia regional state, Ethiopia

Tesfaye Shiferaw Sida was born in 1983 in Burra Aleltu, a rural village to the North East of Finfinne/Addis Ababa (Special Zone surrounding Finfinnee, formerly north Shewa zone of Oromia). His connection with smallholder farming was of not only academic training, but also a lived experience, as he was born to a family whose livelihoods were based on smallholder agriculture and petty trade. He joined Burra Aleltu Elementary school in 1991. At the start of schooling, Tesfaye developed great interest in mathematics classes, mainly because of the difficulty he faced with other sciences due to the non-native language of instruction. He discovered interest in biological and environmental sciences when the language of instruction at his school was made Afan Oromo in 1993. While at the elementary school, Tesfaye developed an ambition to become either a teacher or a medical doctor, conceivably because these were the only professions known to him at the time. After joining Sendafa Senior Secondary School in 1996, he wished to become an engineer, primarily encouraged by his good performance in physics and mathematics classes. In 2000, Tesfaye joined an agricultural college at Hawassa University (formerly, Debub University) in Ethiopia, albeit against his expectations. Although he scored the maximum possible marks in the university entrance exam, the lottery system of university enrolment deterred his ambition to join engineering. The disappointment did not sustain and Tesfaye developed a new interest in the new classes of plant production. In time, classes of applied biological and ecological sciences allowed him to reconnect with his childhood experiences of smallholder farming practiced in his family. He enjoyed the complexity of smallholder farming systems and was excited at the prospect of applying ecological and biological principles to smallholder farming systems. After completing a bachelor of sciences in plant production in 2004, Tesfaye was employed as a graduate teaching assistant at the same university. By then, his interests evolved towards applied research.

However, his childhood desire to become a teacher won over the newly developing aspiration. He decided to take the opportunity to become a graduate teaching assistant. After two years of teaching, he won a quota scholarship from the government of Norway and joined Norwegian University of Life Sciences in the summer of 2006. He graduated from a two years master's program in Agroecology. Tesfaye believed Agroecology, which mainly focused on organic farming, was not directly applicable to smallholder farming systems familiar to him. He decided to attend a more tropic-centric specialization: a European double degree program in tropical natural resources management. In search of courses that would enable him to understand smallholder systems further, he attended the first part of the double degree at Dresden University of Technology in Germany. He moved to Bangor University in the UK for the second part of the double degree, where he specialized in agroforestry. Equipped with practical smallholder experiences from educational tours to Nepal, Thailand, Kenya and Tanzania during the courses, Tesfaye joined Ambo University as a lecturer of Natural Resources Management in 2010. Back to teaching again, he conducted on-farm researches that aimed to explore problem-solving alternatives that existed within the smallholder systems. After nearly two years as a lecturer, he left Ambo University and joined International Centre for Maize and Wheat Improvement (CIMMYT) as a research officer. At CIMMYT, Tesfaye met an inspiring research scientist Dr. Frédéric Baudron who eventually helped him to develop a PhD proposal from the project to which he was hired. The PhD journey started at the celebrated Wageningen University in 2014, when Professor Ken Giller agreed to become his promotor. Tesfaye then continued the study at Wageningen University, while conducting on-farm experiments with CIMMYT in Ethiopia.