Farming with Trees: A Balancing Act in the Shade

Alain Ndoli 2018

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Alain Ndoli

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Abstract

The smallholder agriculture sector in East Africa is the dominant economic and social activity for millions of farm households who are often resource-poor, food-insecure and most vulnerable to climate change. In this region, population pressure has led to shorter fallow periods or continuous cropping even on hillslopes causing erosion and leading to reduced soil organic matter content and nutrient mining without replenishment. Consequently, poor agricultural productivity has led to food shortages and these problems are likely to intensify in the region, as the human population is growing faster than in other parts of the world. Agroforestry, a low-input technology, was shown to contribute to the enhancement of food production while ensuring sustainability in sub-Saharan Africa. Agroforestry may improve food security by increasing soil fertility and providing additional income from tree products. Thus, agroforestry is now receiving increasing attention as a sustainable land-management option and some countries in East Africa (e.g. Rwanda) have pledged to restore up to 100% of their agricultural land mainly through agroforestry by the year 2020. Nevertheless, crop yields reduction in agroforestry are frequent due to competition for resources among trees and crops. In recent studies, tree canopy and root pruning were tested to improve light availability and resource use efficiency but studies that tackle crop management and tillage options to optimize crop productivity in the agroforestry systems are scarce.

This thesis aims to assess the importance of agroforestry across Rwanda and its implication on crop productivity and food security of farm households, explore and recommend the maize varieties and tillage options that could minimize tree-crop competition in the equatorial savannah of Rwanda and Ethiopia. The approach combined household survey on the contribution of trees on household income and food security in six agroecologies of Rwanda, experiments on the microclimate and fertility effects of trees on crops in sub-humid region of Rwanda, maize variety testing in agroforestry systems and trials on conservation agriculture with trees in the equatorial savannah of two East African countries: Rwanda (Bugesera site) and Ethiopia (Meki site). The survey in Rwanda found that food security increases with increasing farm size and farmers with more trees tended to be wealthier (e.g. with larger land and more often higher crop and livestock income) and therefore tended to be more food secure in half of the agroecologies. The proportion of household income that came from tree products was the least among sources of income suggesting that most tree products are not sold but kept by farmers for their own use. Yet tree

income was important for about 12% of the farmers, contributing more than 20% of their overall income. Households having low food security relied more on income from tree products than those with higher food security status. Therefore, income from tree products can be seen as a 'safety net' for the poorest households.

Experiments in the sub-humid environment of Rwanda assessed the effects of mature *Alnus acuminata* (Kunth) and *Markhamia lutea* (Seem.) on maize at different distances from tree trunk for four consecutive seasons. Nutrients availability was higher under *A. acuminata* compared with *M. lutea*, because of higher litter fall but maize nutrient uptake increased only under *A. acuminata* 3 m from tree trunk during a wetter season. None of tree species affected water availability for maize in the topsoil. Total solar radiation, photosynthetically active radiation (PAR), and day air temperature were reduced by both tree species. Whereas crops consistently underperformed in *M. lutea* system, the competitive effect of *A. acuminata* for light was to some extent compensated by extra N input in the wetter seasons (2015 A and 2015 B) at 3 m but not at 1 m from the tree trunk. In an APSIM modelled scenario under low N fertilization, larger N input from trees could compensate for yield loss caused by reduction in radiation and temperature in about 60% of the seasons. This study suggested that adequate pruning and high leaf litter recycling can reduce the negative effect of shade in low intensity farming systems. The low competition of *A. acuminata* with crops was also perceived by Rwandan farmers, who ranked this tree species as the least competing among all the other upper story trees grown on-farm in the highlands.

Experiments compared the performance of four maize hybrids and four OPVs was compared in sole crop and under mature *Grevillea robusta* and *Senna spectabilis* – in Bugesera, Rwanda or *Acacia tortilis* – in Meki, Ethiopia. In Bugusera, grain yields of hybrids (2 t ha^{-1}) was significantly better than OPVs (1.5 t ha^{-1}). Further, the presence of trees significantly reduced maize grain yield and total biomass in both hybrids and OPVs in the same manner. However, trees reduced harvest index significantly more in OPVs than in hybrids, suggesting that competition had a greater impact on grain yield of OPVs than on biomass production. In the experiments in Meki, the grain yield of OPVs (2.08 t ha^{-1}) and hybrids (2.04 t ha^{-1}) did not significantly differ and the presence of trees reduced their grain yields in the same manner. We concluded that agroforestry farmers could benefit from growing hybrids in the equatorial savannahs of Rwanda, but not in the equatorial savannahs of Ethiopia. It appears that the relevance of using either hybrids or OPVs in agroforestry

systems depends on local conditions and the comparative advantages in seed costs. Experiments in the same regions of Rwanda and Ethiopia were carried out to assess the effect of conservation agriculture with trees (CAWT) on crop productivity as compared to conventional tillage with trees (CTWT) in the equatorial savannah. Crop emergence was significantly reduced under CAWT compared with CTWT. Maize emergence rates in CAWT and CTWT were respectively 46.9% and 70.1%, compared with 74.7% and 79.8% in sole maize under conservation agriculture (CA) and conventional tillage (CT). Grain yield in CAWT and CTWT were respectively 0.37 t dry matter (DM) ha^{-1} and 1.18 t DM ha^{-1} as compared with 1.65 t DM ha^{-1} and 1.95 t DM ha^{-1} in CA and CT. It was concluded that CAWT likely exacerbates tree-crop competition for water and nutrients and reduce crop yields and was therefore not considered as a viable alternative to CTWT or to CT in the studied systems.

Overall, this study found that mixing trees and crops produced a worthwhile, if somewhat reduced, crop yield, and that on-farm trees can provide substantial income for the poorest households of Rwanda.

Keywords: Conservation agriculture with trees, soil fertility, crop phenology, hybrids, OPVs, Rwanda, Ethiopia

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This thesis is dedicated to my beloved family, living and deceased, with profound appreciation for their support. I dedicate this thesis in particular to my uncle Gakwerere François and to my late uncle Gatete Emmanuel. They taught me virtues that helped me to develop in my career.

Contents

Chapter 1

General Introduction

1.1 Agroforestry as a sustainable land-management option

Traditional and successful long-fallow land-use systems became more and more impracticable in 1970-1980 in Africa, due to population growth. This created a need for new low-cost alternatives that could be applied by the poor rural population (Radersma 2002). Agroforestry was proposed as one such alternative; it combines fallow and production mechanisms at the same time and space (Kang et al. 1985). During the 1990s, agroforestry was globally recognized as an answer to problems such as the deterioration of family farms, increasing soil erosion, surface and ground water pollution, and decreasing biodiversity. Agroforestry is now considered by more and more experts to be a sustainable land-management option, because of its ecological, economic, and social functions (Garrity 2012).

Positive forest transitions are now under way in many countries in both the tropical and temperate zones (Figure 1.1). The replacement of natural forest by planted tree cover has occurred in a gradual process of agroforest development (by a direct replacement of natural forest, by a transition to plantation forestry or the combined cultivation of trees and crops, and/or after a phase interlinkage), interrupted by 'degraded land' developing a low tree cover. The various components of the 'tree-cover transition' may not spatially move at the same rate, and the zone being in the 'intermediate, low tree cover' stages can expand and contract as a consequence. Agroforestry for land restoration is spreading in the developing world, particularly in areas with resource-poor farmers with limited access to forests.

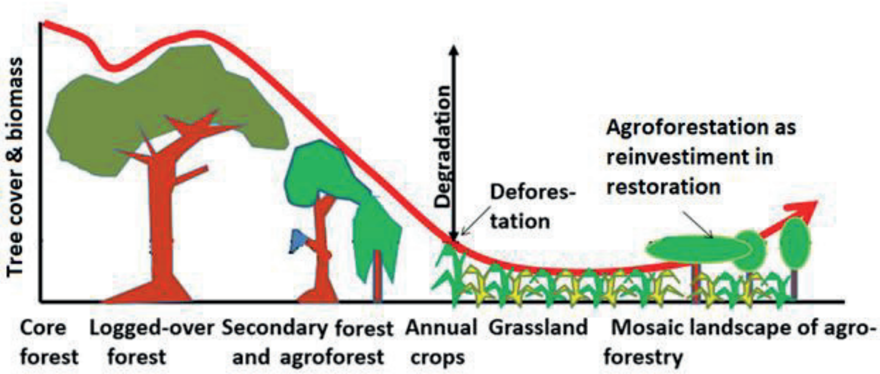

Figure 1.1. Tree cover transitions with agroforestry as a reinvestment in land restoration. Adapted from van Noordwijk M et al. (1995).

Agroforestry was recently defined by ICRAF (2016) as ‘the practice and science of the interface and interactions between agriculture and forestry, involving farmers, livestock, trees and forests at multiple scale’. Agroforestry systems have been classified into two groups, namely 1) those that are sequential, where crops are grown either in natural (herbaceous) fallows or in fields previously improved by growing trees; and 2) those that are simultaneous, where trees scattered on fields and alleys are grown together with crops (Cooper et al. 1996).

Like much of tropical Africa, East Africa is faced with problems of low agriculture productivity, land degradation and massive deforestation because of the expansion of land used for agriculture. A wider adoption of agroforestry may help to reverse the effects of deforestation and land degradation in Africa (FAO 2012). Depending upon the species are used, their arrangement and how they are managed, trees incorporated into crop fields and agricultural landscapes may help to:

(i) increased the nutrient availability for crops through nitrogen fixation and enhanced nutrient recycling (Barnes and Fagg 2003), and to increase soil organic matter content and thereby to ameliorate soil structure (Chirwa et al. 2007a);
(ii) improved water infiltration (Sanou et al. 2010); resulting in increased water use efficiency by reducing the unproductive components of the water balance (Ong et al. 2002);
(iii) ameliorate the micro-climate effects by reducing wind speed, raising humidity and reducing leaf temperature of crops (Brenner 1996);
(iv) increase the abundance and activity of beneficial soil organisms (Barrios et al. 2011);
(v) increase yields of fruit, fodder, fuel, fibre, and timber from trees/shrubs, allowing an income increase directly through sales or indirectly through intensifying the system (Garrity et al. 2010);
(vi) provide pruning mulch that increases C and N in the soils (Youkhana and Idol 2009), and enhances carbon storage both above and below ground (Makumba et al. 2007).

However, the success of agroforestry depends on the balance of positive (facilitation) and negative (competition) interactions between the components (Vandermeer 1992). It is necessary to quantify the balance between positive and negative effects of trees on crops in order to provide a scientific basis for the improvement of traditional as well as evolving agroforestry systems.

1.2 Quantification of tree effects on crops

The nature and intensity of interactions in agroforestry systems depend on the rate at and the extent to which light, water and nutrients resources are captured and utilized by the components of a particular system (Rao et al. 1997). The net effect of these interactions is often determined by measuring the influence of the tree component on the other components, and is usually expressed in quantifiable responses such as soil fertility changes, microclimate modification, or resource availability and utilization (Okorio 2000).

Ong (1995) and Akyeampong et al. (1995) developed a simple equation for quantifying tree-soil-crop interactions (I), distinguishing between the positive effects of trees on crop growth via soil fertility improvement (F) and the negative effects of competition (C) for light, water and nutrients. The interaction term is positive and the combined system may make sense if $F > C$, and not if $F < C$. Their equation was simply $I = F + C$. However, this equation had two weaknesses: it lacked a time frame, and could not be transferred from one environment to another. Kho (2000a) developed a method to overcome these weaknesses. The factors he uses are the tree effects on crop production ($t\ ha^{-1}$) via the availability of different resources (light (L), water (W), Nitrogen (N), Phosphorus and bases (P). These factors are multiplied by an environmental factor (l, w, n, p) indicating the degree of limitation of each resource in a specified environment. The sum of all environmental factors is one ($l + w + n + p = 1$), and each of the environmental factors vary between 0-1. The largest factor indicates the main limitation of an environment, the lowest the least limiting resource. Thus the equation becomes:

$I = l \times L + w \times W + n \times N + p \times P.$

Cannell et al. (1996) have also attempted to clarify the resource base of the production by the crop and the tree, for simultaneous agroforestry systems, such as scattered trees on farms. They express the interaction effect (I) on crop yields as:

$I = F + C + M + P + L + A$

where: F = relates to soil fertility interaction

C = relates to competition for water, nutrients and radiation,

M = relates to micro-comate interactions,

P = relates to pest and disease interactions,

L = relates to soil conservation interaction, and

A = relates to allelopathy interaction.

Many of the above interactions are interdependent; therefore, they cannot be experimentally estimated independently of each other (Cannell et al. 1996). Part of the fertility effect of the tree is based on light, water and nutrient resources which the tree has acquired in competition with the crop (F_{comp}); another part may have been obtained in complement to resources available for the crop ($F_{noncomp}$). Likewise, part of the resources acquired by the tree in competition with the crop is recycled within the system and may thus be used by a future crop (C_{recycl}). Tree products that are not recycled may have direct value for the farmer ($C_{nonrecycl}$). One may argue that F_{comp} is based on the same resources as C_{recycl} and that in the longer run the two terms would cancel each other out. If tree products have no direct value, agroforestry systems may only be justified if $F_{noncomp} > C_{nonrecycl}$. With increasing direct value of the tree products, the requirements of complementarity decrease (Noordwijk et al. 2011).

In addition to competition and complementarity in the capture of light (which figure in crop models), water and nutrients must often be considered in attempts to predict the yield of tree-crop mixtures (Luedeling et al. 2016). Many models have been developed for agroforestry: (i) the WaNuLCAS model, developed as a generic model for water, nutrient and light capture in agroforestry systems (Noordwijk et al. 2011) , (ii) the Agricultural Production Systems Simulator Modelling framework (APSIM), which includes tree sub-models (Luedeling et al. 2016), (iii) the Yield-SAFE model for Europe (van der Werf et al. 2007), (iv) the Simile model (Muetzelfeldt and Massheder 2003) and (v) the Soil Changes Under Agriculture, Agroforestry and Forestry model (SCUAF) (Young et al. 1998). However, the usefulness of these models has remained limited for reasons including insufficient flexibility, a restricted ability to simulate interactions, extensive parameterization needs or a lack of model maintenance. Rapid progress in the reliable modelling of tree and crop performance of agroforestry systems is needed to ensure that agroforestry fulfils its potential to contribute to reducing poverty, improving food security and fostering sustainability (Luedeling et al. 2016).

1.3 Problems of agricultural production and food insecurity in East Africa

In East Africa smallholder agriculture is the dominant economic and social activity for millions of farm households which are often resource-poor, food-insecure and particularly vulnerable to climate change (Salami et al. 2010). Population pressure has led to shorter fallow periods or continuous cropping, which in turn leads to reduced soil organic matter content and to nutrient mining without replenishment (Stoorvogel and Smaling 1990). Intensive cropping on hill slopes has resulted in increased soil erosion and low agricultural productivity (Lewis and Nyamulinda 1996). Due to soil erosion processes and limited fertilizer use, the productivity of the small agricultural plots is no longer sufficient to provide food security for the majority of the farmers (Ansoms and McKay 2010). The East Africa region has four out of the nine hunger and poverty hotspots in Africa, spread out over parts of Ethiopia, Rwanda, Kenya, Uganda, Tanzania and Burundi (Inter-Academy Council 2004). In this region, food shortages are mainly caused by an increase in population pressure coupled with inadequate attempts to increase agricultural production. Poor agricultural productivity and food insecurity problems are likely to intensify in East Africa, as the human population is growing faster here than in other parts of the world (Sanchez and Leakey 1997; Godfray et al. 2010).

The farming systems of Rwanda are mainly focused on subsistence; the agricultural activities of over 70% of the country's households take place on small plots of land (the national average is 0.6 ha per household) dispersed over plateaus and hills with high soil erosion risks (NISR 2014b). Major food crops include cereals, banana, roots and tubers, coffee and legume crops (Bucagu 2013). During the last decades, Rwandan agriculture has made remarkable progress. Accounting for 32.7% of the GDP in 2015, agriculture is the most significant driver of economic growth (7.6%, 2000-15) and poverty reduction, contributing up to 35% to the total drop in the poverty rates over the past decade (REMA 2015). Despite these impressive developments, Rwanda still falls short of its production potential. The key agricultural yields are estimated to be at about 40-50% of their production potential (MINAGRI 2014), which points to a still suboptimal use of production factors. A projected increase of the rural population by 2.5-3.5 million people by 2032 (MINECOFIN 2014) is likely to put more pressure on land resources and farm incomes. Even today, Rwanda is challenged by malnutrition, with a stunting rate of 37.9%, while its food security index lies below the average of the Sub-Saharan African countries. Around 20% of the Rwandan households remain food-insecure; most of the food-insecure households are located in the western and northern parts of the country (Franchis 2012).

The situation described above for Rwanda is common to East African countries. For example, agriculture is the backbone of the Ethiopian economy, contributing about 52% to the GDP. The sector is dominated by small-scale farmers who practice mixed farming, employing traditional technology, relying on a low-input and low-output production system. Agriculture supports 83% of the population, mainly through the production of rain-fed grain, predominantly teff, maize and wheat as well as livestock, principally cattle, sheep and goats (Deressa et al. 2009). Small-scale farmers produce 94% of the food crops. Ethiopian agriculture faces daunting challenges from over-reliance on rain-fed agriculture, high levels of environmental degradation, high poverty levels, rapid population growth, frequent natural drought cycles and low level of adaptive capacity to climate variability and change (Kidanu et al. 2009). Ethiopia continues to be one of the largest recipients of food aid in the world, with overall, about 10% of the population continuously requiring food aid assistance annually (Conway and Schipper 2011).

1.4 Rationale of the study

The integration of on farm trees improves not only food and nutritional security, but also income and energy security, by providing tree products including fruits, fodder, fuel wood, timber, mulch and medical herbs. It allows smallholders to diversify their income sources, especially when they are well-linked to markets. However, while agroforestry can improve food security through increased income from tree products and increased crop productivity (Garrity et al. 2010), it can also reduce crop yields in some instances, due to competition for resources among trees and crops (Kho 2000b). When trees and crops are mixed, tree competition for light, nutrients and water reduces crop yields, while rings of soil fertility around trees may be detected when fields are nutrient deficient (Buresh and Tian 1997). Given the current ambitious political plan to scale up agroforestry in Africa (www.bonnchallenge.org), an improved understanding of the effects of the adoption of agroforestry on the population's food-security situation is of crucial importance. This can be achieved by assessing the effects of trees on the production of food crops and the contribution trees make to the household income.

1.5 Research objectives and hypotheses

The main objective of this study was to assess the importance of agroforestry in Rwanda, determine the impacts of on-farm trees on crop productivity in Rwanda and Ethiopia, and to assess the contribution agroforestry practices can make to food security among smallholder farmers of Rwanda. It was hypothesized that the benefits of on-farm trees outweigh their competition with crops for resources, as the trees provide valuable products and increase soil fertility.

The specific hypotheses tested in this study were these:

i. The adoption of trees on-farm increases income and food-security.
ii. Trees influence crop production by reducing the fraction of radiation intercepted by the crops and by competing for soil water and nutrients.
iii. Conservation agriculture with trees (CAWT) will exacerbate below-ground competition for water and nutrients by trees, and therefore will reduce crop yields.
iv. Open-pollinated varieties of maize (OPVs) outperform maize hybrids under trees, and maize genotypes differ in their response to the presence of trees.

The research objectives were to:

1. determine whether agroforestry practices lead to increased income and improved food security for smallholder farmers;
2. evaluate the direct effects of trees on maize, with emphasis on microclimate variables (e.g. radiation, temperature) and growth resources (e.g. radiation, water, N and P);
3. assess the direct effects of trees on the performance of maize genotypes (hybrids and open pollinated varieties) in nutrient- and water-limited growth conditions;
4. assess the performance of sole maize under conventional tillage (CT) and conservation agriculture (CA), as well as maize under conventional tillage with trees (CTWT) and conservation tillage with trees (CAWT) in two semi-arid regions of East Africa.

A large survey in Rwanda was analysed, and different on-farm experiments with trees mixed with crop were conducted in Rwanda and Ethiopia. The outcomes of this research are reported in the different chapters of this thesis.

1.6 Outline of the thesis

This thesis is composed of six chapters. This chapter presents the general background to the study of problems relating to agricultural production and food security in East Africa, and especially to the question whether agroforestry is a sustainable option to intensify crop production. Chapter 2 offer data on the food-security status of farmers practicing different kinds of agroforestry in the six agroecologies of Rwanda, and on the basis of them, assesses the impact of agroforestry scaling-up efforts on the population. It gauges the current numbers of on-farm trees grown by farmers and the contribution trees make to the households' income and food-security status. Chapter 3 presents the results of research on tree-crop interactions in the smallholdings in northern Rwanda, and discusses how trees affect light, air temperature and soil water, and contribute to soil fertility through litter fall. The chapter also explores, through modelling, scenarios of maize yields production under different microclimate conditions and with different N inputs, in order to produce recommendations that can help to minimize the negative effects and maximize the positive effects of trees.

Chapter 4 describes the performance of maize hybrids and open-pollinated varieties in agroforestry systems in Rwanda and Ethiopia. The chapter stresses the importance of selecting maize genotypes suited to agroforestry conditions. In Chapter 5, the effects of conservation agriculture with trees (CAWT) on maize performance in both Rwanda and Ethiopia are described and discussed. The chapter compares CAWT with conventional tillage with trees (CTWT) and highlights the importance of tillage to limit below-ground competition between trees and crops. In Chapter 6, the major findings of this study are discussed, and the major conclusions to be drawn from them are specified.

Chapter 2

The value of on-farm trees in relation to food security and farm income in Rwanda

This chapter is to be submitted as:

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Abstract

Given the ambitious plans to scale up agroforestry in Africa, an improved understanding of the effect of agroforestry practice on the food security of rural households is crucial. The present study was carried out to understand whether farm households growing more trees on-farm were better off in terms of food security in Rwanda. A survey including 465 farmers, selected from six agroecologies of Rwanda was conducted. For each agroecology, farmers were grouped in four categories of agroforestry practice (i) non practitioners (NoAP) who had no tree on farm, (ii) low practitioners (LAP) represented by the third of the households with the lowest number of trees per farm, (iii) medium practitioners (MAP) represented by the next third of households in terms of tree numbers on farm and (iv) high practitioners (HAP) represented by the third of the households with the highest number of trees on farm. Assets values, household income sources, crop production, farm area, crop yield, cover of household food energy (caloric) needs and farmers' perceptions on tree effects on crops were quantified among the categories of agroforestry practice. The proportion of households that reported to have access to enough amount and diversity of food were higher in HAP when compared to MAP and LAP categories. Coverage of household caloric needs was also highest in the HAP category, coinciding with an increased crop and livestock income as compared to other categories. In half of the agroecologies, households in HAP tended to have relatively more land and their higher food security compared to other categories might be due to more crop income than other sources. Farmers in the eastern agroecologies reported negative effects of on-farm trees on crops which may explain the low tree adoption found in this area. We found no relationship between asset endowment and categories of agroforestry practice, while farmers in agroecologies with smaller farms had more on-farm trees than farms in agroecologies with larger farms. Our results suggest that households with more trees on farm are not better off in terms of food security than those without or with less trees on farm. Large differences between agroecological zones in Rwanda were observed for both food self-sufficiency and food security. Households with larger farms were more food secure than those with smaller farms. The proportion of income that came from tree products was important for a small fraction of farmers, with households with low food security relying more on income from tree products than household with higher food security status. Thus tree income can be seen as a "safety net" for the poorest households.

2.1 Introduction

The double challenge faced by the world is to meet the food demand of the growing population, and to do so in ways that are environmentally and socially sustainable (Von Braun 2007). Sub-Saharan Africa remains amongst the most food insecure regions in the world, with almost one in three people being chronically hungry (FAO 2008). In this region, population pressure has led to shorter fallow periods or continuous cropping, even on hillslopes causing erosion and leading to reduced soil organic matter content and nutrient mining (Stoorvogel and Smaling 1990). Agroforestry, a low-input technology, was shown to contribute to the enhancement of food production while ensuring sustainability in sub-Saharan Africa (Garrity 2012). Agroforestry was recently defined by ICRAF (2016) as "the practice and science of the interface and interactions between agriculture and forestry, involving farmers, livestock, trees and forests at multiple scales". Agroforestry is now receiving increasing attention as a sustainable land-management option because of its ecological, economic, and social attributes.

Agriculture is the primary source of livelihood for 85% of the rural population in the developing world (Dixon et al. 2001). In countries such as Rwanda, low-income agriculture is commonly practiced on farms smaller than one ha (NISR 2010) and is highly vulnerable to weather related shocks, such as drought and irregular rains (Hjelm et al. 2015). Rwanda is characterized by one of the most severe nutrient depletion rates in Africa and low organic carbon content of the soil (Stoorvogel and Smaling 1990; Drechsel et al. 2001). The country is dominated by sloping agricultural land (up to 55%) with 50% of it showing signs of erosion. Producing enough food on nutrient deficient land for the rapidly growing Rwandan population is challenging and buying imported food would be too expensive for the majority of the population that live currently on less than one dollar (USD) per day. Despite the economic recovery of Rwanda since 1994, household food insecurity and undernutrition remain a challenge in Rwanda. In 2012, as many as 460,000 households (21%) were food insecure (Franchis 2012). This number increased to 473,847 households (20%) in 2015 (Hjelm et al. 2015).

In light of recurring food shortages, projected climate change, and rising prices of fossil fuel-based agricultural inputs, interest in agroforestry has recently increased as a cost-effective means to enhance food security, while at the same time contributing to climate change adaptation and mitigation (Mbow et al. 2014). Rwandan government officials, NGOs, and extension specialists perceive smallholder agroforestry as a suitable strategy for Rwandan smallholder farmers (Stainback et al. 2012). Consequently, Rwanda has pledged to restore 2 million of hectares of land (almost 100% of arable land) by the year 2020 mainly through agroforestry (http://www.bonnchallenge.org/content/rwanda). While agroforestry may improve food security through increased income from tree products (Garrity et al. 2010) and enhanced crop productivity (Coulibaly et al. 2017), it may also reduce food self-sufficiency by lowering crop yields (Ndoli et al. 2017) under trees in some instances due to competition for resources between trees and crops (Kho 2000b), threatening food security.

An improved understanding of the role of trees on farm income and the food security status of farmers with different degrees of agroforestry practices is needed to better understand and anticipate the impact that the current efforts to upscale agroforestry are likely to have on rural households in Rwanda. The present study seeks to understand how the number of trees grown and managed on-farm affects farm income and food security of households in the six agroecological zones of Rwanda. The specific objectives were: (i) to determine whether agroforestry practices lead to diversification and increase of income and value of assets; (ii) to assess farmers' perceptions of the impact of trees on crop yields and (iii) to evaluate food security for households that differ in the number of trees on their farms.

2.2 Methods

2.2.1 Data collection

The study was conducted in six agroecologies of Rwanda as defined by Djimde (1988). However, the Eastern savannah lowland, as defined in 1988 was subdivided into two systems, namely Eastern savannah and Eastern plateau (Table 2.1). This because the Eastern savannah became heterogeneous in terms of socioeconomic and biophysical characteristics in the last two decades. The Eastern savannah of 1988 was a less populated parkland with the protected Akagera national park covering half of it. The largest part of the Akagera Park was settled in the late 1990s by former refugees returning in 1994 when land was allocated as farms. A short description of the characteristics of the land use systems is presented in Table 2.1. In each agroecology, one representative district was selected, based on biophysical and socio-economic factors. In each district, two cells were selected for assessment of the contribution of trees on household food security.

A household survey was conducted between November and December 2014 in each cell with about 30-50 randomly selected households. A total of 465 households were interviewed in the 12 selected cells. A structured questionnaire was administered to respondents' household heads or their representatives during the survey. Detailed questions asked were related to tree species, number of trees, products and income from trees and perception of the impact of trees on crop yields. Each farmer was asked for his/her top three priority grown trees to score -1 if these trees had a negative effect on crop, 0 if the effect was neutral and 1 if the effect was positive, thus the higher the mean score, the less these top three trees compete with crops in a particular agroecology. The questionnaire also captured the household socioeconomic characteristics, crop production, and income from crops, from livestock and from off farm activities. Farm area was recorded with a Global Navigation Satellite System (GNSS) receiver (Garmin) and with this on-farm crop productivity (i.e. crop yields converted to GJ energy per ha) was determined. Household asset values were determined. Assets were grouped into four categories: (i) domestic (i.e., sofa set, refrigerator, wood stove, kerosene stove, gas/LPG stove, granary and water tank domestic), (ii) communication (i.e., radio, mobile phone, television), (iii) transport (i.e. bicycle, motorbike, car/truck and ox cart), and (iv) farming assets (i.e. water tank for farm, hoes, machetes, ox-plough, wheelbarrow, grain-mill, water pumps, milk can, shovel, spades, axe, and sprayer). Food security status throughout the year was evaluated by assigning each month to one of the following category: (1) not enough food for all members of the household, (2) enough food but not enough diversity, or (3) enough food and enough diversity.

Table 2.1 Characteristics of the six agroecologies [source: Djimde (1988), if not otherwise specifid with a superscript number]

Characteristics	Eastern Savannah	Eastern Plateau	Buberuka highland	Volcanic highland	Central Plateau	Congo Nile Crest
Elevation (m)	1200-1400	1200-1500	1900-2000	2200-2400	1100-1700	1900- 2500
Rainfall (mm year^{-1})	800-1000	800-1000	1200-1300	1300-1500	1000-1500	1300-2000
Temperature (^{0}C)	> 21	20 – 21	15-18	< 15	18-20	<1 5-18
Proportion of very fertile soil (%)[1]	48	54	37	66	41	6
Food insecure households in the study cells (%)[2]	3-7	8-15	15-28	8-28	15-28	33-43
Dominant agroforestry practices[2]	Trees on farm boundaries	Scattered trees on farm, trees on contour	Woodlot, contour hedgerows and home gardens	Woodlot, contour hedgerows	Scattered trees on farm	Woodlot, contour hedgerows, Scattered trees on farm
Tree Species dominant in the surveyed zones[1]	Grevillea, Eucalyptus, Avocado, Senna, Mango, Papaya	Grevillea, Senna, Eucalyptus, Avocado, Mango, Calliandra	Alnus, Eucalyptus, Avocado, Erythrina, Ficus, Grevillea	Alnus, Eucalyptus, Erythrina	Avocado, Eucalyptus, Calliandra, Grevillea, Citrus, Orange, Mango	Eucalyptus, Grevillea, Avocado, Calliandra, Ficus
Livelihood[2]	Agro pastoral	Banana, cassava and mixed agriculture	Beans, wheat, Irish potato and vegetables	Irish potato	Cassava and coffee	Subsistence food crop farming and labour in tea

[1]Mukuralinda *et al.* (2016)

[2]Franchis *et al.* (2012)

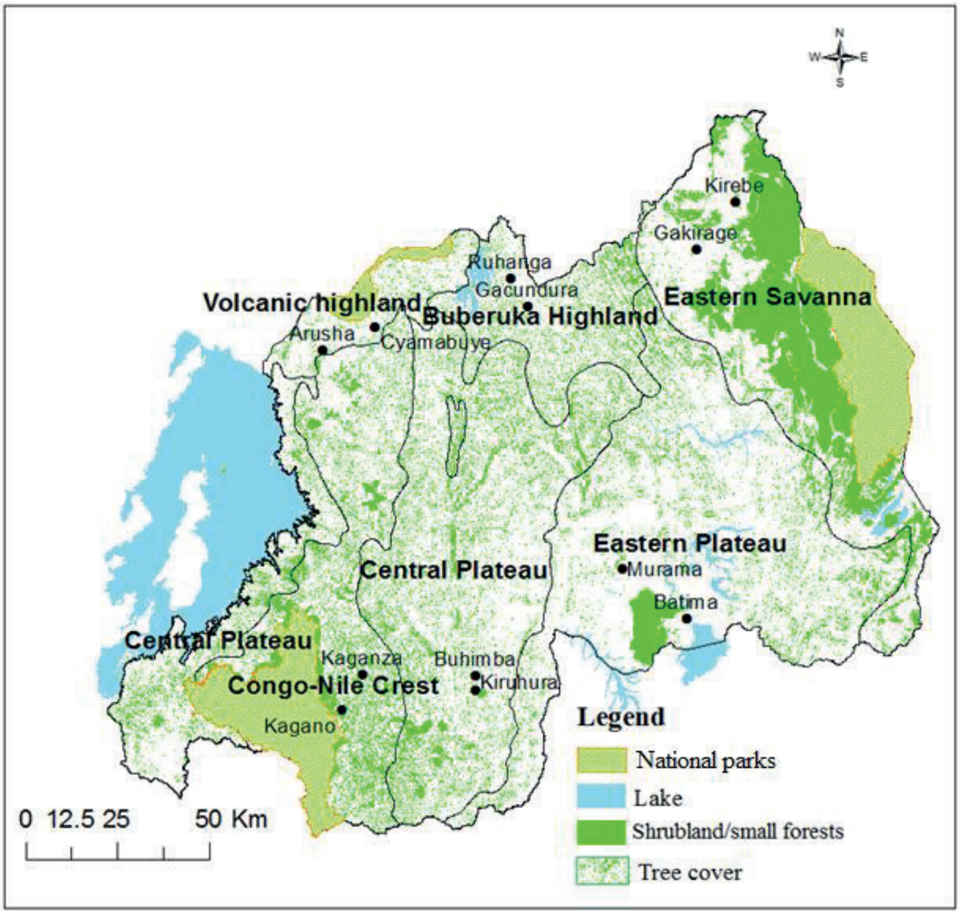

Figure 2.1 Map of tree cover in Rwanda displaying the six agrecologies and the study cells that were selected for this study.

2.2.2 Data analysis

Assets as well as income were compared between categories of agroforestry practice and between agroecologies using a Kruskal Wallis test while proportions of farmers in different food security categories were compared with Chi-square tests. Four relative categories of number of trees on farm were constructed in each agroecology; (i) non practitioners (NoAP) (i.e., no trees on farm),

(ii) low practitioners (LAP) defined as the lower third of the households in terms of tree number, (iii) medium practitioners (MAP) represented by the middle third of the households in term of tree numbers and (iv) high agroforestry practitioners (HAP) represented by upper third of the households in terms of tree numbers.

However, all agroecologies had very few non-practitioners (4 to 14%) with the exception of Eastern savannah. The NoAP were not included in the analysis of food security levels since they were disproportionately few as compared to the rest of the categories. Farmers were asked to rank food security as '1' if they had not enough food and not enough variety, '2' if they had enough food but not enough variety and '3' if they had enough food and enough variety. Generalized linear models were used to assess the source of variability in food security. Model 1 aimed at testing the effect of tree number when controlling for structural variables (e.g. farm area). Model 2 aimed at testing the effect of tree income when controlling for other functional variables (e.g. crop productivity, off-farm income). Both Model 1 and Model 2 were run for the whole dataset and for each agroecology separately (the factor 'agroecology' was removed in the latter case). In the analysis, the scores 2 and 3 for the response variable 'food security status' were combined and considered as food secure households (coded as 1), these were compared to food insecure households (coded as 0). A logistic regression model was then used. The Analysis of Variance (ANOVA) was conducted to compare effects and differences were evaluated for their significance with a Chi-square test. Models were constructed as follows:

(Model 1) $Y_{ijklm} = \alpha + \beta TC_i + \gamma MO_j + \delta FS_l + \mu AE_m + \tau TC_i FS_l + \varepsilon AE_m + \theta FS_l AE_m + R$

(Model 2) $Y_{mnopqr} = \alpha + \beta TI_n + \gamma CI_o + \delta LI_p + \mu AE_m + \varepsilon OI_q + \epsilon CP_r + \theta AE_m TI_n + \vartheta AE_m CI_o + \pi AE_m LI_p + \rho AE_m OI_q + \sigma AE_m CP_r + R$

where $Y_{ijklmnop}$ and $Y_{ijklmno}$ represents the binomial values of food security status (with the value 1 for food secure and 0 for food insecure), TC_i is the *i*th category of trees on-farm, MO_j is the *j*th month of the year, FS_l is the *l*th farm size in hectares, AE_m is the *m*th agroecology, CI_o is the *o*th crop income, LI_p is the *p*th livestock income, OI_q is the *q*th off-farm income, CP_r is the *r*th value of crop production in calories, and *R* is the residual, and where *α, β, γ, δ, μ, τ, ε, θ, ϑ, π, ρ* and *σ* represent effects values. We used R software for all statistical analyses (R Development Core Team 2014).

2.3 Results

The number of households were equally distributed among categories of agroforestry practice after removing the households owning no trees (NoAP), see Table 2.2. The mean number of trees grown by households was higher in the Congo Nile agroecology, followed by Buberuka highlands, Eastern plateau, volcanic highlands, and central plateau while the Eastern savannah had the smallest number of trees. In fact, the latter was the agroecology with the highest number of households not managing any tree on-farm. Total farm area per household was generally larger in agroecologies with fewer trees per household. Farm size was larger in the Eastern plateau and Eastern savannah, followed by Buberuka highlands, Central plateau and lastly the Congo Nile agroecology. Farm size of HAP tended to be larger than the rest of the categories.

Table 2.2 Characteristics of the selected households in the six land use systems of Rwanda. Standard errors are given after the signs '±' for mean number of trees and total land size per household.

Land use	NoAP	LAP	MAP	HAP
No. of households				
Buberuka H	2	14	14	12
Central Plat	15	29	29	29
Congo Nile	6	17	16	17
Eastern Plat	6	23	23	23
Eastern Sav	23	18	17	17
Volcanic H	3	27	28	27
Mean no. of trees				
Buberuka H	0	29 ± 1	95 ± 2	500 ± 30
Central Plat	0	2 ± 0.1	10 ± 0.3	195 ± 14
Congo Nile	0	3 ± 0.1	59 ± 3.4	528 ± 28
Eastern Plat	0	7 ± 0.2	26 ± 0.2	355 ± 40
Eastern Sav	0	2 ± 0.1	7 ± 0.2	143 ± 17
Volcanic H	0	14 ± 0.5	42 ± 1	293 ± 26
Total land size (ha)				
Buberuka H	0.7 ± 0.06	0.64 ± 0.06	0.63 ± 0.05	1.23 ± 0.09
Central Plat	0.7 ± 0.04	0.32 ± 0.02	0.38 ± 0.03	0.77 ± 0.06
Congo Nile	0.86 ± 0.01	0.53 ± 0.06	0.29 ± 0.02	0.61 ± 0.05
Eastern Plat	1.1 ± 0.01	0.75 ± 0.04	0.74 ± 0.06	1.39 ± 0.04
Eastern Sav	0.66 ± 0.03	0.59 ± 0.04	0.92 ± 0.06	1.23 ± 0.05
Volcanic H	0.72 ± 0.07	0.38 ± 0.02	0.46 ± 0.06	0.60 ± 0.04

Income from trees was higher for HAP than MAP and LAP in Central plateau, Congo Nile and Eastern plateau but its contribution to total household income was small compared with other sources of income (crop, livestock, and off-farm activities) in nearly all the agroecologies (Table 2.3). HAP had also higher crop income in the Eastern savannah, Eastern plateau, Central plateau and Volcanic highland agroecologies. Income from livestock was higher for HAP compared to the other categories of agroforestry adoption in the Congo Nile agroecology, but not in the other agroecologies. Off-farm income did not significantly differ between the different categories of on farm tree numbers. Figure 2.4 shows the contribution of four farm income sources to the total household income. Around 35% of farm households earn income from trees, about 25% of households had only income from crops and livestock, while about 40% of households earned off-farm income (Figure 2.4).

Table 2.3 Agroforestry practice levels as a function income sources (USD/year). *P* values from Kruskal-Wallis tests are given to compare levels of adoption per income source. Standard errors are given after the signs '±'.

Agroecolo gy	Income source (USD)	NoAP	LAP	MAP	HAP	P
Buberuka	Tree	0	7 ±1	6 ±1	40 ±5	ns
Higland	Crop	396 ±28	155 ±18	139 ±14	293 ±29	ns
	Livestock	0	10 ±3	22 ±5	34 ±7	ns
	Off farm	0	90 ±10	445 ±96	109 ±18	ns
Central Plateau	Tree	0	5 ±0.1	26 ±4	195 ±20	0.004
	Crop	39 ±5	213 ±24	320 ±34	345 ±42	0.024
	Livestock	51 ±12	39 ±6	25 ±4	262 ±53	ns
	Off farm	52 ±5	216 ±38	144 ±17	135 ±24	ns
Congo Nile	Tree	0	11 ±3	11 ±2	190 ±24	0.001
	Crop	83 ±11	73 ±12	135 ±15	220 ±25	ns
	Livestock	0	68 ±14	60 ±10	152 ±16	0.04
	Off farm	134 ±32	131 ±10	599 ±105	159 ±23	ns
Eastern Plateau	Tree	0	5 ±1	23 ±3	128 ±9	<0.001
	Crop	147 ±17	124 ±13	322 ±35	651 ±54	0.033
	Livestock	0	10 ±1	59 ±13	83 ±10	ns
	Off farm	1940 ±437	430 ±60	678 ±120	556 ±131	ns
Eastern Savannah	Tree	0	0	6 ±2	2 ±0.1	ns
	Crop	295 ±20	298 ±26	525 ±54	1174 ±115	0.02
	Livestock	2 ±1	5 ±1	32 ±8	43 ±9	ns
	Off farm	1321 ±181	1362 ±234	321 ±41	609 ±99	ns
Volcanic Highland	Tree	0	1 ±0.1	2 ±1	43 ±6	ns
	Crop	349 ±25	143 ±10	273 ±19	341 ±17	0.03
	Livestock	199 ±48	69 ±8	218 ±24	191 ±24	ns
	Off farm	0 ±0	99 ±8	170 ±17	271 ±34	ns

Asset ownership tended to be similar among the different categories of on-farm trees, except in the Congo Nile agroecology where communication and farm assets were significant different between HAP and the other categories. On average, HAP had assets worth USD 315, 78, 34, and

52 for domestic, communication, transport and farm assets respectively. MAP had assets worth USD 310, 61, 181, and 29 for domestic, communication, transport, and farm assets respectively (Table 2.4). The corresponding asset value in the LAP category were USD 267, 54, 177, and 19 while they were USD 233, 60, 34, and 61 for the few farming households with no trees (NoAP) (Table 2.4).

Table 2.4 Assets owned (USD) as a function of agroforestry practice categories. The *P* values from Kruskal-Wallis test are given to compare differences per asset type between categories of agroforestry practice. Standard errors are given after the signs ‘±’.

Agroecology	Assets (USD)	NoAP	LAP	MAP	HAP	P
Buberuka	Domestic	0	97 ±27	1 ±0.1	78 ±16	ns
Highland	Communication	90 ±5	44 ±3	46 ±3	77 ±5	ns
	Transport	0	10 ±2	10 ±2	17 ±2	ns
	Farm	10 ±0	15 ±1	11 ±1	21 ±3	ns
Central	Domestic	95 ±25	206 ±46	447 ±71	125 ±33	ns
Plateau	Communication	44 ±3	48 ±2	58 ±3	54 ±2	ns
	Transport	9 ±2	5 ±1	11 ±1	28 ±4	ns
	Farm	196 ±35	19 ±1	64 ±14	116 ±19	ns
Congo Nile	Domestic	112 ±29	358 ±66	72 ±13	353 ±59	ns
	Communication	32 ±4	32 ±4	58 ±5	107 ±5	0.005
	Transport	0	12 ±2	38 ±8	12 ±2	ns
	Farm	6	14 ±1	12 ±1	17 ±1	0.028
Eastern	Domestic	668 ±145	176 ±18	250 ±35	371 ±57	ns
Plateau	Communication	48 ±4	63 ±3	71 ±4	68 ±3	ns
	Transport	111 ±16	910 ±246	922 ±245	72 ±7	ns
	Farm	8 ±0.1	18 ±1	20 ±1	48 ±4	ns
Eastern	Domestic	291 ±42	334 ±68	473 ±66	409 ±63	ns
Savannah	Communication	82 ±5	78 ±4	59 ±3	84 ±5	ns
	Transport	46 ±2	67 ±6	31 ±2	63 ±7	ns
	Farm	13 ±1	12 ±1	18 ±1	20 ±2	ns
Volcanic	Domestic	1 ±0.1	397 ±57	409 ±45	491 ±56	ns
Highland	Communication	29 ±5	58 ±3	67 ±3	89 ±4	ns
	Transport	0	0	7 ±1	10 ±1	ns
	Farm	7 ±0	30 ±3	28 ±2	45 ±3	ns

The proportion of households which reported to not have enough food throughout the year was smaller for HAP when compared with MAP and LAP with an annual average of 25, 39% and 47% respectively (Figure 2.2). The proportion of households with sufficient amounts and variety and insufficient amounts and variety of food was also less for HAP when compared with MAP and LAP. The April-May and October-November months showed an increased number of households with constraints in food access (Figure 2.2).

In model 1, most variation in household food security was explained by the month of the year, and agroforestry categories followed by the farm size (Table 2.5). Larger farms were more food secure than smaller farms. The interaction of agroforestry categories and farm size was significant for all agroecologies except the Eastern plateau and for the overall dataset. This implies that the influence of adoption category on food security is mediated by farm size, positively in most agroecologies. In the 2nd GLM model, tree income was a significant factor in explaining differences in food security, although interactions between income categories and agroecologies indicate strong regional differences (Table 2.6). Tree income negatively affected food security in all regions, indicating that food insecure farmers are selling more wood products than food secure farmers. Income from crops was a positive factor in all regions, indicating that food secure farmers are selling more crop products than food insecure farmers.

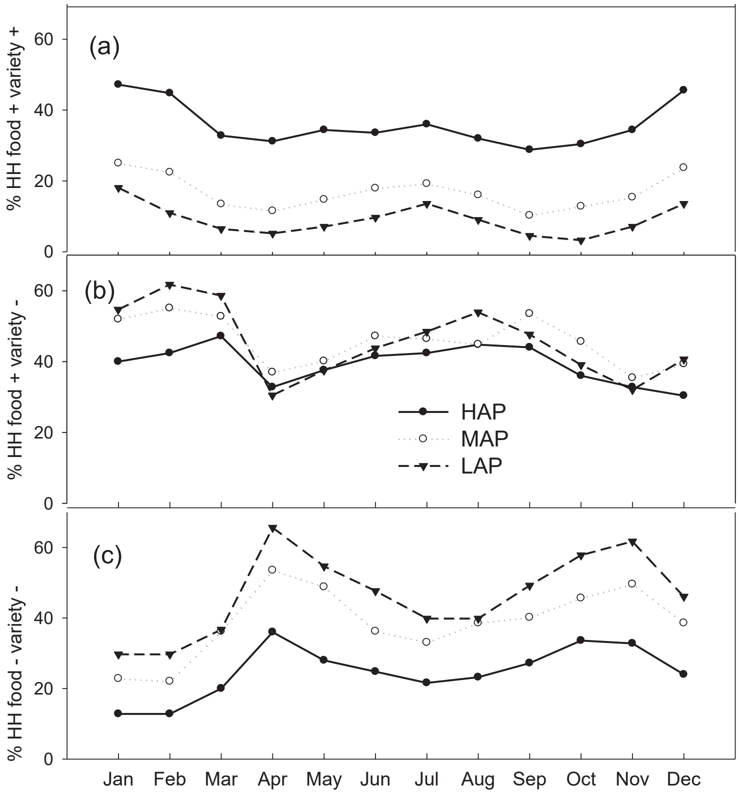

Figure 2.2 Proportion of households with: (a) sufficient food and food variety; (b) sufficient food but insufficient variety; (c) insufficient food and variety as a function of month of the year for three agroforestry categories.

Table 2.5 Summary of the results of the structural GLM model 1 for explaining the effects of households' number of trees, farm size, month of the year and agroecology factors on food security of farm households. Not significant effects (p<0.05) are shown in bold.

Model	F	Estimate	P	DF
Model 1				
Agroforestry categories	151		< 0.0001	2
MAP		-1	0.0009	
LAP		-1.11	0.0002	
Farm size	150	1.03	< 0.0001	1
Agroecology	25		0.0002	5
Months	187		< 0.0001	11
Agroforestry categories × Agroecology	95		< 0.0001	10
Agroforestry categories × Farm size	3		**0.2757**	2
Farm size × Agroecology	87		< 0.0001	1
MAP × Farm size		0.3	0.0483	
LAP × Farm size		0.2	**0.1045**	
Eastern Savannah				
Agroforestry categories	92		< 0.0001	2
MAP	94	-0.35	**0.6305**	
LAP		-1.4	0.0602	
Farm size	26	2.72	0.0039	1
Months	73		< 0.0001	11
Agroforestry categories × Farm size	16		**0.0003**	2
Eastern Plateau				
Agroforestry categories	64		< 0.0001	2
MAP		-1.37	< 0.0001	
LAP		-1.69	< 0.0001	
Farm size	0.63	-0.015	**0.9114**	1
Months	76		< 0.0001	11
Agroforestry categories × Farm size	0.84		**0.6563**	2
Buberuka highland				
Agroforestry categories	31		< 0.0001	2
MAP		-0.98	0.0135	
LAP		-2.1	< 0.0001	
Farm size	57	1.6	0.0237	1
Months	20		0.0444	11
Agroforestry categories × Farm size	24		< 0.0001	2
Volcanic highland				
Agroforestry categories	25		< 0.0001	2
MAP		-1	0.0005	
LAP		-0.63	0.0028	
Farm size	20	0.37	**0.0861**	1
Months	49		< 0.0001	11
Agroforestry categories × Farm size	37		< 0.0001	2
Central plateau				
Agroforestry categories	1.98		0.3704	2
MAP		-0.19	**0.3615**	
LAP		-0.28	**0.1712**	
Farm size	31.3	0.42	0.0039	1
Months	50.5		< 0.0001	11
Agroforestry categories × Farm size	6.1		0.0475	2
Congo Nile				
Agroforestry categories	31		< 0.0001	2
MAP		-2.3	< 0.0001	
LAP		-1.3	0.0007	
Farm size	86	1	**0.0998**	1
Months	38		< 0.0001	11
Agroforestry categories × Farm size	24		< 0.0001	2

Table 2.6 Summary of the results of the functional GLM model 2 for explaining the effects tree, crop, livestock and off-farm incomes and crop productivity and agroecology factors on food security of farm households. Not significant effects ($p<0.05$) are shown in bold.

Model factors	F	Estimate	P	DF
Model 2				
Tree income	45	-0.01	< 0.0001	1
Crop income	270	0.007	< 0.0001	1
Livestock income	7.9	0.002	0.0049	1
Off-farm income	74	-0.0005	< 0.0001	1
Crop productivity	1.3	-0.003	**0.2533**	1
Tree income × Agroecology	3.9		**0.5573**	5
Crop income × Agroecology	119.6		< 0.0001	5
Livestock income × Agroecology	48		< 0.0001	5
Off-farm income × Agroecology	30		< 0.0001	5
Crop productivity × Agroecology	26.9		< 0.0001	5
Eastern Savannah				
Tree income	16	-0.5	< 0.0001	1
Crop income	73	0.002	< 0.0001	1
Livestock income	27	0.017	< 0.0001	1
Off-farm income	43	0.002	< 0.0001	1
Crop productivity	0.1	-0.001	**0.7205**	1
Eastern Plateau				
Tree income	0.7	-0.002	**0.3813**	1
Crop income	24	0.0002	< 0.0001	1
Livestock income	8	0.007	0.0042	1
Off-farm income	19	0.0003	< 0.0001	1
Crop productivity	1.3	0.0001	**0.2472**	1
Buberuka highland				
Tree income	4.5	-0.02	0.0339	1
Crop income	109	0.006	< 0.0001	1
Livestock income	0.029	0.007	**0.8638**	1
Off-farm income	4.9	-0.0001	0.0263	1
Crop productivity	3.9	-0.005	0.049	1
Volcanic highland				
Tree income	9.9	-0.001	0.0016	1
Crop income	36	0.0009	< 0.0001	1
Livestock income	0.04	-0.00001	**0.8422**	1
Off-farm income	12	0.0008	0.0005	1
Crop productivity	8.6	0.004	0.0032	1
Central plateau				
Tree income	19	-0.001	< 0.0001	1
Crop income	38	0.0009	< 0.0001	1
Livestock income	3.5	0.0006	**0.0616**	1
Off-farm income	6.7	-0.00007	0.0097	1
Crop productivity	2.8	-0.002	**0.0929**	
Congo Nile				
Tree income	33	-0.002	< 0.0001	1
Crop income	73	0.005	< 0.0001	1
Livestock income	24	0.003	< 0.0001	1
Off-farm income	0.04	-0.001	**0.8325**	1
Crop productivity	11.4	-0.008	0.0007	1

Most farms were not food self-sufficient: only two out of three categories in the Eastern Savannah agroecology were self-sufficient (Figure 2.3). Coverage of the household caloric needs was significantly different between the categories of trees on-farm with more coverage coming from household income (58%) than own food production (35%) in general. The highest food insecurity was found in Congo Nile, Buberuka Highland and Volcanic highland where none the categories could cover all of their caloric needs (Figure 2.3). The Buberuka and Congo Nile agroecologies with more trees on farm also had smaller farm sizes (Table 2.2) and were more food insecure (Figure 2.3). When comparing farms in in the same agroecology, households in the HAP category were more food secure than other categories, in four out of the six agroecologies due to higher production of food on farm and in three out of six due to more purchased food (Figure 2.3).

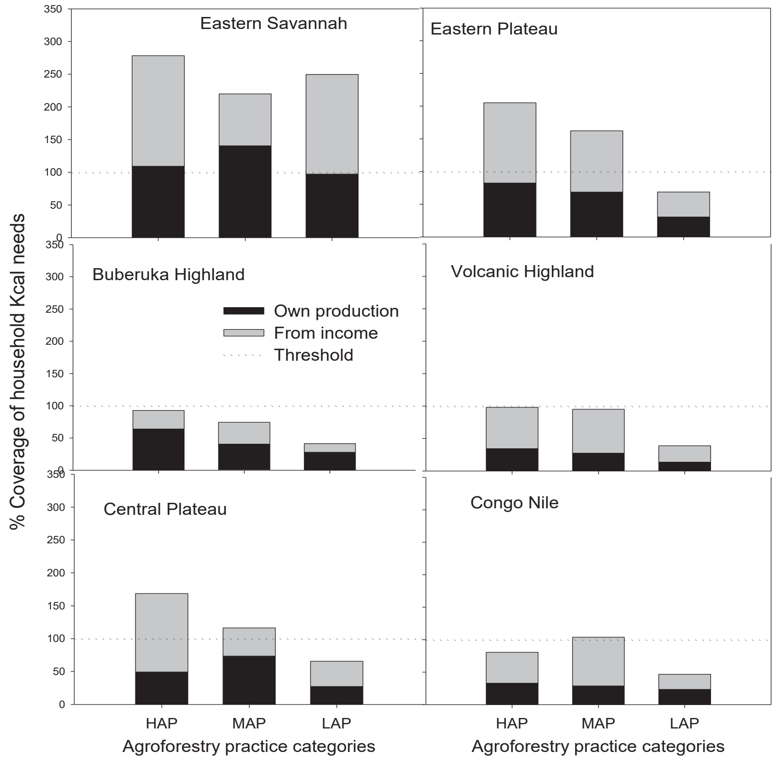

Figure 2.3 Percentage coverage of energy needs of households in different categories of agroforestry practice and in different agroecologies of Rwanda.

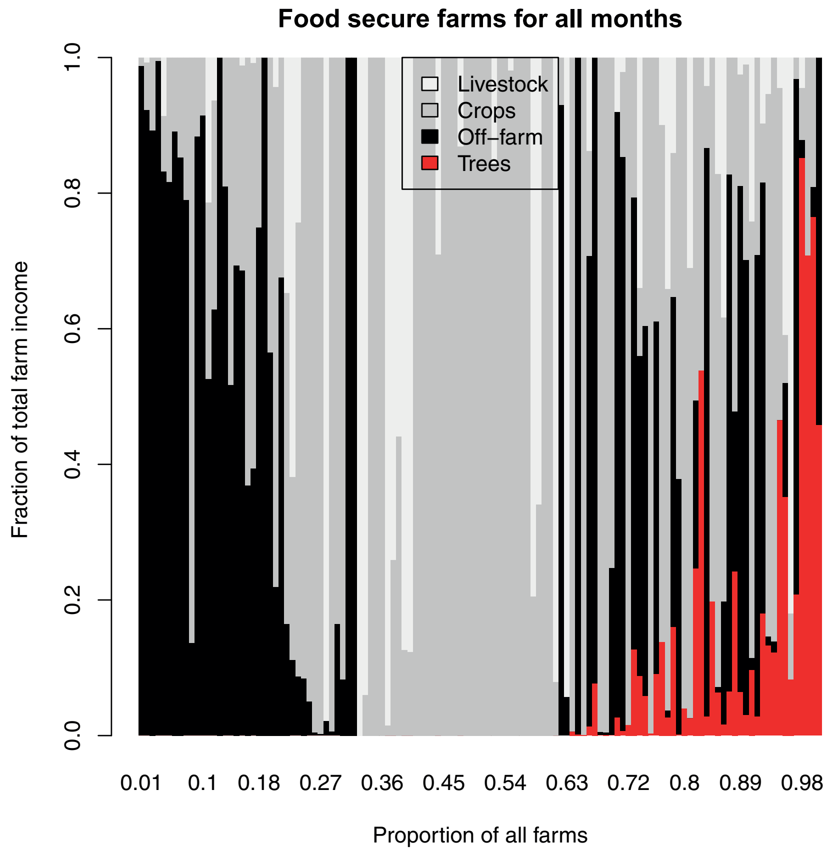

Figure 2.4 Contribution of the four farm income sources to total income across farms in the survey. Farms without tree income were first sorted on off-farm income, followed by income from trees for all other farms.

Farmers scored *Eucalyptus* spp. negatively (-0.5) regarding its interaction with crops across all agroecologies of Rwanda. *Alnus acuminata,* which thrives in the highlands, was the most positively ranked with a mean score of 0.77 followed by *Calliandra calothyrsus* (mean score of

0.59, but negatively ranked in the Volcanic highland), *Grevillea robusta* (overall mean score of 0.42), and avocado (*Persea americana*) with a mean score of 0.17 (Table 2.7).

Table 2.7 Means of farmers scores of tree-crop interaction. Negative scores signify perceived competition of trees with negative impacts on crops, and positive scores indicate a perceived facilitation of trees on crops. Score varies from -1 to +1. Standard errors are given after the sign '±'.

Tree species	Eastern Savannah	Eastern Plateau	Bubureka Highland	Volcanic Highland	Central Plateau	Congo-Nile Crest
Eucalyptus	-0.47 ±0.12	-0.27 ±0.16	-0.46 ±0.17	-0.77 ±0.09	-0.32 ±0.18	-0.42 ±0.18
Alnus	-	-	0.75 ±0.16	0.76 ±0.08	0.89 ±0.53	0.67 ±0.24
Avocado	0 ±0.15	0.29 ±0.14	0.08 ±0.17	0 ±0.11	0.3 ±0.1	0.29 ±0.11
Grevillea	0.2 ±0.11	0.67 ±0.12	0.43 ±0.3	0.12 ±0.24	0.54 ±0.11	0.26 ±0.17
Calliandra	-0.14 ±0.34	0.67 ±0.17	0.91 ±0.11	-0.13 ±0.33	0.67 ±0.1	0.9 ±0.1

2.4 Discussion

2.4.1 Farm household food security increases with increasing number of on-farm trees but does not depend on tree income.

Households in the HAP category were more food secure than those in MAP and LAP categories, mainly due to higher income from crops and livestock but with limited contribution of income from trees. Income from trees was minimal and not well related to the categories of number of trees on-farm in some agroecologies (Table 2.3), suggesting that trees on-farm are probably kept by farmers for other reasons (e.g. own consumption of firewood and fruits, and erosion control). Yet, for about 12% of farmers, tree products contribute more than 20% to their income, where food insecure farmers were more often selling tree products for income than food secure farmers. In this way trees may be seen as a "safety net" to meet the needs of the poorest households. In the eastern part of Rwanda (Eastern savannah, Eastern plateau and Central plateau) where households have relatively larger land, farmers in HAP had larger farms and a higher crop income than in MAP or LAP categories. Thus, despite the lowest income from trees as compared to the rest of the agroecologies, the households in the HAP category the eastern parts of Rwanda were wealthier (e.g. with larger farms and more overall income) and therefore more food secure. In the western part of the country which has a very hilly topography (Congo Nile Crest, Buberuka highland and volcanic highland), farmers have small farms and grow more on-farm trees, but most households were food insecure. However, within each agroecology in this region, households in HAP category were also more food secure than those in MAP and LAP mainly due to more income from crops and livestock as a result of the relatively larger farm sizes. These households in HAP had a higher overall income than the MAP and LAP categories, suggesting that they could have absorbed the costs of trees more than other categories, i.e. expenses of tree planting and the potential detrimental effects on trees on crop yields. Though the income contribution from trees was generally small in absolute terms, farmers in agroecologies of the western part of the country seemed to gain a substantial proportion of their income from trees in contrast to their counterparts in the East. This may reflect the value of wood products and the hypothesized importance of the ability to sell wood for the food security of farm households (Ndayambaje et al. 2014) .

Due to different biophysical (e.g. topography, rainfall, temperature and soil types) and socio-economic conditions in the agroecologies, farm size and food security increased from the west to the east of the country while the number of trees per household and tree cover decreased, as also reported by (Franchis 2012). However, within particular agroecology, household's food security increased with increasing number of trees on-farm but not with tree income. In each agroecology, households in HAP category had usually higher crop and livestock income than the rest of the categories, suggesting that the improved food security of households with higher number of on-farm trees is associated to their higher overall farm income while the contribution of tree income was small. Coulibaly et al. (2017) recently found that agroforestry adoption increased income from both crops and tree products and therefore positively impacted household food security in Malawi. Our study suggests that trees are mostly used on-farm and a higher income from crops and a substantial proportion of income from trees were found in households that were relatively wealthier with larger farms. There is a need for more detailed studies to assess the biophysical and socio-economic contexts where agroforestry may increase households' income and therefore food security since under other circumstances agroforestry may reduce food self-sufficiency.

2.4.2 In the same agroecology context, wealthier households adopt on-farm trees.

This study found no relationship between asset endowment and agroforestry practice categories. However, farm size, crop and livestock income – which are more common wealth indicator for farm households in Rwanda - were related to the number of on-farm trees in most of the agroecologies and positively increased the household food security (Table 2.6). Within the same agroecology, food security increased with increasing farm size and households with more trees were more food secure than those with less. The primary goal for farmers in the same agroecology context is to produce food for households and therefore the privilege of growing more trees on-farm (which compete with crops and might reduce yields) belongs to the ones with relatively more land. In the same agroecology, households with more income from trees had also more income from crops and livestock in contrast to what was observed in Ethiopia where income from trees increased at the expense of income from crops (Sida et al. 2017). In general, higher farm size, crop and livestock income could have been the precondition for practicing agroforestry. This could suggest that poor farmers need assistance to be able to adopt – e.g. access quality tree seedlings- (Kakuru et al. 2014). Besides, on-farm trees seem profitable when farmers integrate crops and livestock since the income from trees increased with the increase of crop and livestock income (Bucagu 2013; Beedy et al. 2013).

2.4.3 *Farmers' perceptions of tree crop interactions influence agroforestry practice levels across agroecologies.*

The perception of tree-crop interactions by farmers in the Eastern province was more negative than in the other agroecologies, probably due to stronger competition for water between trees and crops in this semi-arid agroecology. As a result, the number of trees managed by households were the smallest in the Eastern savannah despite the largest farm size among all other agroecologies, and most of the households with no single tree were also found in this agroecology. Farmers in the Volcanic highland agroecology tended to perceive tree-crop interactions as competitive, with the exception on *A. acuminata* which they ranked as highly compatible with crop farming. *A. acuminata* is most preferred in this area since it provides stakes for climbing beans (Bucagu 2013), fixes nitrogen, and is less competitive with crops especially under the intense pruning regime applied by farmers in this region (Peden et al. 1993; Ndayambaje and Mohren 2011).

Eucalyptus was perceived to have a strong negative interaction with crops in all the agroecologies of Rwanda, explaining why many farmers prefer growing this genus in woodlots rather than integrating it in cropped fields (Mugunga 2016). *Eucalyptus* – which is frequently grown in woodlots in Congo Nile and Central plateau - contributed to increased household income in this study, agreeing with observations from Ethiopia and Kenya where *Eucalyptus* trees grown on-farm and in woodlots were more profitable than sole crops (Jagger and Pender 2003; Kidanu et al. 2005; Peralta and Swinton 2009).

2.5 Conclusion

The present study investigated whether farmers with more trees on their farm were more food secure than those with less trees on their farm in the six agroecological zones of Rwanda. Large differences between agroecological zones were observed for both food self-sufficiency and food security. Households with larger farms were more food secure than those with smaller farms, while food security was reduced by presence of more trees on small farms but also on larger farms. However, the proportion of income that came from tree products was more than 20% for about 12% of the farmers, with food insecure farm households relying more on income from tree products than food secure farm households. In most cases, more trees on farm did not result in higher tree income, suggesting that trees on-farm are mostly used to meet the households demand in firewood, fruits and other tree products. Better coverage of caloric needs was found in the category of households with more trees mainly through food purchase as they were wealthier (e.g. with larger farms and higher income) than the rest. The lack of significant difference in assets endowment between the agroforestry categories while farm size and income were different suggest that assets are probably not the best indicator of wealth for Rwandan farm households. Farmers in the Eastern savannah and Volcanic highlands reported negative effects of on-farm trees on crops which could explain why they have fewer trees on their farms. Introducing agroforestry technologies to these farmers will not be effective, unless they change their perception on tree-crop interaction. There is therefore, a need to investigate farmers' perceptions on tree crop interactions to better understand if increasing the tree density would be of benefit. Our results suggests that within the same agroecology, farm households with more land most probably grow trees on-farm to increase their self-sufficiency in fuelwood, fruits and other tree products rather than growing them for markets.

Chapter 3

Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda

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Abstract

In the sub-humid parts of East Africa, high population density and pressure on land have led farmers to integrate multipurpose trees on farm. Although mixing trees and crops generates numerous benefits (e.g., fuelwood, timber), it often reduces crop yields. Whereas the effects of mature trees on crops are well studied in semi-arid parklands, there are only few studies for the sub-humid environment. The effects of mature *Alnus acuminata* (Kunth) and *Markhamia lutea* (Seem.) on crops were studied on-farm for four seasons in the sub-humid environment of northern Rwanda. Five sampling points for *A. acuminata* and *M. lutea* were: (i) 1 m from tree trunk without maize, (ii) 3 m from tree trunk without maize, (iii) 1 m from tree trunk with maize, (iv) 3 m from tree trunk with maize and (v) sole maize away from any tree. Nutrient availability and uptake, soil water, air temperature, solar radiation, crop growth and yields were measured. The APSIM-maize module was used to assess the sensitivity of maize yields to changes in these variables. Nutrients availability was higher under *A. acuminata* compared with *M. lutea,* because of higher litter fall but maize nutrient uptake increased only under *A. acuminata* 3 m from tree trunk during a wetter season. None of tree species affected water availability for maize in the topsoil. Photosynthetically active radiation (PAR), total solar radiation and day air temperature were reduced by both tree species. Maize crop at 1 m and 3 m from the tree trunk was shorter in height but had the same number and size of leaves when compared to sole maize plots. Crop yield was generally reduced more at 1 m than at 3 m from the tree trunk. A positive interaction between *A. acuminata* and maize was only apparent at 3 m from the tree in one of the four seasons following higher litter fall, suggesting that the negative effect of shade was offset by extra N input during that season. In a modelled scenario under low N fertilization, larger N input from trees could compensate for yield loss caused by reduction in radiation and temperature in about 60% of the seasons. Our findings suggest that adequate pruning and high leaf litter recycling can reduce the negative effect of shade in low intensity farming systems.

3.1 Introduction

Trees play a crucial role in rural Africa providing products – such as firewood, timber, fodder, and fruits (Ndayambaje et al., 2013) – as well as services – such as shade, erosion control and maintenance of soil fertility (Buresh, 1998; Sileshi et al., 2014). The demand for tree products and the expansion of agricultural land in Africa has led to deforestation (Barbier, 2004) and shortage of tree products in densely populated countries. In the highlands of East Africa, the dense population has cleared forests leading farmers to integrate trees on farms of ever decreasing size (Allen and Barnes, 1985; Ndayambaje and Mohren, 2011). The pressure on land availability also led farmers to cultivate steeply sloping areas, sometimes with grades exceeding 60%; this leads to risks of severe soil erosion which could be alleviated by trees. As a result, tree density decreased in forests, but increased on farms (Cooper and Krah, 1996; Garrity, 2012). Thus, improving knowledge on the way on-farm tree species affect crop productivity and designing solutions to overcome the challenges of below and above ground competition is highly relevant (García-Barrios and Ong, 2004).

When trees and crops are mixed, tree competition for light, nutrients and water reduces crop yields, while rings of soil fertility around trees may be observed when fields are nutrient deficient (Buresh and Tian, 1997; Kho, 2000; Rao et al., 1997). Hundreds of different nitrogen fixing leguminous trees are used in agroforestry (Giller, 2001) and their N_2-fixing ability can significantly reduce competition for this resource (García-Barrios and Ong, 2004). In East Africa, the effect of several different tree species such as *Grevillea robusta* (Lott et al., 2000) and *Eucalyptus* spp. (Mugunga, 2016; Tadele and Teketay, 2014) on crop growth has been studied. However, there is limited information on the effects on crops grown under *Alnus acuminata* (Kunth) (Muthuri et al. 2005) or *Markhamia lutea* (Seem.). These two species are often present in agroforestry systems in East Africa (Okorio et al., 1994), and are dominant in the humid highlands of Rwanda (Mukuralinda et al., 2016).

A. acuminata, a nitrogen fixing tree (Carú et al., 2000) can have beneficial effects on crop yield (Muthuri et al., 20005; Okorio et al., 1994; Peden et al., 1993) and soil water availability for crops (Siriri et al., 2013). On the other hand, *M. lutea* was found to reduce crop yield (Okorio et al., 1994) although it did not strongly compete for soil water due to its slow growth (Radersma and Ong, 2004; Yamoah et al., 1989). Yet, Wajja-Musukwe et al. (2008) found that *A. acuminata* reduced yield more than *M. lutea* despite the latter having more roots in the surface soil layers. It is commonly known that the competitive effects of trees tend to increase as trees mature and causing a concomitant decrease in the yields of the associated crops (Srinivasan et al., 1990). Nevertheless, these studies investigated the effects of only young trees (up to 3 years old) on crops. Although the effects of mature trees on crops are well studied in arid and semi-arid parklands (Ong and Leakey, 1999), there are no equivalent studies in sub-humid environments where *A. acuminata* and *M. lutea* are commonly found (Okorio, 2000).

This study aims to unravel the processes involved in tree-crop interactions in sub-humid environment to inform management and produce recommendations that minimize negative effects and maximize positive effects. Our specific objectives were to quantify the effects of mature *A. acuminata* and *M. lutea* on microclimate and resources available to maize crops grown at varying distances from the tree trunk, and to assess how these effects interact. It was hypothesized that the improvement of soil fertility by the trees could compensate the negative effects of shade in these farming systems where little mineral fertilizer is used.

3.2 Material and Methods

3.2.1 Study area

The study area is located in Rubavu district, Nyakiliba sector, Gikombe cell, Kitarindwa village in North West of Rwanda in the Birunga agricultural zone, between 1° 40' 27" and 1° 41' 08" latitude South, and 29° 21' 28" and 29° 21' 10" longitude East. The elevation ranges from 1,941 to 2,024 m above sea level. The area receives annual rainfall varying between 1,300 and 1,600 mm (Verdoodt and Ranst, 2003), distributed over two cropping seasons: the "long rains" from mid-February to mid-July (referred to as season B) and a "short rains" from September to January (referred to as season A), with largest amounts of precipitation in the months of April and November. The soils in this area are typically Mollic Andosols (Verdoodt and Ranst, 2003) which are formed on volcanic deposits and have high organic matter content. Selected sites had soil depth ranging from 100 to 150 cm and a gentle slope ranging from 2 to 6% at the bottom of Gishwati hills.

3.2.2 Experimental design

A total of six experimental sites – three for *A. acuminata* and three for *M. lutea* – were selected in farmers' fields, based on the presence of two quasi identical trees and an open (treeless) field nearby. All fields were previously cropped with climbing beans and fertilized with manure, except for one field with *A. acuminata* and one field with *M. lutea* and maize which were intercropped with cabbages and onions and fertilized with inorganic fertilizers.

At each experimental site three plots were established: a plot with tree and maize, a plot with sole maize, and a plot with sole tree. Each plot was 10 m by 10 m in size. In the tree-maize plot, maize phenology, morphology, biomass and yield were recorded at distances of 1 m and 3 m from the trunk. The same measurements were done in the sole maize plot, located at least 40 m away from any tree. Thus, the experiment included the following five sampling points for *A. acuminata* (Al) and *M. lutea* (Ma):

- Al-1m and Ma-1m: 1 m from the tree trunk of sole trees
- Al-3m and Ma-3m: 3 m from the tree trunk of sole trees
- AlM-1m and MaM-1m: 1 m from the tree trunk in plots of trees associated with maize
- AlM-3m and MaM-3m: 3 m from the tree trunk in plots of trees associated with maize
- AlM-40m and MaM-40m: sole maize, at least 40 m away from any tree

The experiment ran from September 2013 to July 2015, and included two short rainy seasons (2014 A, 2015 A) and two long rainy seasons (2014 B, 2015 B). The maize variety PAN691 was used at a spacing of 0.43 m within rows and 0.9 m between rows with two plants per hill and planted on raised beds. Recommended fertilizer rates were used: 100 kg ha^{-1} of diammonium phosphate applied as basal fertilizer at planting and 100 kg ha^{-1} of urea applied as topdressing 5 weeks after emergence. Trees were managed to produce single stems and lower branches were pruned annually to maintain a canopy of 3.5 m above the ground, according to common local practices (Figure 3.1).

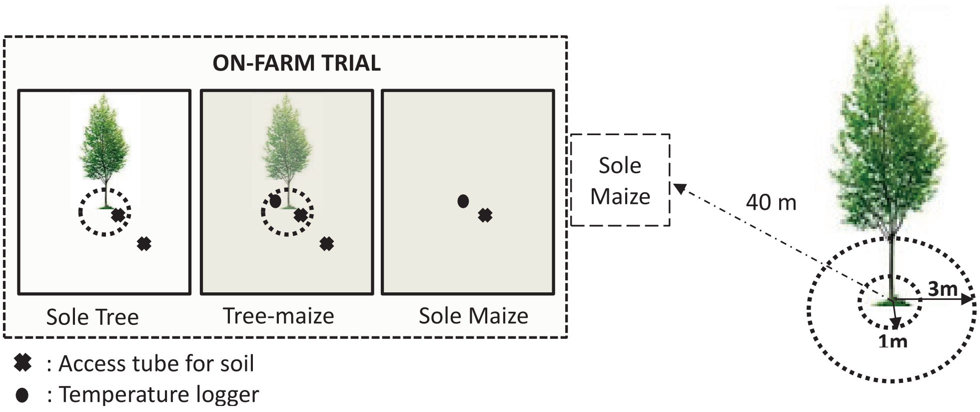

Figure 3.1 Experimental design with treatments in 10 by 10 m plots and illustration of concentric measurement at 1, 3 and 40 m distance from the tree trunk.

3.2.3 Measurements

For each plot, composite soil samples were systematically taken at the on-set of the experiment in 12 quadrats starting from the centre of the plot at three depths (0-20, 20-40, and 40-60 cm). Each plot sample was a combination of 12 cores, including cores taken at 1 m, 2 m and 3 m from the tree trunk in 4 directions from the tree. Cores from the same depth in the plot were then pooled together, resulting in three samples representing three depths per plot. Soil samples were air dried at 40 °C and analysed in the laboratory. Soil pH was measured in a 2.5:1 water to soil suspension (Rhoades, 1982), soil organic carbon (SOC) was measured using the Walkley and Black (1934) method. Total N was determined by semi-micro Kjeldahl digestion and distillation. Available P was estimated using molybdenum blue method on a Bray-P extract (Bray and Kurtz, 1945). Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962).

Daily rainfall, air temperature and total incoming solar radiation were measured using an automatic weather station (Vantage Pro2^{TM}, Davis Instruments Corp, USA) located within 1 km of all plots. Air temperature under tree canopy was recorded for AlM and MaM plots at 1 m distance from the trunk and at 40 m with four automated temperature loggers (Tinytag), mounted on 1 m poles and roofed with a plastic tile to avoid sensor heating by direct sunlight. The logger recorded air temperature every 30 minutes from the onset of the trial up to the last harvest.

Soil water was measured using a dielectric method (microwave probe). A profile probe (PR2-UM-3.0, Delta-T Devices, Cambridge, UK) was used to measure the soil water content at depths of 10, 20, 30, 40, 60 and 100 cm from the soil surface within pre-installed access tubes, at a temporal interval of about 15 days throughout the maize growing seasons. Two access tubes of 1 m depth were permanently installed at 1 m and 3 m from tree trunk of each plot containing a tree. A single access tube was permanently installed at the centre of the sole maize plots.

Incident photosynthetically active radiation (PAR) was measured in all plots including maize at anthesis in the 2015 A season, using a Sunfleck Ceptometer (Delta-T Devices, Cambridge, UK). PAR was measured in transects spaced by 0.5 m starting from the tree trunk in east, west, north and south directions. PAR measurements took place on sunny days around noon, above the maize canopy under and away from tree canopy. Since the Birunga agricultural zone is usually very cloudy throughout the season, diurnal solar radiation was also recorded every 5 minutes for three days at 1 m and 40 m from the trunk in AlM and MaM plots with radiation sensors placed at 1.5 m above the ground and connected to a logger (Vantage Pro2^{TM}, Davis Instruments Corp, USA).

Litter was collected in two litter boxes (0.81 m^2 each) at a distance of 1 m and 3 m from *A. acuminata* and *M. lutea* trunks. Litter was collected on a weekly basis and air dried before being weighted. A subsample was oven-dried at 60ºC until constant weight to determine dry matter content. Total dry weight of litter per tree was determined for each season by summing up all in-season dry litter that was collected. Subsamples of 500 g of the litter collected in the seasons 2014 B and 2015 A from *A. acuminata* and *M. lutea* were collected and milled for laboratory analyses. Total nitrogen and phosphorus were analysed in a single digestion of dried plant sample with hydrogen peroxide, sulphuric acid, selenium and salicylic acid. Total nitrogen was then determined by distillation and titration and total phosphorus by the molybdenum blue method (Okalebo et al., 1993; Thomas et al., 1967).

Weekly non-destructive phenological measurements were made from 30 days after sowing until the end of the vegetative growth stage. Two plants for AlM-1m, AlM-3m, MaM-1m and MaM-3m sampling locations were labelled to enable repeated measurements, providing a total of 4 plants per plot with a tree. In the AlM-40m and MaM-40m plots, four maize plants were labelled at the centre of each plot. The phenological characteristics recorded for maize plants included the number of visible leaves, the number of fully expanded leaves and the sheath length of fully expanded leaves. The duration of the vegetative, reproductive and grain-filling phases, was determined when 50% of the plants in the plot reached that stage. At harvest, fresh and dry weights of maize residues and grains were measured. Eight plants - covering east, west, north and south sides of the trees - were sampled in AlM-1m, AlM-3m, MaM-1m and MaM-3m. Similarly, eight plants were sampled from AlM-40m and MaM-40 m in four directions starting from the centre of the plots. Means of grain, residues and total aboveground biomass per plant (kg/plant) were converted to ton per hectare by multiplication with the number of counted plants (plants per plot of 100 m^2) for each plot. The number of plants per plot was determined before cutting the plants at ground level. Subsamples from maize grain and residues were taken from the 2014 B and 2015 A harvests and were analysed for total N and P content in a single digestion as described above for litter analysis (Okalebo et al., 1993; Thomas et al., 1967).

3.2.4 Statistical analysis

Tree characteristic parameters were tested for normality using Shapiro-Wilk tests. Means of normally distributed variables, including tree height, diameter ad breast height (DBH), diameter at stump height (DSH) and canopy radius means were compared through analysed with an Analysis of Variance (ANOVA) using Fisher's F-test. For variables that were not normally distributed – including tree age and distance to the lowest branch from ground - median values were compared using the non-parametric Kruskal-Wallis test.

The variability of nutrient uptake, number of visible leaves, plant height, and yield was analysed using linear mixed effect models. The fixed effects in the model included the distance from tree and seasons, while random effects included were directions from the plot centre nested within distances from the tree per plot centre and distances nested within sites. ANOVA for the model gave differences between groups, i.e. distances from tree, season and their interaction. For this described model and all the following models, pairwise comparisons between distances from trees for each season were done using Tukey's test in the PredictMeans R package (Welham et al., 2004).

Soil water data were also analysed using a linear mixed model in which fixed effects were treatments (sole tree, sole maize and tree with maize and seasons). Random effects were Treatment nested within Site. Pairwise comparison for soil water was performed and the average least significant difference (LSD) is presented to allow comparison between treatments.

The variability in total solar radiation was analysed in a mixed model with tree species as fixed effect and logging time as a random effect. The variability in photosynthetically active radiation (PAR) was also analysed with a mixed model with tree species and distance from tree considered as fixed factors while directions nested in sites were considered as random effects. Pairwise comparisons were done and the average least significant difference (LSD) value was presented to allow comparison between tree species.

Air temperature data were divided into day (from 6:00 am to 5:30 pm) and night (from 5:30 pm to 6:00 am) for each plot. Cumulative frequency of temperature differences between under trees and sole maize plots for day and night-time were calculated for *Alnus* and *Markhamia*. A linear mixed model, with Treatment as fixed effect and logging date and time as random effects, was used to analyse differences in air temperature and pairwise comparisons between treatments was again established. R software (R Development Core Team, 2014) was used for all statistical analyses.

3.2.5 Sensitivity analysis using APSIM maize module

APSIM version 7.8.2 was calibrated using data from AlM-40m and MaM-40m. Measured values of soil water contents were used to set soil drainage parameters - lower and upper drained limits - and measured soil pH and organic carbon content values were imputed. The phenology and morphology parameters for variety SC501 were selected from APSIM-Maize and adapted to best match the PAN691 cultivar that was used in the experiment. The parameter determining the cumulative temperature until the end of the juvenile period was set to 200 ºC days to better match the observed phenology. The maximum number of grain kernels per ear was also reduced to 450 to match the potential to the observed number of grains for the variety PAN691. After calibration, model predicted (P) yields and soil water estimates were compared to observed (O) values of seasonal yield (2014 A, 2014 B, 2015 A, and 2015 B) and soil water contents at 10, 20, 60, and 100 cm depth during 7 times in 2015 A and 8 times in 2015 B. The Nash-Sutcliffe modelling efficiency (NSE), and the Root Mean Square Error to Standard Deviation Ratio (RSR) were used to evaluate model performance.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2}$$

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(Oi - Pi)^2}}{\sqrt{\sum_{i=1}^{n}(Oi - \bar{O})^2}}$$

Where NSE represents the Nash-Sutcliffe modelling efficiency, RSR is the Root Mean Square Error to Standard Deviation Ratio, Pi is the *i*th observation of maize grain yield, Oi is the *i*th simulated value of maize grain yield, $\bar{O}$ is the mean of observed maize grain yield, and *n* is the total number of observations.

Based on criteria from Moriasi et al. (2007), model calibration resulted was 'satisfactory' for yield (NSE of 0.63 and RSR of 0.61; Fig. S1) and 'good' for soil water (NSE of 0.72 and RSR of 0.52; Fig. S2). The calibrated model was subsequently used to study scenarios with reduced daily radiation (-10%) and lowered maximum temperature (-2 ºC), combined with nitrogen inputs of 64 and 114 kg N ha^{-1}. This scenario reflects a situation of recommended rates of N (64 kg N ha^{-1}) without trees and a situation under a tree with reduced radiation and 50 kg N ha^{-1} extra N input from e.g. *A. acuminata* litter. The situation described above occurred in one of 4 years in this study. Graphs showing scenario with average N inputs from tree litter and the scenario with higher fertilization system of 150 kg N ha^{-1} without trees and situation with reduced radiation and temperature and 200 kg N ha^{-1} - including an extra 50 kg N ha^{-1} from tree litter - are presented in the supplemental materials (Fig. S3). Simulations included the years 2006 to 2016 - with two seasons in each year - for which complete weather data was available. Simulations for three seasons did not produce any yield due to drought, therefore only 19 simulated yields are presented for each scenario. Cumulative distribution functions were utilized to get insights into how yields varied in different microclimate and N inputs scenarios.

3.3 Results

3.3.1 Local climate and tree dimensions

Unusually low (286 mm) and high (758 mm) seasonal rainfalls were experienced in seasons B as compared with the long-term average of 538 mm. Seasons A received average (664 mm and 420 mm) rainfall as compared to the long-term seasonal average of 692 mm (Figure 3.2). Season

A tended to have higher radiation than season B which was also observed in the long-term averages where season A received a total of 434 kW m^{-2} while season B received 390 kW m^{-2} (Figure 3.2).

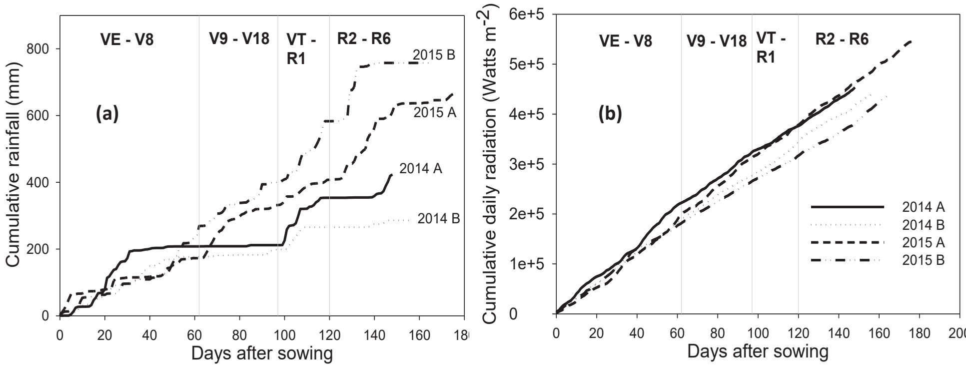

Figure 3.2 Cumulated daily rainfall (a) and daily total radiation (b) during maize growing period. VE–V8: from emergence to 8th leaf stage (seedling stage); V9–V18: from 9th leaf stage to 18th leaf stage (jointing stage); VT–R1: from tasselling to silking; R2–R6: from blister stage to physiological maturity.

The *A. acuminata* trees were taller and had larger diameter at breast height (DBH), diameter at stump height (DSH) and canopy radius than *M. lutea* trees although the latter were reported by farmers to be much older. The lowest branch of *M. lutea* trees was at a similar height from the ground as with *A. acuminata* (Table 3.1).

Table 3.1 Characteristics of *A. acuminata* and *M. lutea* trees used in the experiment at the on-set of the trial (beginning of season 2014 A). Standard deviations are given after the signs '±' and *P* values are given for means comparison between tree species.

Measurement	***A. acuminata***	***M. lutea***	***P-value***
Height (m)	9 ± 1.3	7 ± 0.7	0.0002
Diameter at breast height (DBH, cm)	31 ± 2.8	19 ± 3.7	<0.0001
Diameter at stump height (DSH, cm)	46 ± 6.3	29 ± 8.1	<0.0001
Canopy radius (m)	3.3 ± 0.3	2.3 ± 0.5	<0.0001
Distance of lowest branches from ground (m)*	3.4 ± 0.5	3.7 ± 0.8	0.2279
Tree age by farmer recall (years)*	7 ± 0.0	22 ± 5.7	<0.0001

** data analysed with a non-parametric Kruskal-Wallis test.*

3.3.2 Nutrient availability and uptake

Table 3.2 describes the soil properties for the different treatments for *A. acuminata* and *M. lutea*. The soils at the experimental site had a favourable pH, and good soil organic carbon but medium to low contents of phosphorus and nitrogen. Soil texture shows more sand (or volcanic ash) which could favour nutrient leaching. Results of soil analysis indicate that samples from the three depths were not significantly different for all the soil characteristics, reflecting the soil mixing effect of the bed-furrow tillage practice used by farmers in the area, where raised beds that are formed every season attain 0.7 m in height. Soil characteristics from different treatments were not different with the exception of pH in the *A. acuminata* system and for phosphorus in the *M. lutea* system which could have resulted from the different fertilization history of the fields. Indeed, one site of sole *A. acuminata* and one site of *M. lutea* and maize were located in the farmer's cooperative land and were cropped with vegetables in rotation with potatoes under heavy fertilization rates of around 300 kg of DAP ha^{-1}. The residual nutrients from these previous fertilizers could be the source of high P measured in these plots at the start of the experiment.

Table 3.2 Soil characteristics in the study area at the beginning of the experiment. Data are means of three composite samples per depth and for three depths (0-20 cm; 20-40 cm and 40-60 cm). Values at the three sampling depths were not significantly different for any of the soil characteristics and these values were thus averaged. Standard deviations are given after the sign '±' and reflect the variation between sites

Treatments	**pH (H_2O)**	**SOC (%)**	**Total N (%)**	**Avail. P (ppm)**	**Clay (%)**	**Silt (%)**	**Sand (%)**
A. acuminata							
AlM-40m	6.2 ±0.1	2.3 ±0.3	0.4 ±0.1	17 ±19.1	11 ±2	25 ±4	65 ±4
Al(1&3m)	6.0 ±0.1	2.1 ±0.5	0.4 ±0.1	28.7 ±21.2	12 ±3	24 ±3	64 ±4
AlM(1&3m)	6.1 ±0.1	2.3 ±0.2	0.4 ±0.1	18.1 ±18.7	11 ±2	23 ±3	66 ±3
P	*<0.0001*	*0.621*	*0.383*	*0.1255*	*0.0397*	*0.5262*	*0.3503*
M. lutea							
Ma-40m	6.0 ±0.1	3.1 ±0.5	0.5 ±0.2	11.8 ±8.6	9 ±2	22 ±6	69 ±7
Ma(1&3m)	6.0 ±0.1	3.2 ±0.5	0.6 ±0.2	10.1 ±3.4	8 ±1	22 ±6	69 ±6
MaM(1&3m)	6.0 ±0.2	3.2 ±0.3	0.6 ±0.1	32.6 ±10.7	9 ±1	21 ±6	70 ±7
P	*0.4961*	*0.5351*	*0.1268*	*<0.0001*	*0.08*	*0.9341*	*0.9499*

The long dry spell period during the season 2014 B induced a higher litter fall especially for *A. acuminata*, resulting in a significantly larger input of nutrients during that season: around 50 kg of N and 5.6 kg of P per hectare (Table 3.3). On the other hand, *M. lutea*, a species with low primary productivity added less nutrients in litter than *A. acuminata* and its input was not significantly different among different seasons.

Table 3.3 Dry matter (DM), and N and P amounts in per ha equivalents (± standard deviations) from tree litter fall collected in 0.81 m^2 boxes at 1 m and 3 m from the trunk of the tree

Season	***A. acuminata* litter**			***M. lutea* litter**		
	DM ($t\ ha^{-1}$)	**Total N ($kg\ ha^{-1}$)**	**Total P ($kg\ ha^{-1}$)**	**DM ($t\ ha^{-1}$)**	**Total N ($kg\ ha^{-1}$)**	**Total P ($kg\ ha^{-1}$)**
2014 A	0.53 ±0.2	10.9 ±3	1.22 ±0.3	0.24 ±0.0	4.2 ±0.4	1.12 ±0.1
2014 B	2.43 ±0.7	49.8 ±14	5.58 ±1.6	0.39 ±0.1	7.0 ±0.9	1.86 ±0.2
2015 A	0.87 ±0.0	17.9 ±0	2.01 ±0.0	0.35 ±0.1	6.3 ±2.0	1.66 ±0.5
2015 B	0.52 ±0.1	10.6 ±3	1.18 ±0.3	0.23 ±0.0	4.1 ±0.3	1.09 ±0.1
LSD	*1.03 **	*21.1 **	*2.36 **	*0.17*	*3.1*	*0.83*

*: Means for seasons are significantly different at p (0.05)

In both season 2014 B (relatively dry) and 2015 A (relatively wet), maize at 3 m from *A. acuminata* (AlM-3m) accumulated more N than at 1 m (AlM-1m) and 40 m (AlM-40m) from tree trunk while there was no significant difference in maize nitrogen uptake for maize at different distances from *M. lutea* (Table 3.4). P uptake was higher in AlM-3m than in AlM-1m and AlM-40m in the relatively wet season but P uptake of maize in AlM-40m was higher than AlM-1m but not different to AlM-3m during the relatively dry season. There was no significant difference in P uptake by maize at different distances from *M. lutea*. The P and N uptake were significantly greater during the relatively wet season at all distances (Table 3.4).

Table 3.4 Amounts of nutrients in above-ground plant organs of maize growing at 1, 3 and 40 m from the trunks of *A. acuminata* (AlM) and *M. lutea* (MaM) tree species. Means followed by the same letter in the same season do not differ significantly at α= 0.05.

Season	Above ground N uptake (kg ha^{-1})			Above ground P uptake (kg ha^{-1})		
	1 m	**3 m**	**40 m**	**1 m**	**3 m**	**40 m**
			A. acuminata			
2014 B	61^{a}	83^{b}	53^{c}	18^{a}	25^{b}	28^{b}
	±18	±18	±8	±7	±6	±3
2015 A	83^{a}	149^{b}	109^{a}	17^{a}	32^{b}	21^{c}
	±31	±52	±24	±2	±7	±2
Season (p)	*<.0001*			*0.8531*		
Distance (p)	*0.0117*			*0.0295*		
SeasonXdistance (p)	*0.0202*			*<.0001*		
			M. lutea			
2014 B	38^{a}	55^{b}	51^{b}	10^{a}	15^{b}	16^{b}
	±20	±25	±14	±6	±7	±4
2015 A	62^{a}	81^{a}	70^{a}	15^{a}	20^{b}	26^{b}
	±41	±50	±24	±8	±9	±14
Season (p)	*0.0008*			*0.0003*		
Distance (p)	*0.1965*			*0.1522*		
Season×distance (p)	*0.8851*			*0.5016*		

3.3.3 Soil water

Soil water contents and changes in soil water between 10 and 40 cm (height of raised bed) were similar and these depths were therefore grouped and are referred to as ‘topsoil’. Similarly, soil water contents and changes in soil water were similar between 40 and 100 cm (below furrow height) and these depths were therefore grouped and are referred to as ‘subsoil’. Plots with maize under *A. acuminata* had more soil water than plots with sole *A. acuminata* (average of Al-1m & Al-3m) but was not significantly different to sole maize (AlM-40m) in the top soil while there was no significant difference between the treatments in the subsoil (Figure 3.3).

Plots with maize under *M. lutea* had less soil water than plots with sole *M. lutea* but no difference was found with sole maize in the top soil throughout the study period. There was no difference in the sub-soil water between treatments (Figure 3.3).

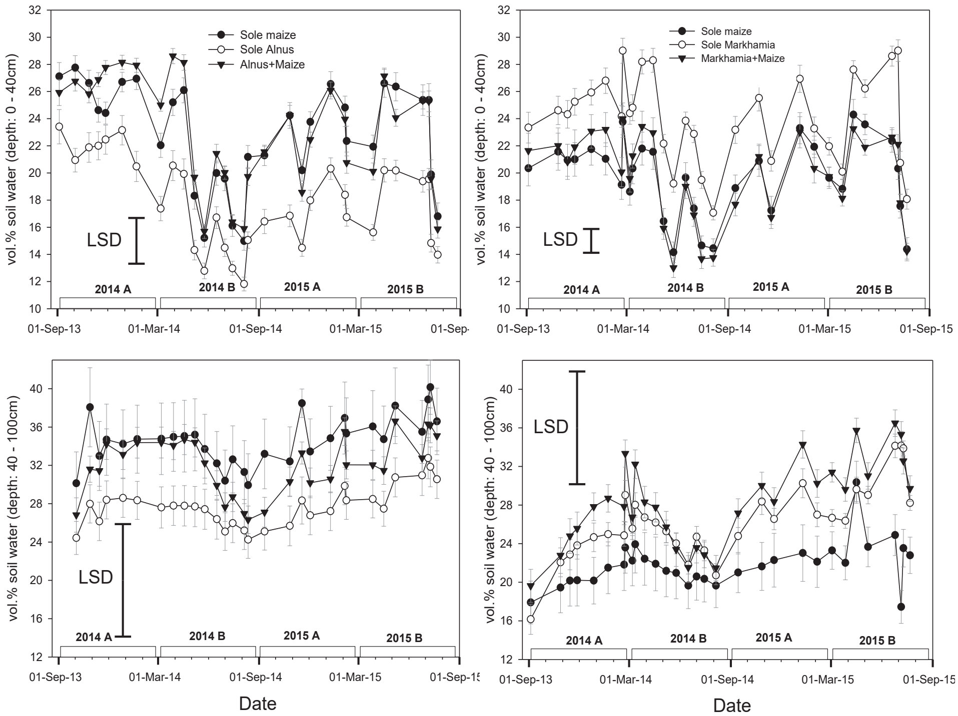

Figure 3.3 Soil water in the top soil (0-40 cm) and sub-soil (40-100 cm) in sole maize plots (AlM-40m and MaM-40m), sole tree plots (average of Al-1m & Al-3m), and tree-maize plots (average of AlM-1 and AlM-3m; average of MaM-1m and MaM-3m) for four cropping seasons. Error bars are standard error of the mean.

3.3.4 Maize yield and sensitivity to microclimate and N inputs

During the 2014 A and 2014 B seasons (with low rainfall), maize grain yield, stover yield, and total biomass at 1 m and at 3 m from tree trunk were all smaller than in the sole maize treatment, for both *A. acuminata* and *M. lutea* (Table 3.5). Maize grain yields were about 45% and 19% less than in sole maize at 1 m and 3 m from *A. acuminata* respectively. During the 2015 A and 2015 B seasons (with higher rainfall), grain yield, stover yield, and total biomass were smaller at 1 m from *A. acuminata* trunk but equal or increased at 3 m from the tree trunk when compared to sole maize. Maize grain yields during these seasons were about 23% smaller at 1 m but around 3 to 38% greater at 3 m from *A. acuminata* trunk relative to sole maize. A consistent yield reduction was observed at 1 m and 3 m from *M. lutea* trunk relative to sole maize. During the relatively drier season of 2014 B, maize grain yield was 44% and 21% lower at 1 m and 3 m from *M. lutea* trunk compared to sole maize. During the relatively wetter season of 2015 B, grain yield was 35% and 8% lower at 1 m and 3 m from *M. lutea* than in sole maize. The interaction between season and distance from the tree trunks were significant for *A. acuminata* but not for *M. lutea* (Table 3.5).

Table 3.5 Comparison of maize grain yield, stover yield and total biomass at different distances from two tree species – *A. acuminata* and *M. lutea* - and during four consecutive seasons in the experimental plots. Standard deviations are given after the sign '±'. *P* values are given for differences in seasons, distance from trees and the interaction of both. Means followed by the same letter in the same season do not differ significantly at α= 0.05.

Season	Maize grain yield ($t\ ha^{-1}$)			Maize Residues ($t\ ha^{-1}$)			Maize total biomass ($t\ ha^{-1}$)		
	1 m	**3 m**	**40 m**	**1 m**	**3 m**	**40 m**	**1 m**	**3 m**	**40 m**
				A. acuminata					
2014 A	1.86^{a}	2.93^{b}	4.26^{c}	3.19^{a}	4.94^{b}	4.57^{b}	5.05^{a}	7.87^{b}	8.83^{b}
	±0.2	±0.2	±1	±0.7	±0.9	±1.1	±0.8	±1.0	±1.8
2014 B	2.76^{a}	3.97^{b}	4.22^{b}	4.06^{a}	5.43^{b}	6.18^{b}	6.81^{a}	9.39^{b}	10.4^{b}
	±1.4	±1.5	±1.4	±0.6	±1.2	±1.2	±1.9	±2.0	±1.2
2015 A	3.9^{a}	7.2^{b}	4.5^{a}	3.68^{a}	6.76^{b}	5.17^{c}	7.57^{a}	13.96^{b}	9.67^{c}
	±0.7	±1.6	±1.9	±0.5	±1.6	±1.6	±1	±2.9	±1.4
2015 B	3.42^{a}	5.27^{b}	5.12^{b}	4.16^{a}	5.61^{b}	4.55^{a}	7.58^{a}	10.88^{b}	9.67^{b}
	±1.1	±0.7	±1.1	±1.4	±1	±1.2	±2.2	±1.6	±1.2
Season (p)		*<.0001*			*<.0001*			*<.0001*	
Distance (p)		*0.006*			*0.0008*			*0.0016*	
Season×distance (p)		*<.0001*			*0.0002*			*<.0001*	
				M. lutea					
2014 A	3.53^{a}	4.87^{b}	5.35^{b}	3.6^{a}	4.37^{b}	5.7^{c}	7.13^{a}	9.24^{b}	11.05^{c}
	±1.3	±2.0	±0.5	±0.8	±1.2	±0.9	±2.1	±3.2	±1.3
2014 B	1.32^{a}	1.95^{a}	2.88^{b}	2.48^{a}	3.53^{b}	2.95^{ab}	3.8^{a}	5.48^{b}	5.83^{b}
	±0.6	±0.6	±0.8	±1.4	±1.6	±0.8	±1.9	±2.2	±1.5
2015 A	4.19^{a}	5.6^{b}	6.49^{b}	3.44^{a}	4.44^{b}	4.53^{b}	7.63^{a}	10.04^{b}	11.02b
	±2.3	±2.8	±2	±2.4	±2.8	±1.8	±4.6	±5.6	±3.7
2015 B	2.88^{a}	4.32^{b}	4.38^{b}	3.37^{a}	5.37^{b}	5.18^{b}	6.25^{a}	9.68^{b}	9.56^{b}
	±1	±1.6	±1.3	±1	±1.9	±1.8	±2	±3.4	±3.1
Season (p)		*<.0001*			*<.0001*			*<.0001*	
Distance (p)		*<.0001*			*<.0001*			*<.0001*	
Season×distance (p)		*0.856*			*0.2734*			*0.8426*	

In the APSIM model simulations, the scenario presented (Figure 3.4) reflects the under *A. acuminata* tree situation with 50 kg ha^{-1} of extra N input, a 10% reduction in radiation and 2 degree lower maximum temperatures that occurred in 2015 A season. This scenario of under tree situation shows a higher maize yield for about 60% of the seasons (from 2006 to 2016) when compared to the sole maize (Fig. 4). For seasons like 2014 A, 2014 B and 2015 B with around 10 kg N ha^{-1} inputs from tree litter, a yield reduction of about 300 to 400 kg DM ha^{-1} can be expected (Figure S1). Under higher N fertilization scenarios, negative effects of radiation and temperature were not compensated by additional N from litter (Figure S1).

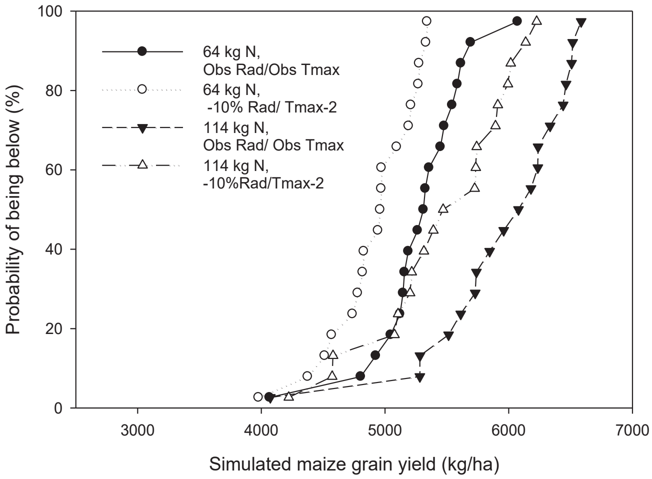

Figure 3.4 Cumulative distribution function (CDF) of maize grain yield (kg DM ha^{-1}) under observed (Obs) radiation (Rad) and maximum temperatures (Tmax) compared with scenarios with reduced solar radiation and/or maximum temperature with N fertilization set to 64 kg ha^{-1} and 114 kg ha^{-1}. Simulations included the years 2006 to 2016 with two season per year (3 seasons showed no yields due to drought).

3.3.5 Light and air temperature

PAR under *A. acuminata* was reduced by 67 % at 1 m distance from the tree trunk (AlM-1m) and by 17 % at 3 m distance from the tree trunk (AlM-3m) while reduced PAR under *M. lutea* was reduced by 47 % at 1 m distance from the tree trunk and by 14 % at 3 m distance from the tree trunk. The diurnal reduction of total solar radiation at 1 m from the tree trunk was 44% under *A. acuminata* and 25% under *M. lutea* (Figure 3.5a).

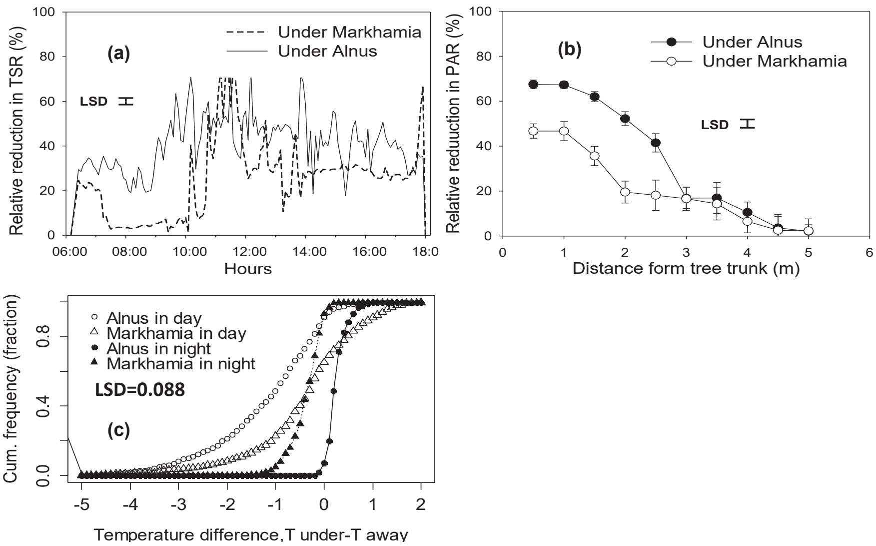

Figure 3.5 Relative reduction in total solar radiation (TSR) under *A. acuminata* and *M. lutea* (a). For each tree species, data are averages of 3 days measurements on identical weather stations simultaneously logging every 5 minutes under and away from a tree. Relative reduction in PAR under *A. acuminata* and *M. lutea* (b) with distance from tree trunk. Vertical bars show standard error of the mean. Cumulative relative frequencies of temperature differences under and away from canopies of *A. acuminata* and *M. lutea* trees (c).

A. acuminata reduced temperature during the day, with half of the observations showing a reduction of more than 1ºC due to shading. During the night, the temperature was higher under the *A. acuminata* canopy, with half of the nights having a temperature of more than 0.2 ºC higher than in the sole maize plots due to the insulation or 'blanket' effect. The *M. lutea* canopy reduced temperature during the day, with half of the observations showing a reduction of more than 0.28 ºC and temperatures were reduced by more than 0.3ºC on half of the nights.

3.3.6 Maize phenology

It took around 38 degree days for a maize leaf to appear and there was no significant difference between sole maize and maize under *A. acuminata* and *M. lutea* trees (Figure 3.6). In contrast to the leaf number and appearance rates, maize height was reduced at 1 m and 3 m from the tree trunks starting from two months after sowing until physiological maturity.

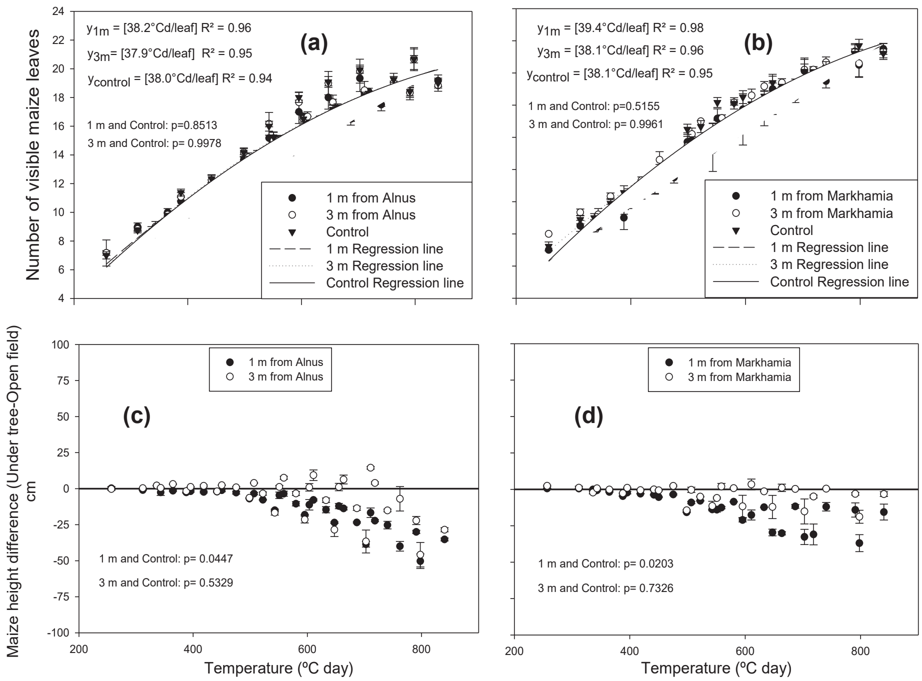

Figure 3.6 Leaf appearance rates for maize plants in the sole maize compared to plants under *A. acuminata* (a) and *M. lutea* (b), and maize height difference under *A. acuminata* relative to sole maize (c) and under *M. lutea* relative to sole maize (d) as function of cumulative degree days in the study site. Displayed values are means of the four seasons (2014 A, 2014 B, 2015 A and 2015 B). Bars represent standard errors.

3.4 Discussion

3.4.1 Effects of trees on maize yield and sensitivity to varied microclimate and N inputs

Maize yields were smaller at 1 m and 3 m from *M. lutea* trunk than in sole maize plots in all seasons, whilst strong season-dependent effects were found for *A. acuminata*. For both tree species, maize yielded least close to the tree trunks (at 1 m) compared with at the canopy edges (3 m). Others also report that the competitive effect of trees decreases with distance from the trunk (Muchiri et al., 2002). Reduced maize yields with *A. acuminata* during seasons with relatively lower rainfall concurs with Muthuri et al. (2005) who reported a similar negative effect. Furthermore, the smaller maize and stover yields under *M. lutea* relative to sole maize demonstrates the strong competitiveness of this tree species (Okorio et al., 1994).

Whereas crops consistently underperformed in *M. lutea* system, the competitive effect of *A. acuminata* for light was to some extent compensated by extra N input in the wetter seasons (2015 A and 2015 B) at 3 m but not at 1 m from the tree trunk. For instance, in 2015 A season, the maize crop under *A. acuminata* received average rainfall (664 mm) and higher radiation than during the other seasons. The average rainfall and higher radiation, in combination with greater nitrogen input from tree litter received during the previous season, may have been responsible for the larger maize yield at 3 m from *A. acuminata* trunks than in both sole maize and maize at 1 m away from the trunk. Besides, *A. acuminata* as a nitrogen fixing tree species could have had an added fertility advantage over *M. lutea* though only few nodules were found during root excavation (work not reported in this study).

Previous studies have found yield benefits close to young (2 to 3 years) *A. acuminata* trees of 2 to 3 m heights (Muthuri et al., 2005; Okorio et al., 1994; Peden et al., 1993) and attributed it to the tree's ability to fix atmospheric nitrogen but authors expressed the needs to further study how tree-crop interactions change as the trees mature. However, Okorio (2000) found that maize yield reduction by *A. acuminata* could extend to 4.5 m from the tree trunk in the 3rd year of tree establishment.

Our results suggest that as trees mature, crop yields decline under canopy, but the decline is moderated under *A. acuminata* as compared to *M. lutea*, following seasons receiving a higher litter input. Other researchers in Rwanda (Bucagu, 2013; Mugunga, 2016) argued that yield decline in agroforestry could be compensated for by the value of tree products. While yield benefits are a good starting point for an economic evaluation (Cannell et al., 1996), agroforestry might give greater economic benefits than sole-crop or sole-tree systems (Price, 1995) especially in highly populated areas where the demand for forest products is not met (Ndayambaje and Mohren, 2011) and alternative food sources are available on local markets.

Simulated maize grain yield for the scenario of tree adding around 50 kg N ha^{-1} to the recommended fertilizer rates observed in one out of the four seasons under observation, suggested that *A. acuminata* could compensate yield loss caused by reduction in radiation and temperature in about 60% of the seasons. However, for the other three out of four seasons, the N input from litter ranged from 10.6 to 17.9 kg ha^{-1} and simulated yields were reduced. In the simulations without extra N input from tree litter, a yield reduction of about 300-400 kg DM ha^{-1} can be expected for all seasons due to shade. The scenario of a system with higher fertilization rates (e.g. 150 kg N ha^{-1} where trees could contribute to extra 50 kg N ha^{-1}) showed that shade would reduce yields more than in low fertilization scenario, in the range of 500 kg to 700 kg DM ha^{-1} in all seasons. Thus as trees mature, it is vital to control shade while taking advantage of tree litter for soil fertility improvement (Schroth et al., 2001). Nevertheless, the APSIM-maize module simulated observed maize yield under trees canopy but did not take tree productivity into account. Further, the APSIM-maize model uses the air temperature –sensors protected from direct sunlight- and not crop temperature to simulate crop yields while the latter may be more appropriate (Luedeling et al., 2016), potentially over-estimating impacts of trees on crop yields.

3.4.2 *A. acuminata* recycles more nutrients than *M. lutea*

The tree species studied here exhibited different litter production and hence different nutrient-cycling rates. The measured *A. acuminata* leaf litter and its N and P content were comparable to the reported figures on *A. nepalensis* in agroforestry systems of India (Sharma et al., 1996). On the other hand, *M. lutea* litter fall was less than that reported by Muzoora et al. (2011) in Uganda probably due to the larger tree canopies left by the Ugandan livestock farmers. Their reported N and P content in litter were comparable to the values measured in this study. As expected, *A. acuminata* – a semi-deciduous species – contributed more litter and nutrients than *M. lutea* – an evergreen species – in all seasons. Nutrient turnover in semi-deciduous species is much higher than in evergreen species that retain a full canopy throughout the year (Eamus, 1999).

A significant effect of distance from tree trunk was observed for N uptake by crop grown in combination with *A. acuminata*, with relatively more uptake at 3 m than at 1 m and 40 m from tree trunk. These results suggest that though *A. acuminata* increased the available N through litter fall, the shading effect reduced uptake at 1 m from the tree trunk. P uptake was small at 1 m and at 3 m from the trunk of the tree in the drier 2014 B season probably due to the combination of the effects of soil-drying-induced P-deficiency (Radersma et al., 2005) and the negative effect of shade on biomass production. These findings could be supported by the fact that, in the following 2015 A season with enough rainfall, P uptake at 3 m from the tree trunk increased but not at 1 m from the tree trunk. For *M. lutea*, there was no significant distance effect from the tree trunk for N and P uptake by crop. The dry spell period during the season 2014 B induced a higher litter fall especially for *A. acuminata*, resulting in a significantly larger input of nutrients during that season: around 50 kg of N ha^{-1} and 5.6 kg of P ha^{-1}. These N and P inputs from litter represent a respective increase of 78 % and 28 % as compared to the applied inputs through mineral fertilizers. Thus in systems with few fertilizer inputs, the beneficial effects of *A. acuminata* on soil fertility can compensate for the negative effect of tree shade if trees are intensively pruned at the beginning of the season and the leaves used as organic amendment.

3.4.3 *A. acuminata* and *M.* lutea did not influence water availability of maize in the topsoil

Soil water content in topsoil did not differ between treatments with sole maize and maize associated with *A. acuminata* or with *M. lutea*. There was an offset in the initial soil water between these treatments involving maize and the sole *A. acuminata* or sole *M. lutea*. This difference was maintained throughout the four seasons under observation with no difference in the patterns of water use among treatments. These differences may be due to site differences in soil depth. In addition, the soil water content was always above the permanent wilting point (from pedo-transfer functions at 12.6 volume % soil water) in both topsoil and subsoil. Thus, our study suggests that the presence of the trees did not influence water availability for maize in this sub-humid high rainfall environment. This neutral effect was assisted by seasonal tree root disturbance in the topsoil caused by the deep bed-furrow tillage (Verdoodt and Ranst, 2003), thus giving chances for maize roots to establish in the surface soil horizons with less active tree roots. Other workers (Rao et al., 1997; Siriri et al., 2013), found little or no competition for soil water between trees and the associated crops in wet environments.

3.4.5 Both *A. acuminata* and *M. lutea* reduce incident light and day air temperature reducing maize height and yield

Results from this study show that *A. acuminata* reduced total solar radiation and PAR more strongly than *M. lutea*. PAR was only measured near mid-day on a clear day and was more strongly reduced by trees than diurnal total solar radiation which was measured on dominantly hazy days. Both *A. acuminata* and *M. lutea* similarly reduced day air temperature. *A. acuminata* slightly increased night air temperature through blanket effect while *M. lutea* reduced it; suggesting that the thinner *M. lutea* canopy caused no blanket effect. Tree canopy reduces light intensity (Bayala et al., 2002) and moderates temperature under trees (García-Barrios and Ong, 2004; Rao et al., 1997).

The microclimate of both *A. acuminata* and *M. lutea* did not significantly affect the leaf appearance rate, number of leaves and leaf area (Figure S4 and Figure S5) but did reduce plant height and yield. The observed reduction of maize yield (Ong et al., 2000) calls for intensive pruning to reduce competition for light when crop production is the primary objective of the farmer, although less intensive pruning may be acceptable in agroforestry systems where tree production is a primary objective (Bai et al., 2016). It is essential for farmers to understand that there is a need to manage trees to maintain the balance between tree and annual crop products (Ong et al., 2015; Wilson et al., 1998).

3.5 Conclusions

This study investigated the effects of *A. acuminata* and *M. lutea* trees - the most abundant trees in farmers' fields in the highlands of Northern Rwanda - on maize microclimate and resources available to maize. Both tree species reduced total incident solar radiation and PAR, as well as day temperature with *A. acuminata* having a stronger shading effect than *M. lutea*. *A. acuminata* contributed more nutrients than *M. lutea* through litter fall. Neither tree species affected water availability for maize in the topsoil.

The presence of trees significantly reduced the growth and yield of the associated maize with the effect varying depending on tree species and distance from tree trunk. *M. lutea* reduced maize productivity in all seasons whilst the effect of *A. acuminata* was season dependent. A positive interaction between *A. acuminata* and maize was only apparent at 3 m from tree trunk in one of the four seasons and following higher litter fall, suggesting that the negative effect of shade was occasionally offset by extra N input. Simulations indicate that an increase in yield can only be expected in 30% of the years, and only under low to moderate N fertilization scenarios. In all other situations, a net negative effect of trees on yield can be expected.

As trees mature, their effects on solar radiation, air temperature, water and nutrients become important, influencing the balance of competitive and facilitative effects on crops. While these trees provide a number of essential products (e.g., fuelwood, timber and stakes) in the rural sub-humid environment, it is clear that without proper pruning and high extra N inputs from leaf litter, a yield reduction can always be expected due to shade. The farmers' priorities will ultimately determine the balance of crop and tree products on farm.

Chapter 4

Do open pollinated maize varieties perform better than hybrids in agroforestry systems?

This chapter is submitted as:

Ndoli, A., Baudron F., Sida T.S., Schut A.G.T., van Heerwaarden J., & Giller, K. E. (2017). Do open pollinated maize varieties perform better than hybrids in agroforestry systems? *Experimental Agriculture*

Abstract

A large body of evidence demonstrates the agronomic superiority of maize hybrids over open pollinated varieties (OPVs) in intensive agriculture. However, comparisons of the performance of hybrids and OPVs in agroforestry systems of resource poor farmers are scarce. In this study, performance of four maize hybrids and four OPVs was compared in sole crop and under mature *Grevillea robusta*, *Senna spectabilis* or *Acacia tortilis* trees. A total of six on-farm experiments were conducted during four consecutive seasons in Bugesera, Rwanda and three on farm experiments during two seasons in Meki, Ethiopia. In Bugusera, grain yields of hybrids (2 t ha^{-1}) was significantly better than OPVs (1.5 t ha^{-1}). Further, the presence of trees significantly reduced maize grain yield and total biomass in both hybrids and OPVs in the same manner. However, trees reduced harvest index significantly more in OPVs (from 0.35 to 0.19) than in hybrids (from 0.32 to 0.23), suggesting that competition had a greater impact on grain yield of OPVs than on biomass production. In Bugesera, the estimated reduction in grain yield was 0.9 and 1.1 t ha^{-1} in hybrids and OPVs, respectively, while estimated reduction in biomass was 1.5 and 1.7 t ha^{-1}. In the experiments in Meki, the grain yield of OPVs (2.08 t ha^{-1}) and hybrids (2.04 t ha^{-1}) did not significantly differ and the presence of trees reduced their grain yields in the same manner by 0.4 t ha^{-1}. Trees reduced leaf area index (LAI) more in OPVs than in hybrids in Bugesera but not in the Meki experiment. The presence of trees also reduced plant height more in OPVs than in hybrids in Bugesera but had no significant effect in Meki. Our results showed that hybrids yielded more than OPVs under *G. robusta* and *S. spectabilis* in Bugesera but performed equally well under *A. tortilis* in Meki. We conclude that agroforestry farmers could benefit from growing hybrids in the equatorial savannahs of Rwanda, but not in the equatorial savannahs of Ethiopia.

4.1. Introduction

Maize is the most important cereal food crop in sub-Saharan Africa and its demand is predicted to double by 2050 (Anley et al. 2013). In Rwanda, maize has larger production volumes than any other grain crops, including pulses (NISR 2014a). In rural Ethiopia, maize is the most important staple food in terms of calorie intake (Abate et al. 2015). Maize is genetically diverse, with germplasm adapted to a wide range of growing conditions (Anley et al. 2013). However, while maize breeding has had great impact in sub-Saharan Africa (Smale and Jayne 2003), little attention has been paid to developing germplasm specifically suited to complex environments such as agroforestry systems (Tiwari et al. 2009). Almost all of the maize varieties have been bred and tested in open fields and may not be well adapted to agroforestry conditions (Desclaux et al. 2016).

Due to the effect of heterosis (i.e., hybrid vigour), maize hybrids are generally expected to yield more and to provide greater quality – e.g. uniform grain colour and size – than OPVs in open field conditions (van Heerwaarden et al. 2009). In the United States of America, 50% of the yield gain since the 1930s is attributed to the introduction of hybrid maize and improved genetics (Duvick 1999). In sub-Saharan Africa, improvement in maize yield as a result of adoption of hybrid maize was also reported (Byerlee and Eicher 1997; Smale and Mason 2014). However, seed of maize hybrids is expensive for resource-poor farmers and cannot be recycled without severe yield penalty (Lyimo et al. 2014; Macharia et al. 2010).

In developing countries where agroforestry is a common practice, farmers claim that local landraces are better adapted to shade than genotypes bred on experimental stations (Tiwari et al. 2012). Some smallholder farmers believe that hybrid maize can perform well, but only under high input management practices which poor farmers seldom achieve (Macharia et al. 2010). There is a need to advise farmers whether hybrids have an advantage over OPVs in agroforestry systems, characterized by reduced light intensity due to shade and competition for water and nutrients.

The objective of this study is to fill this knowledge gap and compare the performance of OPVs and hybrids in two agroforestry systems in East Africa. We hypothesize that OPVs outperform hybrids under trees. We assessed the effects of trees (*Grevillea robusta* and *Senna spectabilis* in Rwanda and *Acacia tortilis* in Ethiopia) on the performance of commonly-used maize hybrids and OPVs.

4.2. Material and methods

Experiments were conducted in two agroecological zones to evaluate the effect of trees on the performance of maize varieties (hybrids vs. open pollinated varieties): Bugesera, Rwanda, and Meki, Ethiopia. Both zones are classified as semi-arid in the national systems and are classified as equatorial savannah with dry winter in the Köppen-Geiger system (Kottek et al. 2006).

4.2.1 Experimental sites in Bugesera, Rwanda

In Rwanda, six farms were selected to host trials in Bugesera, located at a latitude of 2° 21’ S, a longitude of 30° 15'E, and an elevation of 1,397 m above sea level (a.s.l). The climate is characterized by a bimodal rainfall pattern with a major peak in April and a secondary peak in November. The ‘long rains’ (also known as ‘season B’) usually start around mid-February and lasts up to mid-July and the ‘short rains’ (also known as ‘season A’) start in September and last until January. The rainfall varies between 850 and 1,000 mm per year with an average annual temperature of about 21 °C (Verdoot and van Ranst, 2003). Soils in the Bugesera experiments are humic Ferralsols at lower elevations and haplic Ferralsols at higher elevations with depths of about 100-200 cm. The selected plots were cropped with maize or sorghum in rotation with bush beans in the previous seasons. The experiments in Bugesera were conducted in the 2014 B, 2015 A, 2015 B and 2016 A seasons.

4.2.2 Experimental sites in Meki, Ethiopia

In Ethiopia, three farms were selected to host trials in the lowlands of the Central Rift Valley in Meki, located at a latitude of 8° 11' N, a longitude of 38° 51' E, and an elevation of 1,500 m a.s.l. The climate is characterized by a unimodal rainfall pattern peaking around July-August. The rainy season or “*Kiremt*” normally runs from June to September with the annual total rainfall ranging from 281 to 1,131 mm with a long-term average of 729 mm per year (Getachew and Tesfaye 2015). The average annual temperature is 19.3ºC. Soils in Meki are deep Andosols with high organic matter and good water holding capacity. The selected plots for the experiments were cropped with maize in the preceding seasons. The experiments in Meki were conducted in 2014 and 2015.

4.2.3 Experimental layout

Three tree species were used in the experiments: two in Bugesera and one in Meki. For each tree species, three farms were selected, each including two plots with almost identical trees in their centre and one open plot (without tree). This resulted in six on-farm experiments (with two tree species) in Bugesera and three experiments (with one tree species) in Meki. The size of plots with trees was 10 x 10 m while the size of open plots was 10 x 20 m. The plots with trees were divided into four subplots while the open plots were divided into eight subplots (Figure 4.1).

Two main factors were studied (i) presence or absence of tree and (ii) vigour (hybrids vs. OPVs as proxy). In Bugesera, Rwanda, the selected tree species were *G. robusta* and *S. spectabilis* since they are dominant in the landscape. The four selected hybrid cultivars were among the most popular cultivars in the area, and included PAN4M21, PAN67, SC403 and SC513 and the four selected OPVs were ISARM081, ISARM101, Pool32 and ZM607. In Meki, Ethiopia, the selected tree species was *A. tortilis* – the most frequent tree on farms in the area - and the four maize hybrids included MH138Q, MH140, BH540 and MH130 while OPVs were Melkassa-6Q, Gibe-2, Melkassa-4 and Melkassa-2. For each tree species, the eight varieties selected for the site (four hybrids and four OPVs) were randomly assigned each season to one of the eight subplots under one of the two trees and to one of the eight subplots of the open plot (Figure 4.1).

In each season, fertilization rates followed general recommendations for both areas, that is 100 kg di-ammonium phosphate per hectare (18 kg N ha^{-1} and 20 kg P ha^{-1}) applied at planting, top-dressed with 100 kg urea per hectare (46 kg N ha^{-1}) applied as top-dressing six weeks after plant emergence. Maize was planted at a spacing of 0.4 m within rows and 0.8 m between rows with two plants per hole in Bugesera. In Meki, maize was planted at a spacing of 0.3 m within rows and 0.7 m between rows with 1 plant per hole left after thinning.

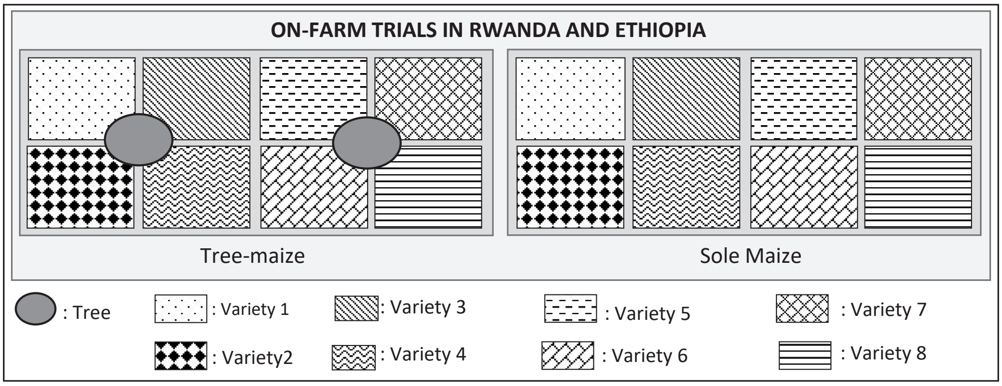

Figure 4.1 Layout of the experiments in Bugesera, Rwanda and in Meki, Ethiopia.

4.2.4 Measurements

Tree characteristics measured included tree height, diameter at breast height (DBH), diameter at stump height (DSH), canopy radius and tree age. In both Bugesera and Meki, daily rainfall and air temperature were measured using automatic weather stations (Vantage Pro2™, Davis Instruments Corp, USA) positioned at a maximum distance of 1 km of all plots. Weekly phenological measurements were taken from 20 days after sowing (DAS) to the end of the vegetative growing period, in all plots of the experiments in Rwanda. In Meki, phenological measurements were taken twice a month from 20 DAS but only in the 2014 season. The phenological parameters measured included the number of fully expanded leaves, the length and the width of the last fully expanded leaf, and the plant height. Leaf area index (LAI) values were calculated using the following formula:

$$LAI = (0.75 \times L \times B) \times NL \times D$$

where L represents the length from the leaf base to the tip of a leaf, B represents the maximum width of the leaf, NL represents the total number of leaves per plant and D represents the plant density (plants/m^2). The value of 0.75 (Maddonni and Otegui 1996) reflects the shape of the leaf in-between values for a triangle and a square. Stover and grain yields were measured and dry weights of maize grain and stover were determined gravimetrically. Subsamples were oven-dried at 60ºC for one week.

4.2.5 Statistical analysis

Means of tree characteristics were compared through an Analysis of Variance (ANOVA) using Fisher's *F*-test. Maize grain dry matter yield, total dry matter biomass, harvest index, LAI and plant height data were analysed with a linear mixed-effect model (LMM) with vigour – OPVs or hybrids - and tree presence/absence as fixed effects and farm and plot (with each tree and sole maize being separate plots) as random effects. A separate random season effect was modelled for each farm, with successive seasons coded as an ordered factor. For analyses within a single country, season was also included as a fixed effect while this term was replaced by a country term in analyses across the two countries. Adding a random genotype (i.e. different cultivars) term did not result in a better model fit (based on Akaike's Information criterion): this factor was thus not included. Differences in genotypes were assessed using a similar model but with vigour – OPVs and hybrids - replaced by genotypes.

The significance of fixed effects was tested using a type-III ANOVA with Satterthwaite approximation for the denominator degrees of freedom. Predictmeans functions (Welham et al. 2004) from the lme4 library were used to test tree presence/absence, vigour and interaction effects on maize LAI, height and yields in each country separately. All analyses were carried out using R software (R Development Core Team 2014).

4.3 Results

4.3.1 Local climate and tree characteristics

In Bugesera, rainfall was higher in the 2015 A season (350 mm) followed by 2014 B (325 mm) and 2015 B (250 mm) and lastly 2016 A (211 mm) (Figure 4.2a). Seasonal rainfall was very variable in Meki during the seasons under observation, with 536 mm rainfall received in the season of 2014, more than double the amount received in 2015 (230 mm) (Figure 4.2b). In Bugesera, air temperature was higher than in Meki with a maximum and a minimum of 26.7 °C and 19.6 °C respectively and an overall mean of 22.3 °C in Bugesera compared with a maximum temperature of 21.5 °C, a minimum temperature of 16.5 °C and an overall mean of 19.5 °C in Meki.

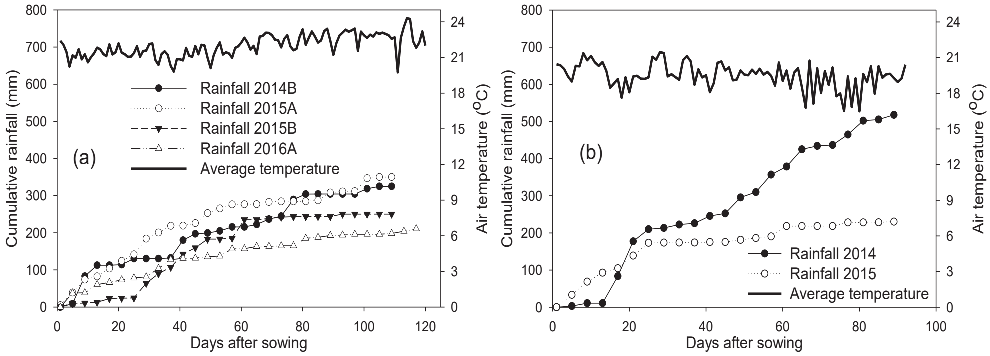

Figure 4.2 Cumulated rainfall and average daily air temperature during growing seasons under observation at Bugesera, Rwanda (a) and Meki, Ethiopia (b).

G. robusta and *A. tortilis* trees had about the same heights but were taller than *S. spectabilis* trees (Table 4.1). The latter had the largest DSH but the smallest DBH for individual shoots. *S. spectabilis* was the only tree species in the study to have many stems. *S. spectabilis* and *A. tortilis* had similar canopy radius, which was larger than the canopy radius of *G. robusta*. *S. spectabilis* trees had about the same age as *G. robusta* based on farmer recall.

Table 4.1 Characteristics of *G. robusta, S. spectabilis* and *A. tortilus* trees used in the experiment at the on-set of the trial (beginning of 2014). Standard deviations are given after the signs '±'. Means followed by the same letter in the same row do not differ significantly at α= 0.05.

Measurement	***G. robusta***	***S. spectabilis***	***A. tortilis***
Height (m)	$8.3^{a} \pm 1.1$	$5.9^{b} \pm 1.1$	$8.3^{a} \pm 1.2$
Diameter at breast height (DBH, cm)	$24.3^{b} \pm 4$	$10.8^{c} \pm 3$	$27.2^{a} \pm 2.3$
Diameter at stump height (DSH, cm)	$37.8^{b} \pm 11$	$55.7^{a} \pm 11$	-
Canopy radius (m)	$2.30^{b} \pm 0.2$	$4.25^{a} \pm 0.5$	$4.31^{a} \pm 0.5$
Tree age by farmer recall (years)	$16.3^{a} \pm 1$	$18.5^{a} \pm 5.2$	-
Number of shoots	$1^{a} \pm 0$	$5.1^{b} \pm 1.7$	$1^{a} \pm 0$

-: are characteristics not measured

4.3.2 Grain yield, above-ground biomass and harvest index

The observed grain yield was 2.06 t ha^{-1} in Meki and 1.76 t ha^{-1} in Bugesera, mean total biomass was 9.1 t ha^{-1} in Meki and 5.5 t ha^{-1} in Bugesera and mean harvest index was 0.22 in Meki and 0.27 in Bugesera (Table 4.2). These differences were not significant. In Bugesera, grain yields and total biomass differed significantly between hybrids and OPVs but harvest index was similar (Table 4.4, and Table 4.5). In Meki, grain yield, total biomass and harvest index of hybrids did not differ from OPVs and there was no season effect (Table 4.4, and Table 4.5). In Bugesera, drought in seasons 2015 B and 2016 A affected both grain yield and total biomass but did not affect the harvest index. The presence of trees significantly reduced maize grain yield, total biomass and harvest index in Bugesera but only affected grain yield in Meki (Table 4.2, Table 4.4 and Table 4.5).

There was no evidence of significant differences between genotypes within vigour class, but in Bugesera, larger grain yields in both sole crop and under trees were observed for the hybrid genotypes SC403 (2.7 t/ha in sole crop vs 1.7 t/ha under tree) and SC513 (2.4 t/ha in sole crop vs 1.8 t/ha under tree), while the smallest grain yield was observed for the OPV genotype ISARM081 (2 t/ha in sole crop vs 0.9 t/ha under tree) (Table 4.3). The genotypes SC403 and SC513 had the highest observed total biomass under trees while ISARM081 had the least.

The presence of trees affected grain yield and total biomass of hybrids and OPVs in the same manner in both Bugesera and Meki. However, trees strongly decreased the harvest index of OPVs more than hybrids in Bugesera. In the latter site, estimated reduction in grain yield was 0.9 and 1.1 t ha^{-1} in hybrids and OPVs, respectively, while reduction in biomass was 1.5 and 1.7 t ha^{-1}. In Meki grain yield reduction was 0.5 t ha^{-1} for both vigour classes and the corresponding reduction in biomass was 1.1 and 0.6 for hybrids and OPVs, respectively. Across the two sites there was no significant interaction between the presence of trees and vigour class although in Bugesera, reduction in harvest index was stronger in OPVs than in hybrids (Table 4.4, and Table 4.5). Harvest index decreased from 0.32 to 0.23 in hybrids and from 0.35 to 0.19 in OPVs for example. Interaction of season and presence/absence of trees was only observed in Bugesera and was significant for grain yield (P=0.05) and total biomass (P=0.055).

Table 4.2 Comparison of observed maize grain yield, total biomass and harvest index of hybrids and OPVs in sole crop and under *G. robusta* and *S. spectabilis* trees in Bugesera, Rwanda and under *A. tortilis* trees in Meki, Ethiopia. Standard deviations are given after the sign '±'.

			Grain yield (t/ha)		Total Biomass (t/ha)		Harvest Index	
Tree sp.	Season	Treatment	Hybrid	Opv	Hybrid	Opv	Hybrid	Opv
G. robusta	2014 B	Sole	3.08 ±1.5	2.94 ±1.5	8.51 ±3.1	7.81 ±3.7	0.34 ±0.1	0.39 ±0.1
		Under	1.8 ±2	0.93 ±1	6.51 ±3.9	5.64 ±1.8	0.2 ±0.2	0.16 ±0.2
	2015 A	Sole	4.41 ±1	4.22 ±1.3	10.73 ±1.3	9.32 ±2.2	0.41 ±0.1	0.45 ±0.1
		Under	3.24 ±1.6	2.23 ±1.1	9.87 ±4.1	6.67 ±2.5	0.33 ±0.1	0.32 ±0.1
	2015 B	Sole	2.2 ±2.1	1.19 ±1.1	4.4 ±3	2.68 ±1.9	0.38 ±0.2	0.37 ±0.2
		Under	0.86 ±0.7	0.36 ±0.3	2.67 ±1.3	1.71 ±0.8	0.29 ±0.1	0.2 ±0.1
	2016 A	Sole	1.08 ±0.8	0.84 ±0.6	4.27 ±1.1	3.48 ±1.7	0.25 ±0.2	0.23 ±0.1
		Under	0.65 ±0.5	0.5 ±0.3	3.4 ±1.1	2.98 ±1	0.19 ±0.1	0.16 ±0.1
S. spectabilis	2014 B	Sole	2.58 ±1.7	2.16 ±1.6	8.13 ±3.7	6.4 ±2.1	0.32 ±0.2	0.3 ±0.2
		Under	1.75 ±0.9	1.35 ±1.5	5.93 ±2.2	5.52 ±3.1	0.29 ±0.2	0.18 ±0.2
	2015 A	Sole	3.44 ±1.5	2.79 ±1.2	9.82 ±2.5	8.37 ±2.5	0.34 ±0.1	0.33 ±0.1
		Under	2.93 ±1.3	1.44 ±1.1	7.24 ±1.7	5.01 ±2.3	0.4 ±0.1	0.25 ±0.2
	2015 B	Sole	0.52 ±0.7	0.75 ±0.6	2.21 ±1.5	2.39 ±1.5	0.19 ±0.2	0.34 ±0.2
		Under	0.19 ±0.4	0.08 ±0.1	2.18 ±1.6	1.55 ±0.8	0.05 ±0.1	0.05 ±0.1
	2016 A	Sole	1.91 ±0.8	1.73 ±0.7	6.29 ±2.4	5.07 ±1.1	0.31 ±0.1	0.34 ±0.1
		Under	0.8 ±1	0.66 ±0.6	4.36 ±1.5	2.93 ±1.6	0.16 ±0.2	0.18 ±0.1
A. tortilis	2014	Sole	2.24 ±1	2.54 ±1	9.12 ±4.1	10.91 ±4.2	0.25 ±0.1	0.24 ±0
		Under	1.95 ±0.6	1.82 ±0.7	9.02 ±3.1	8.15 ±3.1	0.22 ±0	0.23 ±0
	2015	Sole	2.27 ±1	2.05 ±1	9.26 ±1.3	8.46 ±2.2	0.24 ±0.1	0.24 ±0.1
		Under	1.66 ±1.2	1.85 ±1.1	7.22 ±4.6	9.94 ±2.9	0.17 ±0.1	0.19 ±0.1

Table 4.3 Comparison of mean grain yields, total biomass and harvest index (HI) of genotypes in sole crop and under trees in Bugesera, Rwanda and Meki, Ethiopia. Standard deviations are given after the sign '±'.

		Grain yield (t/ha)		Total Biomass (t/ha)		HI	
Genotypes	Vigour	Sole	Under	Sole	Under	Sole	Under
Bugesera, Rwanda							
PAN 4M21	Hybrid	2.5 ± 1.8	1.4 ± 1.5	7.3 ± 4.3	4.8 ± 3.3	0.3 ± 0.2	0.24 ± 0.2
PAN 67	Hybrid	2 ± 1.4	1.2 ± 1.4	6.2 ± 3.4	5.1 ± 3.6	0.28 ± 0.2	0.2 ± 0.2
SC403	Hybrid	2.7 ± 1.9	1.7 ± 1.4	7 ± 3.2	5.4 ± 3.1	0.35 ± 0.2	0.27 ± 0.1
SC513	Hybrid	2.4 ± 1.8	1.8 ± 1.8	6.7 ± 3.8	5.7 ± 3.7	0.33 ± 0.1	0.24 ± 0.2
ISARM081	OPV	2 ± 1.4	0.9 ± 1	5.2 ± 2.5	3.9 ± 2.5	0.37 ± 0.1	0.19 ± 0.2
ISARM101	OPV	2.3 ± 1.8	0.9 ± 1	6.8 ± 4	4.3 ± 2.4	0.3 ± 0.2	0.18 ± 0.1
Pool32	OPV	2.2 ± 1.3	1.1 ± 1.3	5.4 ± 3.3	4.2 ± 3.1	0.42 ± 0.1	0.22 ± 0.2
ZM607	OPV	2.1 ± 1.8	1 ± 1.2	5.7 ± 3.4	3.9 ± 2.7	0.32 ± 0.2	0.18 ± 0.2
Meki, Ethiopia							
BH540	Hybrid	2.1 ± 0.6	2.2 ± 0.7	8.6 ± 2.5	10.4 ± 3.1	0.25 ± 0.1	0.22 ± 0.1
MH130	Hybrid	1.9 ± 1.1	1.3 ± 0.9	8.6 ± 4.3	5.4 ± 3.7	0.22 ± 0.1	0.19 ± 0.1
MH138Q	Hybrid	2.6 ± 1	2.1 ± 0.7	9.7 ± 2.8	9.6 ± 1.9	0.27 ± 0.1	0.21 ± 0.1
MH140	Hybrid	2.4 ± 1.2	1.7 ± 1	9.7 ± 4	7.8 ± 4.8	0.25 ± 0.1	0.18 ± 0.1
Gibe-2	OPV	2.1 ± 1	2.1 ± 1.2	10.3 ± 4.1	8.2 ± 3.2	0.2 ± 0.1	0.26 ± 0.1
Melkasa-2	OPV	2.6 ± 1.2	1.9 ± 0.9	10.6 ± 4.9	10.6 ± 4.5	0.26 ± 0.1	0.2 ± 0.1
Melkasa-4	OPV	2.6 ± 1.1	1.6 ± 0.6	11.2 ± 3.1	8.4 ± 1.9	0.22 ± 0.1	0.19 ± 0.1
Melkasa-6Q	OPV	2 ± 0.9	1.7 ± 0.9	7.7 ± 2.4	8.3 ± 2.5	0.26 ± 0.1	0.2 ± 0.1

Table 4.4 Comparison of the model predicted means for maize grain yield, total biomass and harvest index of hybrids and OPVs in sole crop and under *G. robusta* and *S. spectabilis* trees in Rwanda, under *A. tortilis* trees in Ethiopia and the overall predicted means for both countries.

		Grain yield (t ha^{-1})		Total Biomass (t ha^{-1})		Hi		LAI		Plant height (cm)	
Country	treatment	hybrid	OPV	hybrid	OPV	hybrid	OPV	hybrid	OPV	hybrid	OPV
Rwanda	Under	1.49	0.98	5.24	4.02	0.23	0.19	2.02	1.60	75	64.9
	Sole	2.38	2.10	6.77	5.72	0.32	0.35	2.23	2.06	89.2	89.3
	LSD vigour	*0.526*		0.569		0.096		0.044		1.99	
	LSD tree presence/ absence	0.237		0.547		0.033		0.267		12.85	
Ethiopia	Under	1.89	1.92	8.72	9.64	0.20	0.21	1.21	1.08	120.7	115.7
	Sole	2.34	2.38	9.79	10.29	0.24	0.23	1.53	1.35	134.1	126.9
	LSD vigour	0.538		1.712		0.058		0.051		2.50	
	LSD tree presence/absence	*0.538*		1.712		0.041		0.276		14.37	
Overall	Under	*1.58*	1.31	6.41	6.07	0.23	0.21	1.56	1.28	95.4	87.9
	Sole	2.25	2.16	7.60	7.46	0.29	0.30	1.82	1.64	109.2	105.6
	LSD vigour	0.462		0.723		0.078		0.105		4.81	
	LSD tree presence/absence	0.283		0.719		0.036		0.195		9.31	

4.3.3 Crop leaf area index and stem height

Leaf area index (LAI) was significantly larger and stem height significantly shorter in Bugesera. In Bugesera and Meki, LAI and stem height were significantly higher in hybrids than in OPVs (Figure 4.3, Figure 4.4, and Table 4.5). In Bugesera, hybrids had an estimated LAI of 2.1 while it was 1.8 for OPVs. In Meki, estimated LAI for hybrids was 1.4 as compared with 1.2 for OPVs.

Overall, the presence of trees decreased LAI and stem height in Meki but only plant height was reduced in Bugesera (Figure 4.3, Figure 4.4, and Table 4.5). In Bugesera, reduction in LAI was marginal (P=0.07) but higher reduction was observed in OPVs than in hybrids (Table 4.4, and Table 4.5). In this site, stem height reduction under trees was also stronger with OPVs than in hybrids. In Meki, there was no interaction between vigour and tree presence for both LAI and plant height. Hybrids in Bugesera had an average LAI of 2.2 in sole crop and 2.0 under trees while the corresponding values of LAI for OPVs were 2.1 and 1.6. These differences were already present shortly after emergence (Figure 4.3).

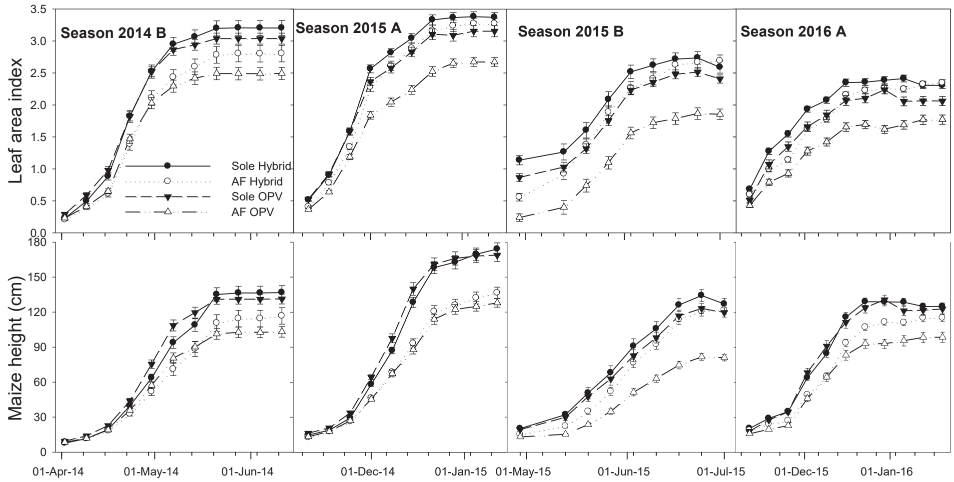

Figure 4.3 Time-courses for leaf area index and height of maize hybrids and OPVs growing under trees (AF: Agroforestry) or as sole maize during four consecutive seasons (2014 B, 2015 A, 2015 B and 2016 A) in the genotype experiment in Bugesera, Rwanda. Standard errors of the mean are shown.

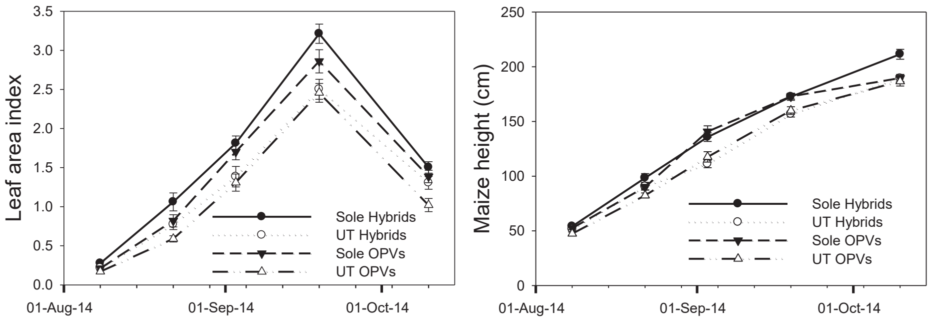

Figure 4.4 Time-courses for leaf area index and height of maize hybrids and OPVs growing under trees (UT) or as sole maize during the 2014 season in the genotype experiment in Meki, Ethiopia. Standard errors of the mean are shown.

Table 4.5 P-values results of the LMM model for the effects of fixed factors - vigour, tree species, presence/absence of tree and their interactions - on maize grain yield, total biomass, harvest index (HI), leaf area index (LAI) and plant height in the on-farm trials. Significant effects (P<0.05) are shown in boldface.

Factors	Grain yield	Total Biomass	HI	LAI	Stem height
Bugesera, Rwanda (*G. robusta* & *S. spectabilis*)					
Season	**0.013**	**0.001**	0.085	0.151	0.157
Vigour	**< 0.001**	**< 0.001**	0.784	**< 0.001**	**< 0.001**
Presence/absence of tree	**0.002**	**< 0.001**	**0.025**	0.070	**0.045**
Vigour x presence/absence of tree	0.185	0.675	**0.003**	**< 0.001**	**< 0.001**
Season x presence/absence of tree	0.050	0.055	**0.006**	0.095	**0.037**
Season x vigour	0.297	0.188	0.695	**< 0.001**	**< 0.001**
Meki, Ethiopia (*A. tortilis*)					
Season	0.811	0.275	0.094	-	-
Vigour	0.857	0.247	0.937	**< 0.001**	**< 0.001**
Presence/absence of tree	**0.019**	0.163	0.210	**0.002**	**0.031**
Vigour x presence/absence of tree	0.978	0.728	0.453	0.344	0.552
Season x presence/absence of tree	0.782	0.347	0.263	-	-
Season x vigour	0.791	0.682	0.758	-	-
Both countries					
Country	0.410	0.051	0.216	**0.005**	**< 0.001**
Vigour	0.078	**0.359**	0.919	**< 0.001**	**< 0.001**
Presence/absence of tree	**0.002**	**<0.001**	0.060	**0.014**	**0.013**
Vigour x presence/absence of tree	0.391	0.708	0.331	0.051	0.074
Country x presence/absence of tree	0.236	0.224	0.250	0.766	0.488
Country x vigour	**0.028**	**<0.001**	0.904	**0.031**	0.368

-: Measurements were only taken for one season.

4.4 Discussion

4.4.1 Hybrids outperformed OPVs in agroforestry systems of Bugesera, but not Meki

Maize hybrids performed significantly better than OPVs under trees in Bugesera but this was not observed in Meki. Presence of trees reduced yields of maize hybrids and OPVs in the same manner, but hybrids yielded significantly more than OPVs under trees in Bugesera. The interaction of season and the presence of trees in Bugesera was about significant for grain yield (P = 0.050) and for total biomass (P = 0.055) but highly significant for harvest index. Thus, the larger yields of hybrids even in drier seasons suggest that they withstand water stress better than OPVs in Bugesera. This contrasts with Kamara et al. (2003) who reported that maize hybrids are more susceptible to drought than OPVs.

In Meki, hybrid yields did not significantly differ from OPV yields under trees, probably OPVs used in the experiment were genotypes produced after significant breeding efforts from CIMMYT (the International Maize and Wheat Improvement Center) and the Ethiopian Institute of Agricultural Research to include traits of stress resistance (e.g., drought resistance) (Melkassa-ns varieties) (Beshir 2011). There was severe early water stress in Meki during the 2014 season and terminal water stress during the 2015 season. The early water stress in 2014 season reduced maize emergence rate and negatively affected the yields despite the season's higher total rains when compared to the region's average annual rainfall. OPVs available in Ethiopia (e.g. Melkassa-2, Melkassa-4 and Melkassa-6Q) are higher yielding and likely better adapted to drought than OPVs available in Rwanda (Gebre and Mohammed 2015; Kidane et al. 2016). This better adaptation to water stress, a frequent constraint in agroforestry systems of equatorial savannahs (Ong and Leakey 1999), may explain why these OPV cultivars yielded equally to hybrids.

In Bugesera, the 'SEEDCO' hybrids SC403 and SC513 performed better than the 'PANNAR' hybrids (PAN4M21 and PAN67) at P=0.08, and much better than all the OPVs under trees. The selection of traits under optimal growing conditions may also improve performance under sub-optimal conditions (Russel 1984). This appears to have been the case under agroforestry conditions in the equatorial savannahs of Rwanda where best performing hybrids in sole crop also performed better under trees. All the varieties that were used in both Bugesera and Meki were officially released and among the most popular varieties in the region, but the presence of trees strongly reduced their grain yields. Tiwari et al. (2009) and Desclaux et al. (2016) proposed participatory plant breeding methods to breed for agroforestry conditions targeting traits influencing agroecological structure and function rather than the classical breeding that targets higher yields in optimum conditions, and this is supported by our findings.

Our results showed that hybrids yielded more than OPVs in both sole crops and under trees in Bugesera. In Meki, the yields of hybrids and OPVs were reduced in the same manner under trees when compared to open fields. In contrast to farmers in Meki, Ethiopia where dryland OPVs development is advanced (Georgis et al. 2009; Abate et al. 2015), farmers in equatorial savannahs of Rwanda could benefit from cropping hybrids (e.g. SC403 and SC513) in agroforestry systems since their current OPVs are highly sensitive to agroforestry conditions.

4.4.2 LAI and plant height are reduced by tree presence for OPVs, but not for hybrids

Tree presence reduced leaf area index (LAI) and maize stem height, more so for OPVs than for hybrids. This reduction explained lower maize grain yield and above ground biomass under trees as compared to open fields in Bugesera (Lott et al. 2000; Dilla et al. 2017). Desclaux et al. (2016) suggest that it is crucial to consider plant, leaf shape and phenology while breeding for shade tolerance in agroforestry. We find that hybrids produce more total biomass than OPVs which could provide more feed for livestock (Tiwari et al. 2004). Based on the higher cost of hybrid seeds when compared to OPVs (Efa et al. 2005), and the comparable yield and biomass production for OPVs and hybrids we recommend farmers in Meki to grow OPVs rather than the more expensive hybrids in the stressed conditions (Alemu et al. 2008).

4.5 Conclusion

We hypothesized that maize OPVs outperform hybrids under trees. The presence of trees consistently reduced yields of both OPVs and hybrids. However, despite significant differences for vegetative traits in Bugesera, Rwanda, the hypothesis was rejected for grain yield, since reduction in yield and biomass was similar in both Bugesera, Rwanda and Meki, Ethiopia. We conclude that in tropical savannah regions of Rwanda agroforestry farmers could benefit from cropping hybrids, both under trees and in the open field. In contrast, farmers practicing agroforestry in tropical savannah regions of Ethiopia are better off using the current OPVs instead of more expensive hybrid seeds. It appears that the relevance of using either hybrids or OPVs in agroforestry systems depends on local conditions and the comparative advantages in seed costs.

Chapter 5

Conservation agriculture with trees amplifies negative effects of reduced tillage on maize crops in East Africa

This chapter is submitted as:

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Abstract

Conservation agriculture (CA) is widely promoted in sub-Saharan Africa both in open fields and in agroforestry where the practice is known as 'conservation agriculture with trees' (CAWT). The performance of open pollinated maize varieties under CA, CAWT, sole maize under conventional tillage (CT) and conventional tillage with trees (CTWT) was compared on-farm in semi-arid areas over four consecutive seasons in Rwanda and two seasons in Ethiopia. The tree species considered in the study were mature *Grevillea robusta* and *Senna spectabilis* in Rwanda and mature *Acacia tortilis* in Ethiopia. Both conservation agriculture and the presence of trees consistently reduced maize emergence, leaf area (LA) and leaf area index (LAI), plant height, and maize yields. Crop emergence was significantly reduced under CAWT compared with CTWT. Maize emergence rates in CAWT and CTWT were respectively 46.9% and 70.1%, compared with 74.7% and 79.8% in sole maize under CA and CT. Grain yield in CAWT and CTWT were respectively 0.37 t dry matter (DM) ha^{-1} and 1.18 t DM ha^{-1} as compared with 1.65 t DM ha^{-1} and 1.95 t DM ha^{-1} in CA and CT. We conclude that CAWT strongly reduces crop yield in semi-arid areas of East Africa, most likely due to maximising below-ground competition between crops and trees. Conservation agriculture is incompatible with agroforestry under the conditions of our study. There is an urgent need for rigorous research to revisit if, when and where CAWT can provide benefits for farmers.

5.1 Introduction

Agroforestry, the association of annual crops and trees , is an option advocated to increase crop production sustainably in sub-Saharan Africa where the use of external inputs is low (Pretty et al. 2011; Robert and Peter 1987). However, competition for light (Rao et al. 1997) and below-ground competition between crops and trees are important aspects concerning yield reduction in semi-arid tropics where water and nutrients are the major factor limiting crop growth (Ong et al. 1991; Radersma and Ong 2004). This can be addressed by shoot and root pruning of the trees to limit below- and above-ground competition between trees and crops (Rao et al. 1997; Mugunga et al. 2017). Most published work has focused on above-ground tree management, such as pruning regimes, while below-ground management of tree roots was seldom considered. Recent studies recommended pruning of tree roots to limit nutrients and water competition between trees and crops in semi-arid areas (Bayala et al. 2015; Muthuri et al. 2005). Beyond tree pruning, improved soil management options could be explored to optimize crop productivity in agroforestry systems (Hulugalle and Ndi 1993; Guto et al. 2012).

Conservation agriculture (CA) is a set of principles for resource-efficient agricultural crop production based on three principles: (1) minimum soil disturbance; (2) permanent organic soil cover (consisting of a growing crop or a dead mulch of crop residues); and (3) diversified crop rotations (www.fao.org/ag/ca). CA has been reported to increase and stabilize maize yields, conserve soil moisture, increase soil carbon stocks, and improve soil physical and chemical properties in many countries in sub-Saharan Africa (Rosenstock et al. 2014; Rockström et al. 2009).

Kassam et al. (2009) reported that CA and agroforestry practices have many features in common, such as increased ground cover and incorporation of legumes in the system. Combining CA with agroforestry was recommended as a sustainable approach to the production of food, fodder, fuel, fibre and income from intercropped trees while restoring exhausted soils (Garrity et al. 2010). A fresh approach - conservation agriculture with trees (CAWT) - was coined by combining conservation agriculture with agroforestry and adding a fourth principle to the three CA principles - that of tree-crop integration (Ngrsquo et al. 2013).

Although advantages and disadvantages of CA are well documented in field crops under sole cropping (Giller et al. 2009; Chivenge et al. 2007; Rockström et al. 2009), less is known about its impact in agroforestry systems despite the intense promotion of CAWT in many developing countries (Mutua et al. 2014). We hypothesize that CAWT will exacerbate below-ground competition for water and nutrients by trees and therefore reduce crop yields. We assessed the performance of sole maize under conventional tillage (CT) and CA, as well as maize with trees under conventional tillage (CTWT) and CA (CAWT) in two semi-arid regions of East Africa. Common open pollinated maize varieties were used. The tree species considered were *Grevillea robusta* (A. Cunn.) and *Senna spectabilis* (DC.) in Rwanda and *Acacia tortilis* (Forssk.) in Ethiopia. The experiment was conducted on-farm during four consecutive seasons in Rwanda, and two consecutive seasons in Ethiopia.

5.2 Material and methods

5.2.1 Site characteristics

Experiments were conducted in two locations: Bugesera in Rwanda and Meki in Ethiopia. Both are classified as semi-arid in the national systems with a Köppen-Geiger classification "equatorial savannah with a dry winter" (Kottek et al. 2006). Bugesera is located at 2° 21' S, 30° 15'E, at an elevation of about 1400 m above sea level (a.s.l). The climate is characterized by a bimodal rainfall pattern with primary and secondary peaks in April and November, respectively. The first harvest is in January/February, after the "short rains" from September to January (season A), and the second harvest is in August, after the "long rains" (season B) from mid-February to mid-July. Annual rainfall varies between 850 and 1,000 mm per year with an average annual temperature of about 21 °C (Verdoot and van Ranst, 2003). Soils are humic Ferralsols at lower and haplic Ferralsols at higher landscape positions with soil depths of about 100-200 cm. This region is characterized by large densities of termites which accelerate turnover of crop residues and consume tree bark (Musebe et al. 2017; Balasubramanian and Sekayange 1991). The selected plots were cropped with maize or sorghum in rotation with bush beans in previous seasons.

In Ethiopia, experiments were carried out in Meki, in the lowlands of the Central Rift Valley located at 8° 11' N, 38° 51' E and an elevation of about 1,500 m a.s.l. The agroecology is classified as equatorial savannah with a dry winter (Kottek et al. 2006) characterized by a unimodal rainfall pattern peaking in July-August. The rainy season or "*Kiremt*" normally runs from June to September with the annual total rainfall ranging from 281 to 1131 mm with a long-term average of 729 mm per year (Getachew and Tesfaye 2015). The average annual temperature is about 19.3 ºC. Soils are predominantly deep Andosols. The selected plots were previously cropped with maize.

5.2.2 Experimental layout

Experiments compared maize crops under CT, CA, CTWT and CAWT during the 2015 A, 2015 B, 2016 A and 2016 B seasons in Rwanda and during the 2014 and 2015 seasons in Ethiopia. Mature *G. robusta* and *S. spectabilis* trees were selected in Rwanda and mature *A. tortilis* trees in Ethiopia. Tree height, diameter at breast height (DBH), diameter at stump height (DSH; i.e. at 10 cm from the ground), canopy radius were measured and tree age was assessed from farmer recall. Three farms were selected per tree species. In Rwanda, for each farm included in the experiment, one plot with a tree in the centre and one plot in an adjacent open field were selected. The plot size was 10 × 10 m, and each plot was split into two subplots of 5 × 10 m; one managed with CT and the other with CA (Figure 5.1a). In Ethiopia, there were four plots per selected farm: two plots were located under almost identical trees and two control plots in an open field: one plot with tree and one control plot in open field were managed under CA while the other plot with tree and the other control plot in open field were managed under CT. The plot size was 10 × 10 m, but here plots were split into four subplots to accommodate four open pollinated maize varieties (OPVs) (Figure 5.1b). Unfortunately, one replicate in the Ethiopian experiment was damaged by livestock and was excluded from the analysis.

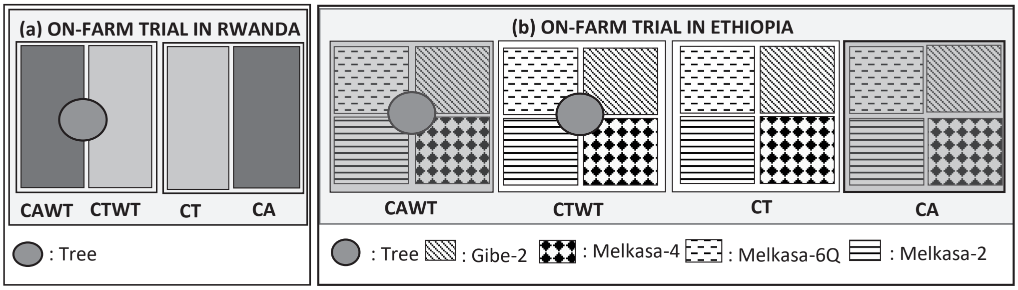

Figure 5.1 Layout of the experiments in Bugesera, Rwanda (a) and in Meki, Ethiopia (b) comparing conventional tillage in sole maize (CT), conservation agriculture in sole maize (CA), conservation agriculture with trees (CAWT) and conventional tillage with trees (CTWT) for four open pollinated maize cultivars.

In Rwanda, the most frequently used OPV cultivar i.e., ZM607 was used in all plots (Fig. 1a). In Ethiopia, the selected OPVs were Gibe-2, Melkasa-4, Melkasa-6Q and Melkasa-2 and these were randomly assigned to the four subplots per treatment each season, controlling for differences between the subplots (Figure 4.1b). Maize was sown with a spacing of 0.4 m within rows and 0.8 m between rows with two seeds per station in Rwanda. In Ethiopia, maize was sown at a spacing of 0.3 m within rows and 0.7 m between rows with 1 plant per station left after thinning.

In the CA and CAWT treatments, seeds were sown after slashing weeds with a sickle, without prior land preparation. Planting stations were opened with a hand-hoe to a depth of about 10 cm at the onset of the rainy season. Fertilization included the application of 18 kg of N ha^{-1} and 20 kg of

P ha^{-1} as di-ammonium phosphate at sowing and 46 kg of N ha^{-1} as urea as top-dressing six weeks after plant emergence, following general recommendations for the area. Fertilizers mixed with soils were placed in the hole before sowing seeds and covered by 2-3 cm of soil. Glyphosate was applied to control weeds in Ethiopia, but not in Rwanda. Weeding was done manually twice a month in all treatments. Crop residues were kept *in situ* in the CA and the CAWT plots but amounts produced and maintained were too small to cover the soil and were rapidly consumed by termites within one month after each harvest. In CT and CTWT treatments, crop residues were removed as commonly practiced in the area.

5.2.3 Maize growth measurements

In Rwanda, the number of fully expanded leaves, the length and the width of the last fully expanded leaf, and the plant height were recorded weekly from 20 days after sowing (DAS) to the end of the vegetative growth. In Ethiopia, these measurements were only recorded at anthesis. Leaf area (LA) and leaf area index (LAI) were calculated using the following formula:

$$LA = 0.75 \times L \times B$$

$$LAI = LA \times NL \times D$$

where L indicates the length from the leaf base to the tip of a leaf, B indicates the maximum width of the leaf, NL indicates the total number of leaves per plant and D indicates the plant density. The value of 0.75 (Maddonni and Otegui 1996) reflects the shape of the leaf in-between values for a triangle and a square. Emergence rates were measured 12 days after sowing. Fresh stover and grain weights were recorded in the field and dry weights of maize grain and stover were determined after oven-drying a sub-sample at 60 ºC for one week.

5.2.4 Statistical analysis

Means of tree characteristics were compared with an Analysis of Variance (ANOVA), the significance of differences was tested using Fisher's F-test. Maize grain dry matter yields, total biomass, harvest index, LA, LAI and plant height data were averaged per plot, which in the case of Ethiopia meant averaging over varieties. All variables were analysed with the following linear mixed-effect model (LMM) in R software:

$$Y_{ijklm} = \alpha + \beta C_i + \gamma TL_j + \delta TP_k + \varepsilon S_l(F_m) + \zeta C_i \text{ x } TL_j + \eta C_i \text{ x } TP_k + \theta TL_j \text{ x } TP_k + \kappa C_i \text{ x } TL_j \text{ x } TP_k + R$$

where Y_{ijklm} represents the response variable, C_i is the ith country, TL_j is the jth tillage intensity, TP_k represents the presence or absence of tree, S_l is the lth season, F_m is the mth farm and R is the residual, and where α, β, γ, δ, ε, ζ, η, θ, and κ represent fixed and random effects values.

Country, tillage (CA or CT) and tree presence/absence were included as fixed effects and whole plot, subplot and farm were random effects. The sub-plot factor was defined as tillage type nested within a treatment within a farm. The whole plot factor was defined as treatment within a farm for Rwanda but was equal to the sub plot factor in Ethiopia as the four sub plots under one tree included only one tillage type. Season was accounted for as a farm specific random effect. A tree type specific treatment interaction effect was modelled for each farm, with successive seasons coded as an ordered factor. For LA and plant height, means per plot were calculated and used as response variables. Significance of fixed effects was tested using a type-III ANOVA with Satterthwaite approximation for the denominator degrees of freedom. R software (R Development Core Team 2014) was used for all statistical analyses.

5.3 Results

5.3.1 Tree characteristics

The *G. robusta* and *A. tortilis* had about the same heights but were taller than *S. spectabilis* trees. The latter had the largest diameter at shoot height but with smaller diameter at breast height for the individual shoots. *S. spectabilis* and *A. tortilis* had a similar but larger canopy radius than *G. robusta* (Table 5.1).

Table 5.1 Characteristics of *G. robusta, S. spectabilis* and *A. tortilus* trees at the on-set of the trials (beginning of 2014). Standard deviations are given after the signs '±'. Means followed by the same letter in the same row do not differ significantly at α = 0.05.

Measurement	***G. robusta***	***S. spectabilis***	***A. tortilis***
Height (m)	$9.1^{a} \pm 0.3$	$6.8^{b} \pm 0.5$	$8.3^{a} \pm 1.2$
Diameter at breast height (DBH, cm)	$23.5^{b} \pm 0.7$	$11.4^{c} \pm 2.7$	$27.2^{a} \pm 2.3$
Diameter at stump height (DSH, cm)	$29.4^{b} \pm 0.9$	$63.3^{a} \pm 7.0$	-
Canopy radius (m)	$2.9^{c} \pm 0.1$	$4.7^{a} \pm 0.2$	$4.31^{b} \pm 0.5$
Tree age by farmer recall (years)	$18.3^{a} \pm 0.6$	$21.9^{a} \pm 3.5$	-
Number of stems	$1^{a} \pm 0$	$5^{b} \pm 0.5$	$1^{a} \pm 0$

-: are characteristics not measured

5.3.2 Maize emergence rates

Emergence rates were generally lower in Ethiopia (58.0%) than in Rwanda (77.8%) probably due to the El Niño induced drought in 2015. Overall, maize emergence rates were smaller for CA than for CT, and even less for CTWT than CAWT in both Rwanda and Ethiopia. The average emergence rates in CAWT and CTWT were respectively 46.9% and 70.1%, compared with 74.7% and 79.8% in CA and CT. The lowest emergence rates were observed in Ethiopia under *A. tortilis* in the CAWT treatment, the highest emergence rates were observed in the CT treatment in Rwanda (Figure 5.2). The effects of country, tillage management, and presence/absence of trees on the emergence rate were significant. The maize emergence rates differed between the combinations of tillage and tree presence as evidenced by the significant interaction terms (Table 5.2).

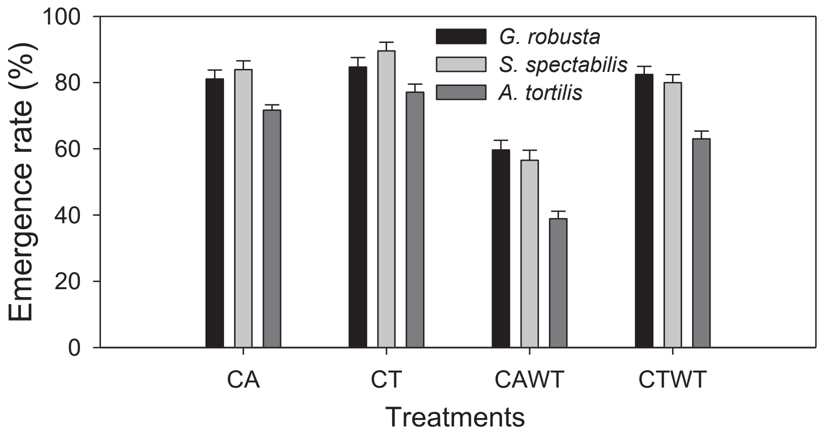

Figure 5.2 Means of maize emergence rates for conventional tillage in sole maize (CT), conservation agriculture in sole maize (CA), conservation agriculture with trees (CAWT) and conventional tillage with trees (CTWT). Trees are *G. robusta*, *S. spectabilis* in Rwanda and *A. tortilis* in Ethiopia. Data are from 4 seasons in Rwanda and 2 seasons in Ethiopia. Error bars indicate standard error of the means over seasons and varieties.

5.3.3 Maize leaf area, leaf area index and plant height

Maize LA of the 7^{th} to the 16^{th} leaf from the ground was lower in the presence of trees (CTWT and CAWT) than in the absence of trees (CT and CA) (Figure 5.3). This trend was observed in both Rwanda and Ethiopia. LA was lower in the treatments without tillage than in the treatment with tillage, more so in the presence of trees. The maize LA of the 7^{th} to the 16^{th} leaf was smaller in CAWT when compared with CTWT or CT (Figure 5.3).

Plants were shorter in treatments with trees as compared with sole maize treatments, with a larger difference in Rwanda than in Ethiopia. Observed mean plant height at harvest was 143 and 163 cm in CAWT and CTWT, respectively, and 170 and 191 cm in CA and CT respectively (Figure 5.3). The statistical predicted means of plant height were 91 and 106 cm in CAWT and CTWT, respectively as compared to 113 cm in CA and 125 cm in CT. LAI was smaller in CAWT as compared to CTWT and highest in CT treatments (Figure 5.4). The effect of tillage intensity and of the presence or absence of trees were significant for LA, LAI and plant height while only the interaction of country and tree presence or absence was significant for plant height (Table 5.2).

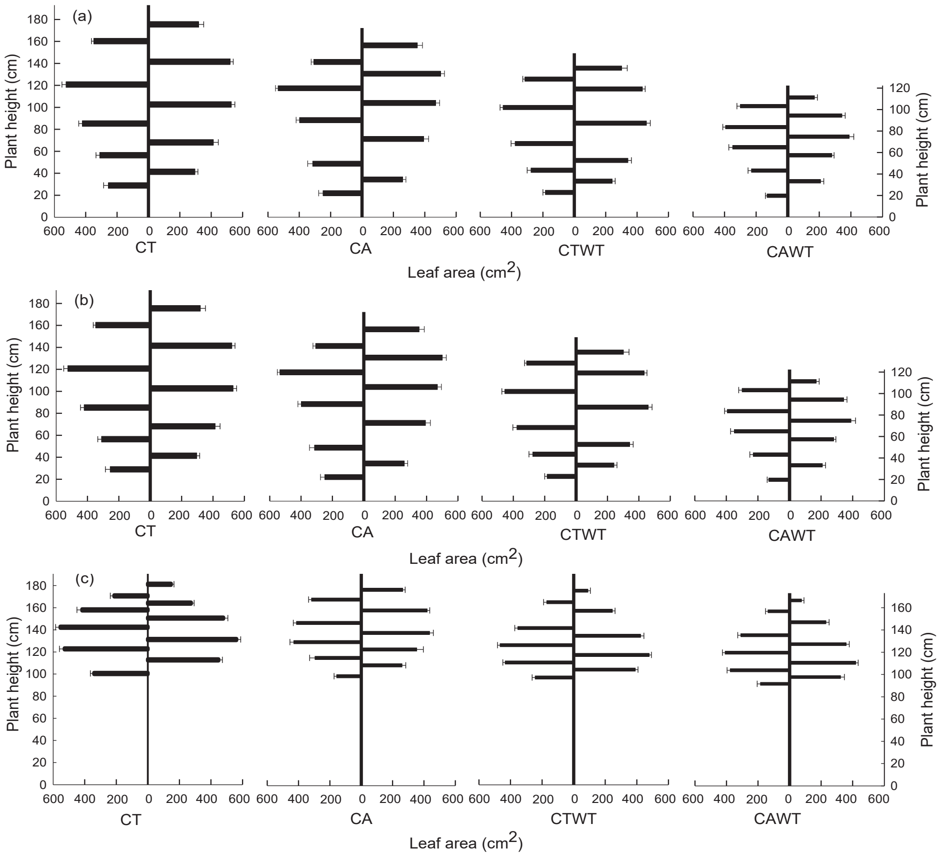

Figure 5.3 Mean plant height and mean area per leaf of maize (from 7th to 16th leaf) in conventional tillage in sole maize (CT), conservation agriculture in sole maize (CA), conservation agriculture with trees (CAWT) and conventional tillage with trees (CTWT) for the tree species *G. robusta* (a), *S. spectabilis* (b) in Rwanda and *A. tortilis* (c) in Ethiopia. In (a) and (b) the mean area of fully expanded leaves for four seasons is presented while in (c) the mean leaf area measured at maize anthesis for two seasons is presented. Maize leaf area is represented by horizontal bars including the standard error of the mean.

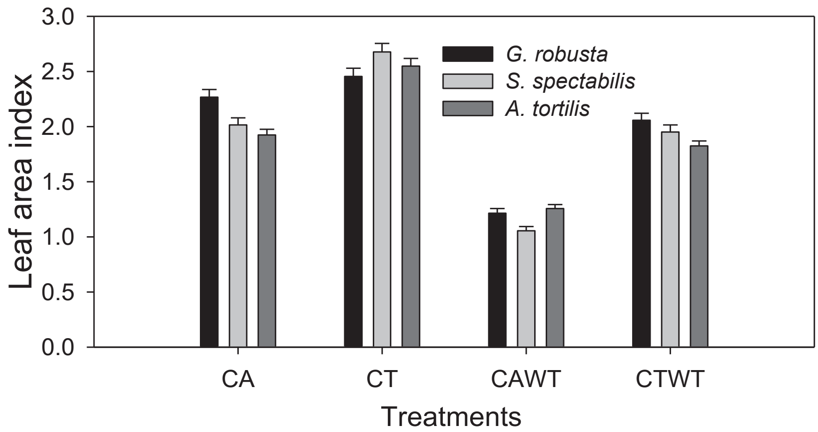

Figure 5.4 Maize leaf area index in conventional tillage in sole maize (CT), conservation agriculture in sole maize (CA), conservation agriculture with trees (CAWT) and conventional tillage with trees (CTWT) under *G. robusta*, *S. spectabilis* in Rwanda and *A. tortilis* in Ethiopia. Data are means of 4 seasons in Rwanda and of 2 seasons in Ethiopia. Error bars represent the standard errors of the means.

Table 5.2 *P*-values for fixed factors in the LMM model, corresponding to effects of tree species, tillage intensity, and presence/absence of trees on maize emergence rate, leaf area (LA), leaf area index (LAI) and plant height in the on-farm trials. Significant effects ($P < 0.05$) are shown in boldface.

Factors	Emergence	Leaf area	LAI	Plant height
Country	**<0.001**	0.690	0.289	**0.045**
Tillage	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Tree presence/absence	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Tillage x tree presence/absence	**<0.001**	0.342	0.857	0.725
Tillage x Country	**<0.001**	0.867	0.648	0.230
Country x tree presence/absence	**<0.001**	0.691	0.286	**0.011**
Tillage x tree presence/absence x country	0.898	0.968	0.127	0.920

5.3.4 Above-ground biomass, grain yield and harvest index

Grain yield, total biomass and harvest index were smaller in CA than in CT and smaller in CAWT than in CTWT, but with a much larger difference between CAWT and CTWT (Table 5.3). Mean estimated grain yields in CA and CAWT were respectively 2.38 t DM ha^{-1} and 0.91 t DM ha^{-1}, compared with mean grain yields values in CT and CTWT of 2.58 t DM ha^{-1} and 1.72 t DM ha^{-1}. Mean total biomass in CA and CAWT were respectively 7.55 t DM ha^{-1} and 4.5 t DM ha^{-1}, compared with mean total biomass values in CT and CTWT of 8.61 t DM ha^{-1} and 6.53 t DM ha^{-1}. The mean harvest index in CA and CAWT were respectively 0.32 and 0.2, compared with mean harvest index values of 0.33 and 0.27 in CT and CTWT. The effects of tillage intensity (CA or CT) and presence/absence of trees were significant for grain yield and total biomass. Country and treatment effects were significant for harvest index. The interaction between tillage intensity and tree presence or absence was only significant for harvest index whereas the interaction between tree presence or absence and country was significant for grain yield and harvest index (Table 5.4).

Table 5.3 Comparison of maize grain dry matter (DM) yield, total biomass and harvest index of maize as sole crop under conventional tillage (CT), sole crop under conservation agriculture (CA), conventional tillage with trees (CTWT) and conservation agriculture with trees (CAWT), with the tree species *G. robusta* and *S. spectabilis* in Rwanda and *A. tortilis* in Ethiopia. Standard deviations for the observed and standard error for the model estimated means are given after the sign '±'.

	G. robusta (Rwanda)			*S. spectabilis* (Rwanda)			*A. tortilis* (Ethiopia)		
Treatment	Grain yield (t DM ha^{-1})	Total biomass (t DM ha^{-1})	Harvest Index	Grain yield (t DM ha^{-1})	Total biomass (t DM ha^{-1})	Harvest Index	Grain yield (t DM ha^{-1})	Total biomass (t DM ha^{-1})	Harvest Index
	2015A						2014		
CA	3.91 ±1.7	7.02 ±2.7	0.55 ±0	3.94 ±0.2	6.97 ±0.5	0.57 ±0	2.42 ±1.7	9.32 ±6.7	0.23 ±0.1
CT	4.45 ±1.8	9.21 ±4.5	0.5 ±0.1	4.51 ±0.9	8.13 ±1.2	0.55 ±0	2.54 ±1	10.91 ±4.2	0.24 ±0
CAWT	1.82 ±1.4	3.81 ±2.3	0.47 ±0.1	1.03 ±0.2	1.96 ±0.2	0.52 ±0.1	1.7 ±1	7.62 ±4.9	0.24 ±0
CTWT	3.25 ±2	4.85 ±4.6	0.51 ±0	2.36 ±0.9	4.42 ±1.6	0.54 ±0	1.82 ±0.7	8.15 ±3.1	0.23 ±0
	2015B						2015		
CA	2.15 ±1.2	3.56 ±1.8	0.58 ±0.1	2.42 ±0.5	4.41 ±0.7	0.55 ±0	1.51 ±0.7	7.58 ±1.3	0.2 ±0.1
CT	2.42 ±1.2	3.78 ±1.8	0.63 ±0.1	2.47 ±0.5	4.31 ±1.3	0.59 ±0.1	1.82 ±1.2	8.31 ±2.1	0.21 ±0.1
CAWT	0.64 ±0.7	1.54 ±0.9	0.34 ±0.2	0.04 ±0.1	0.88 ±0.4	0.05 ±0	0.73 ±1	5.02 ±4.9	0.1 ±0.1
CTWT	1.67 ±1.3	2.8 ±1.6	0.54 ±0.1	0.53 ±0.5	1.75 ±0.7	0.27 ±0.1	2.08 ±0.9	8.71 ±2.3	0.23 ±0
	2016A								
CA	0.36 ±0.4	2.19 ±2.7	0.16 ±0.2	0.6 ±0.4	5.38 ±2.2	0.1 ±0	-	-	-
CT	0.52 ±0.3	2.15 ±2.2	0.34 ±0.1	0.68 ±0.4	6.35 ±1.2	0.1 ±0	-	-	-
CAWT	0.1 ±0.2	3.65 ±1.9	0.02 ±0	0.24 ±0	2.84 ±0.7	0.09 ±0	-	-	-
CTWT	0.23 ±0.1	3.87 ±1.6	0.06 ±0	0.42 ±0.1	3.91 ±0.6	0.11 ±0	-	-	-
	2016B						-	-	-
CA	3.94 ±0.4	14.12 ±1.3	0.28 ±0	3.85 ±0.1	11.95 ±1	0.33 ±0	-	-	-
CT	3.67 ±0.5	13.57 ±0.6	0.27 ±0	4.04 ±0.1	13.05 ±1.7	0.31 ±0	-	-	-
CAWT	1.26 ±0.8	7.62 ±3.3	0.15 ±0	0.38 ±0.4	4.37 ±0.3	0.08 ±0.1	-	-	-
CTWT	2.41 ±1.6	9.98 ±4	0.22 ±0.1	1.53 ±1	8.38 ±3	0.17 ±0.1	-	-	-
	Means (model estimates) in Rwanda						Means (model estimates) in Ethiopia		
CA	1.79 ±0.2	5.75 ±0.6	0.55 ±0				1.52 ±0.6	8.2 ±1.3	0.23 ±0
CT	1.99 ±0.2	6.36 ±0.6	0.57 ±0				1.92 ±0.6	10.32 ±1.3	0.23 ±0
CAWT	0.17 ±0.2	2.13 ±0.6	0.37 ±0				0.91 ±0.6	6.69 ±1.3	0.18 ±0
CTWT	0.69 ±0.2	3.79 ±0.6	0.46 ±0				1.68 ±0.6	9.07 ±1.3	0.22 ±0

Table 5.4 *P*-values for fixed factors in the LMM model, corresponding to effects of country, tillage intensity, and presence or absence of trees on maize yield, total maize biomass and maize harvest index in the on-farm trials. Significant effects ($P < 0.05$) are highlighted in bold.

Factors	Grain yield	Total Biomass	Harvest Index
Country	0.387	**< 0.016**	**<0.001**
Tillage	**0.007**	**0.008**	0.100
Tree presence/absence	**< 0.001**	**0.003**	**0.002**
Tillage x tree presence/absence	0.202	0.594	0.241
Tillage x country	0.901	0.367	0.493
Country x tree presence/absence	**0.006**	0.215	**0.011**
Tillage x tree presence/absence x country	0.699	0.751	0.795

5.4 Discussion

5.4.1 CAWT maximizes tree-crop competition and reduces crop yields

CAWT decreased grain yield and total biomass when compared with CTWT in semi-arid areas of East Africa. In Rwanda, the presence of a tree caused a much stronger reduction in yield and harvest index for CAWT compared to CTWT, suggesting that competition had a greater impact on grain yield than on biomass production (Muthuri et al. 2005). The greater yield difference between CA vs CT compared with CAWT vs. CTWT was due to lower emergence rates (Hulugalle and Ndi 1993) and lower maize LAI. Maize yield was larger in CTWT compared with CAWT, most likely because of reduced below-ground competition due to tillage pruning superficial tree roots. The importance of root pruning to limit water and nutrient competition in agroforestry was highlighted elsewhere by experiments that either physically separated the root systems of trees and crops using barriers (Singh et al. 1989) or pruned the tree roots (Bayala et al. 2013). Practicing CAWT over many seasons would lead to more tree root establishment in the top soil, likely exacerbating below-ground competition between trees and crops. We found no evidence for the anticipated benefits of CAWT claimed by (Kassam et al. 2009) who suggested that less soil disturbance would benefit both the trees and the associated crops.

Quantities of biomass produced and retained as surface mulch in CA and CAWT were small and rapidly - around one month - consumed by the abundant termites in these semi-arid regions, especially in Rwanda (Musebe et al. 2017) hence leaving soils prone to crusting and compaction. Chassot et al. (2001) found that minimum tillage reduced maize yield as it increased topsoil compaction which restricted the growth of roots and shoots of maize seedlings. Although cases can be found where trees improve soil structure (Silva et al. 2011), others report that soil compaction increased due to the weight of trees and wind pressure (Greacen and Sands 1980; Godefroid and Koedam 2010). Therefore, combining CA and agroforestry could have increased crusting and top-soil compaction in this study and eventually contributed to the observed lowest maize yields in CAWT compared with the three other treatments (CT, CA, and CTWT).

Literature on the effect of CAWT on crop yields is very limited despite the current active promotion of the practice in Eastern and Southern Africa (Muriuki et al. 2012), and in the Sahel (Bayala et al. 2011). Our results provide empirical evidence that CAWT strongly reduces crop yields in the semi-arid areas of East Africa. These findings are similar to those from Hulugalle and Ndi (1993) who also observed strong yield penalties when CA was combined with *S. spectabilis* trees. The positive impact of CAWT on crop yield reported when the tree species *Faidherbia albida* is used (Garrity et al. 2010) may be an exception, due to the unusual reverse phenology of the tree species (as well as its nitrogen-fixing ability).

5.4.2 CAWT reduces emergence rate, LA, LAI and plant height

CAWT reduced maize emergence rates as compared with CTWT. This could be due to the increased crusting and soil compaction often found with CA when amounts of mulch retained are small (Baudron et al. 2012). One of the critical factors in maize production is an evenly distributed plant population where emergence is the most important factor (Weaich et al. 1996). Regular plant stands become even harder to obtain in agroforestry systems, where soil recharge by the first rains after the dry season could take longer than in open fields due to interception of rain by the tree canopies (Samba et al. 2001; Jackson 2000). In addition, available soil water at the beginning of the cropping season tends to be lower in agroforestry systems since the trees continue to deplete available soil water even during the dry season (Chirwa et al. 2007b). This study shows that CTWT favours maize emergence and early growth in the semi-arid areas when compared with CAWT since it helps break crusts and could favour rapid soil water recharge at the beginning of the rainy season.

LAI was lower in CAWT than in CTWT due to a combination of low LA and poor plant emergence rates. While maize LA was not affected by the presence of trees in sub-humid region (Ndoli et al. 2017), it was strongly reduced in semi-arid region, more so under CAWT than under CTWT in this study. This appears to be a sign of water competition that could have prevailed in CAWT when compared to CTWT in the semi-arid areas. Maize LAI is an important determinant of productivity (Prasad and Brook 2005), particularly under tree canopies where solar radiation is limited (Tiwari et al. 2012). In this study, LAI was reduced in CAWT, which may have contributed to low maize productivity. The stronger reduction in maize plant height under CAWT when compared to CTWT suggests that plants grew more slowly, pointing at stronger nutrient and water competition between the tree and the crop, as reported by Namirembe (1999).

5.5 Conclusion

We conclude that CAWT is not a viable alternative to sole cropping under conventional tillage in the semi-arid areas of East Africa, given its detrimental effects on maize performance. The presence of trees consistently reduced maize emergence rate, LA, LAI, plant height and maize yields, but more so in CAWT than in CTWT. Poorer maize yield under CAWT as compared with CTWT was attributed to the observed poor emergence rate, lower LAI and lower harvest index values. CAWT likely exacerbates tree-crop competition for water and nutrients and consequently reduces crop yields. Thus, CAWT should be strongly discouraged in semi-arid areas of Eastern Africa. There is a crucial need for detailed research to investigate where and in which conditions CAWT can provide benefits for farmers.

Chapter 6

General Discussion and Conclusions: Agroforestry – a pathway to meet food and fuelwood demand in East Africa?

6.1 Introduction

Comprehensive discussions on the research findings have been presented in Chapters 2, 3, 4 and 5. The main purpose of this chapter is to synthesize and discuss some of the most important points concerning the effects of trees on crop growth and yield resulting from their impact on the microclimate and soil fertility. This includes assessing the combined effect of conservation agriculture and the presence of trees on maize productivity, as well as the effect of better genotypes in agroforestry systems. Finally, the overall contribution of agroforestry to household food security is discussed. The tree effect on maize crop productivity is discussed in Sections 6.2, 6.3, and 6.4. Section 6.5 presents an evaluation of the contribution of agroforestry to household food security. Section 6.6 elaborates on the policy implications and the recommendations for further scientific study, while the last part of the chapter, Section 6.7, gives a summary of the main conclusions reached, based on the results of the study.

6.2 Microclimate and fertility effects of trees on crop

I have demonstrated that crop growth and yields in close proximity to mature trees are significantly reduced. This result suggests that there are no microclimate benefits for yields of maize associated with trees. Indeed, the presence of trees reduced the incident solar radiation reaching maize crops in this study (Figure 6.1). In the system of scattered trees on-farm, the tree and maize canopies are separated vertically in space. Since the maize is shorter, it is permanently shaded by the tree. The fraction of photosynthetically active radiation reaching the under-storey maize is, therefore, reduced by the presence of the trees. This reduces the net photosynthesis of the shaded maize plants, and therewith plant growth and maize yields (Chapter 3). The results on competition for light between the tree species and maize in this study are in agreement with findings of Tiwari et al. (2012) and Okorio (2000).

The incorporation of trees into farming systems may have either beneficial or detrimental effects on crop production. Generally, above and below ground competition have a negative effect on crop performance, but are unavoidable in simultaneous agroforestry systems such as scattered on-farm trees. The above-ground competition is related to microclimate modification which involves changes in light, temperature, relative humidity, and rain interception (Jonsson et al.

1999; Kater et al. 1992; Sanou et al. 2012), while the below-ground competition is about water and nutrients (Schroth 1995). The competition for light reduces yields of C4 crops more than those of C3 crops (Sanou et al. 2012; Bayala et al. 2015). In contrast to microclimate benefits, soil fertility improvement seems to be an accepted evidence in agroforestry systems. However, controversy still exists as to whether trees really contribute to nutrients, recycle them, or just 'harvest' them and concentrate them from within their laterally extensive root zone (Bayala et al. 2006).

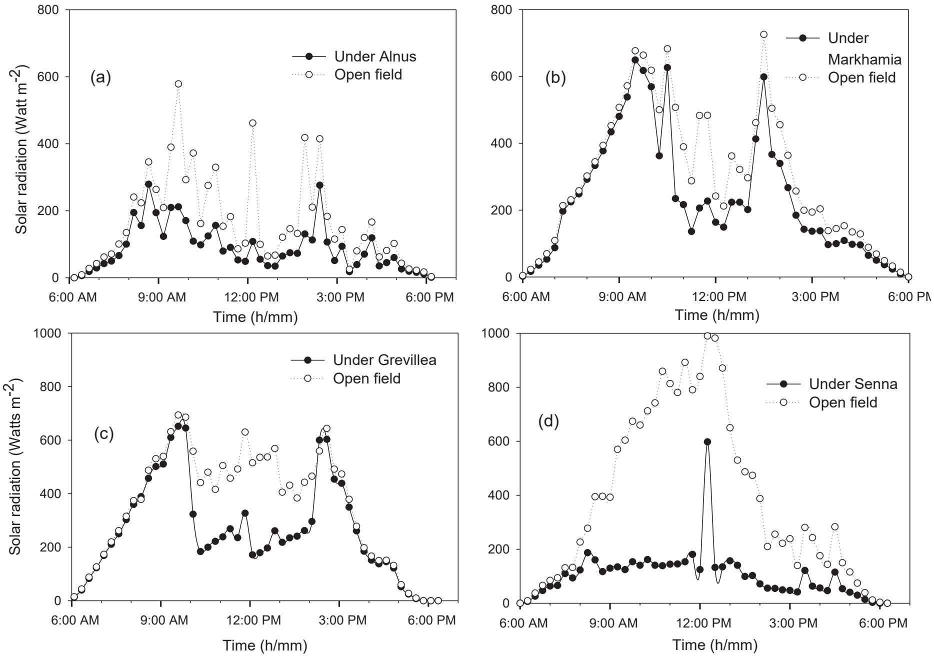

Figure 6.1 Daily global solar radiation, 1 m northward from the trunk and 20 m northward from the trunk under *Alnus acuminata* (a) and *Markhamia lutea* (b) in the sub-humid region of Rwanda, and under *Grevillea robusta* (c) and from *Senna spectabilis* (d) in the equatorial savannah of Rwanda. Data are averages of three days' measurements on identical weather stations simultaneously logging every five minutes.

While trees did not significantly reduce the soil water available to crops in the sub-humid region of Rwanda (Chapter 3 and Chapter 4), they can actually increase the soil water in the semi-arid regions. By reducing the evapotranspiration from the soil and the associated crops underneath, trees can increase soil water content (Bayala et al. 2015). Another process leading to increased soil water content under trees is the hydraulic lift or water redistribution, which is the passive movement of water through the roots of trees, from deeper and wetter soil layers to shallower and drier layers, along a gradient of soil water potential (Richards and Caldwell 1987). However, the effects of these processes were not observed in this study.

In this study, *Alnus acuminata*, a nitrogen-fixing tree with high litter biomass, was the only species that appeared to increase crop yields at the canopy edges in some seasons following substantial litter fall. It therefore appeared to improve soil fertility in the low intensity farming systems. These results are in agreement with findings from Peden et al. (1993) and Okorio et al. (1994). When trees and crops are mixed, rings of higher soil fertility around trees may be observed when fields are nutrient-deficient (Buresh and Tian 1997; Bayala et al. 2015). Many different nitrogen-fixing leguminous trees are used in agroforestry (Giller 2001) and their ability to fix N_2 can significantly reduce competition for this resource (García-Barrios and Ong 2004).

A. acuminata modified the microclimate by reducing air temperature towards mid-day and slightly increasing air temperature in the night due to the blanket effect (Figure 6.2). This buffered the effect of the tree on the growth degree days through effects on the maximum and minimum air temperatures. Similarly, the relative humidity under this tree was higher than in the open field around mid-day, but it was lower in the night time (Figure 6.2). Except for the reduction of the incident solar radiation under *A. acuminata* (Figure 6.1), the modification of air temperature and relative humidity by the tree did not influence crop performance in this study. While the microclimate modification of the trees might be beneficial to crops in hot climates like in the Sahel region (Bayala et al. 2015), it was not so in this study. I conclude that crops growing under these trees may benefit from the improved soil fertility, but shade provided by the trees will prevent crops from fully benefiting from it until the trees are harvested or intensively pruned (e.g. pollarded). This implies that canopy management should be much emphasized to limit the negative effects of shade on the associated crops, if shade-tolerant crop varieties are not yet developed or available. The optimizing of crop production in agroforestry will require specific tree management (e.g. pruning) and crop management practices (the use of adapted varieties and adequate tillage).

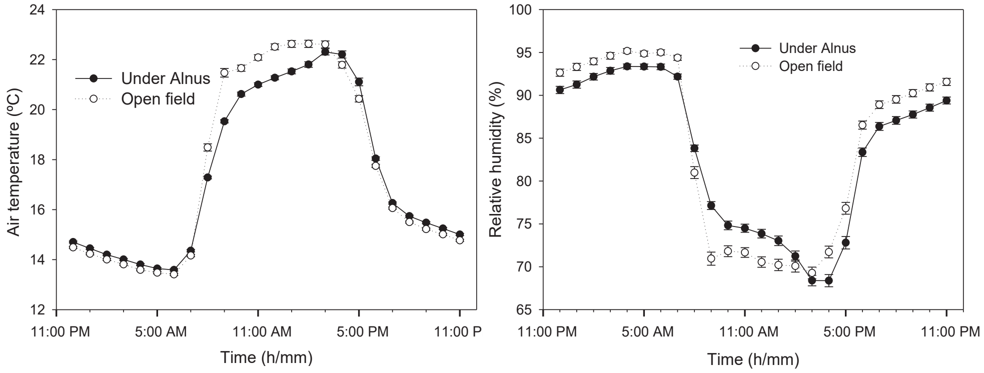

Figure 6.2 Air temperature and relative humidity under *Alnus acuminata* and in open fields during season 2015 B in the sub-humid agroecology (Gishwati) of Rwanda. Vertical bars are standard errors of the means.

In this study, trees reduced day air temperature but did not delay the phenology of maize in either sub-humid or semi-arid regions. The microclimate modification under trees in the sub-humid climate of Rwanda did not affect the leaf area index, but it did reduce plant height and yield. In the semi-arid regions of Rwanda and Ethiopia (see Chapter 3 and Chapter 4), the microclimate modification by trees shade contributed to the reduction in leaf area index, plant height and yields. The tree canopy moderates temperature underneath (García-Barrios and Ong 2004; Rao et al. 1997), and potentially increases resource use efficiency, for example by reducing evapotranspiration from the soil and the associated crops or by preventing supra-optimal temperatures (Sanou et al. 2012). The lower temperature under trees can delay crop phenology and elongate the grain filling stage, which can improve crop yield (Craufurd and Wheeler 2009; Sida et al. 2018) when water and nutrients are sufficiently available (Anwar et al. 2015), but this effect was not observed in this study.

A thorough understanding of how agroforestry system components utilize available resources is crucial for determining species combinations, planting arrangements, tree spatial densities and management strategies suitable for different locations and different farmer objectives and for the long-term sustainability of the system (Ong and Huxley 1996). In this study, the trees and the crops generally competed for growth resources. Management of the trees in the studied agroforestry systems could minimize this competition and hence improve the yield of the associated crops. In recent studies, tree canopy and tree root pruning were tested to improve light availability and resource use efficiency (Bayala et al. 2015), but studies that deal with improved agronomic practices in the agroforestry systems are rare. Two such practices tested in this study, and discussed below, are tillage options and the selection of crop varieties that are better adapted to agroforestry conditions.

6.3 Conservation agriculture with trees exacerbates tree-crop competition

Conservation agriculture (CA) is defined as the simultaneous application of minimal soil disturbance, permanent soil cover through a mulch of crop residues or living plants, and crop rotation (www.fao.org/ca). CA has been reported to increase and stabilize maize yields, conserve soil moisture, increase soil carbon stocks, and improve soil physical and chemical properties in many countries in sub-Saharan Africa (Rosenstock et al. 2014), but the uptake in this region is still restricted, mainly because of the limited availability of crop residues (Giller et al. 2009). Kassam et al. (2009) highlighted the common features of CA and agroforestry, such as increased ground cover and the incorporation of legumes in the system. Ngrsquo et al. (2013) suggested that one way to solve the problem of mulch scarcity and increase CA uptake would be to incorporate of agroforestry into CA practices, creating a fresh approach – conservation agriculture with trees (CAWT). It is claimed that combining CA with agroforestry will help to increase food production in Africa (Garrity et al. 2010). However, this study found that conservation agriculture with trees (CAWT) decreased crop growth and yields in the semi-arid regions of East Africa when compared to conventional tillage with trees (CTWT).

The study conducted in the semi-arid regions of Rwanda – Bugesera – and Ethiopia – Meki – (Chapter 5) led us to conclude that CAWT is not a viable alternative to sole cropping under conventional tillage or to CTWT, given its detrimental effects on maize performance. CAWT reduced maize emergence rates, leaf area index, plant height and yields, when compared to CTWT. Minimum tillage under trees highly reduced the maize emergence rates when compared to conventional tillage under trees. When the roots of trees are left undisturbed by tillage, they will grow densely in the topsoil and strongly compete with crops for water and nutrients. Tilling prunes the tree roots in the top soil and reduces below-ground competition between trees and crops. The importance of root pruning to limit below-ground competition in agroforestry was also highlighted by Singh et al. (1989) and Bayala et al. (2013).

Van Noordwijk and Ong (1999) hypothesize that land-use systems that mimic patterns of resource use in natural systems are most likely to achieve long-term sustainability. One of the farming systems that closely approach natural systems is the combination of CA and agroforestry. Indeed, this system has been recommended as a sustainable approach which allows the production of food, fodder, fuel, fibre and income from intercropped trees while restoring exhausted soils (Garrity et al. 2010). However, despite the separate theoretical potential of both CA and agroforestry practices to halt land degradation and improve the sustainability of farming systems in East Africa, it appears that the combination of these two practices increases tree-crop competition and leads to poor crop performance in semi-arid areas. It is therefore crucial to provide convincing evidence on the basis of on-farm demonstration trials before such practices are recommended to farmers. Farmers are concerned with meeting their immediate needs, and are therefore easily deterred from adopting technologies that entail no yield benefits in the short term (Giller et al. 2009).

6.4 Better maize genotypes in agroforestry systems can increase crop productivity

The 20th century Green Revolution, which dramatically increased crop yields in Latin America and Asia, never gained a foothold in sub-Saharan Africa, because of the daunting ecological, and farm inputs challenges (Blaustein 2008). In sub-Saharan Africa, maize is the most important cereal food crop and its consumption demand is predicted to double by 2050 (Anley et al. 2013). Although maize breeding has had great impact in sub-Saharan Africa (Smale and Jayne 2003), few attempts have been made to develop germplasms specifically adapted to complex environments as found in agroforestry systems (Tiwari et al. 2009), which are key crop production systems in sub-Saharan Africa (FAO 2007). In Chapter 4, we compared the performance of open-pollinated varieties of maize (OPVs) and maize hybrids in two agroforestry systems in East Africa – in Rwanda and Ethiopia. It was concluded that farmers in the semi-arid regions of Rwanda could benefit from using hybrids, in contrast to farmers in the semi-arid regions of Ethiopia, where hybrids were not significantly better than OPVs in agroforestry systems.

Maize is the principal staple food in East Africa. Yet this study has shown that the use of the presently available maize germplasm in agroforestry systems leads to significant yield reduction. An implication for food security is that, because of the sub-optimal environment agroforestry systems offer for maize production, it is necessary to breed specially adapted and robust varieties of maize. The current varieties proposed to farmers were bred for full sun and optimum soil moisture conditions, and therefore are not optimally adapted to agroforestry conditions. Tiwari et al. (2009) and Desclaux et al. (2016) proposed participatory plant breeding methods to breed for agroforestry conditions targeting traits influencing agroecological structure and function rather than the classical breeding that targets yield and quality. The selection of traits under optimum growing conditions may also improve performance under sub-optimal conditions (Russel 1984). This appears to have been the case in the semi-arid region of Rwanda, where the best-performing hybrids in sole crop also performed better under trees.

In light of recurring food shortages, projected climate change, and rising prices of fossil fuel-based agricultural inputs, agroforestry has recently experienced a surge of interest among the research and development communities. It is considered to be a cost-effective and sustainable method to enhance food security, which at the same time contributes to climate change adaptation and mitigation (Mbow et al. 2014). A substantial increase of trees on croplands, is an inevitable phenomenon in the future (Garrity 2012). This increase has to be achieved together with the goal to double food production to feed the world's ever-growing population.

In the past decades, agroforestry research has only focused on tree management to limit competition with crops; but little was done to improve the capacity of the associated crops to withstand competition with trees. More than 22000 articles (published from 1970 to 2015), referenced in Web of Science Thomson Reuters contained the two keywords 'Agroforestry' and 'Crop'. However, when adding the keyword 'Breeding', the number of articles falls to less than 1700 (Figure 6.3), and these articles almost exclusively bear on the breeding of trees (Desclaux et al. 2016). If nothing is done on the side of crop breeding to fit in with the agroforestry system which is potentially the future in global land use (Garrity 2012), crop yields in this system could continuously decrease or stagnate, with direct consequences for food security and at the expense of 'sustainability'.

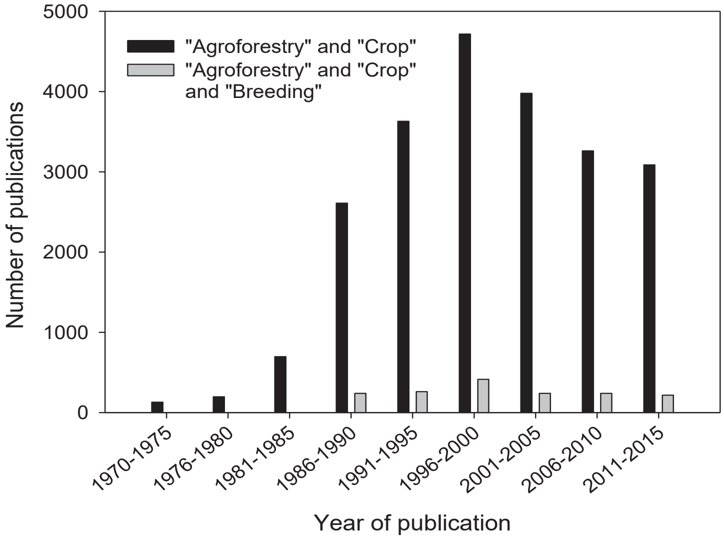

Figure 6.3 Number of agroforestry publications in the Web of Science [figure from Desclaux et al. (2016)]

6.5 Can growing on-farm trees improve food security?

Often the planting and keeping of on-farm trees is the result of a deliberate decision by farmers, taken in order to satisfy multiple needs, and depending on available resources and knowledge systems. In view of rapidly increasing population pressures and the depletion of natural resources, the adoption of agroforestry has been advocated as a potentially productive and environmentally-friendly solution for farming systems, which can improve food and nutritional security (Leakey 2014). Even smallholder farmers who endure crop yield losses due to tree-crop competition often still keep trees on their small farms due to the value they attribute to them. Trees provide products that are used directly by households (food, fuel, and construction materials) or that are used as inputs to agriculture (fodder, green manure and mulches). Trees also provide income and service functions (erosion control, shade for people and livestock, and demarcation of land to ensure land tenure). In the survey conducted in Rwanda (Chapter 2), households' food security was reduced by the presence of more trees on small farms as well as on larger farms. In general, households with low food security relied more on tree income than households with a higher food-security status, indicating that tree income serves as a 'safety net' for the poorest households.

The International Food Policy Research Institute in Washington has indicated that the world population will rise from the current 7.6 billion to approximately 10 billion by 2050, and that to support all these people, food production will have to increase by at least 70%. This target might not be reached if the food production has to take place in the current agroforestry systems, where yields are generally depressed by the sub-optimal growing conditions. The global effort to bring 150 million hectares of degraded and deforested land into restoration by 2020, and 350 million hectares by 2030, has created an unprecedented momentum, with 40 governments, companies and organizations already having allotted over 148 million hectares to this restoration ambition. There is strong voluntary commitment of the part of African countries, even beyond the 'negotiated' commitments. In East Africa, some countries have pledged to restore up to 100% of their national arable land. Rwanda has pledged to restore 2 million hectares of land, Ethiopia 15 million ha, Kenya 5.1 million hectares, Uganda 2.5 million hectares, and Burundi 2 million hectares (http://www.bonnchallenge.org). This ambitious political plan to scale up land restoration, mainly with agroforestry, could affect negatively crop yields and food security.

Agroforestry for improved crop yields?

A major tenet of agroforestry, that trees increase crop yields, is based primarily on the improved soil fertility measured near trees or where trees were previously grown. Tree litter and prunings provide nutrients which can meet crop demands, but the amounts provided are determined by the production rate and nutrient concentrations, both depending on climate, soil type, tree species, plant parts, tree densities and tree pruning regimes (Palm 1995). In this study trees generally depressed crop yields in both sub-humid and semi-arid regions of East Africa. Among five tree species evaluated in this study only one, *Alnus acuminata*, a nitrogen-fixing tree with high litter, showed signs of crop yield improvement at the canopy edges in some seasons. Although crops under trees may benefit from the improved soil fertility, light and water competition provided by the trees usually prevent them from benefiting.

The hypotheses that led many to have high expectations of agroforestry systems in the 1980s were mostly based on the assumption that trees have the potential to improve soil fertility. The hypotheses were that (i) trees would be able to supply nitrogen to the system by biological nitrogen fixation (BNF) from the air, and pump other nutrients from the depth and recycle them to the surface soil through litter; (ii) trees would minimize nutrient losses by erosion and leaching because of their always-present root systems, and (iii) trees would restore soil organic matter content and temper microclimate (Young 1989). From the 1980s, agroforestry research evolved: descriptive studies made way for studies based on a more scientific approach. The latter confirmed some tree advantages, but (disappointingly) also found disadvantages due to competition for resources between trees and crops which largely off-set the tree advantages (Ong 1995). The total primary production of trees and crops could still be larger than that of the crop alone, but the crop yield itself was often lower. This meant that only a high value of trees and a valid marketing infrastructure could make the system economically viable and attractive for farmers (Radersma 2002). Indeed, crop yields in the agroforestry systems with high-value trees were sometimes considered as a bonus to farmers (Bai et al. 2016).

Rao et al. (1997) argue that in spite of substantial crop yield decreases under scattered trees, the overall effect of the trees on crop yields could still be small, since only a small proportion of the area is subjected to tree-crop interactions. For instance, in Ethiopia farmers usually grow between 1 to 20 trees of a selected species per hectare and minimize the impact on the companion crops by occasional lopping and pollarding the trees (Poschen 1986; Iiyama et al. 2017). In such a system of 20 scattered trees ha^{-1} with each tree reducing the crop yield by 50% over a 100 m^2 area, the crop yields in the field would be only 10% lower than it had been without the trees. We should also realize that on-farm trees have a value for farmers that compensates for the reduction in crop yields. The survey done in this study (Chapter 2) did not find any significant difference in crop productivity at the farm level between farmers mixing trees with crops and those applying sole cropping. This shows that the negative effects of trees on crops at the plot level could fade out at the farm level, since farmers adjust the tree density to balance crop and tree products. Strangely enough, farmers perceiving high competition between trees and crops were mostly found in the agroecologies of Rwanda with the least numbers of on-farm trees. Thus, research should be done to investigate the rationale behind the negative perception of trees before policies pushing for the adoption of agroforestry are made.

Agroforestry for woody products and income

In Africa as a whole, 90 % of the total wood removal consists of fuelwood (Ridder 2007), and in sub-Saharan Africa, 90 % of the households use fuelwood for cooking (Maiangwa 2010). Woody biomass is the primary source of energy in East Africa, and this situation is expected to remain unchanged for at least the two coming decades (Iiyama et al. 2017; Drigo et al. 2013). Agroforestry supplies large amounts of fuelwood and contributes to reducing deforestation (Ndayambaje and Mohren 2011). In Rwanda, the forest area was estimated at 29.6% in 2015, with only 0.6% of the country remaining to reach the 30% maximum forest area target. The annual shortage in wood biomass is projected to reach 2.1 million tons by 2020 in a business-as-usual scenario, while there will be no space for new forests. Doubling the tree cover in agroforestry systems (from 5.2 to 10.4%) can close this gap by half (Drigo et al. 2013).

Over 50% of the surveyed households across six agroecologies in Rwanda referred to fuelwood as the major utility derived from tree species planted or regenerated on farms (Mukuralinda et al. 2016). In this study (Chapter 2), it was found that woody products (e.g. firewood, poles and stakes for climbing beans) harvested on-farm contributed only a small part of the household income compared to the crop and livestock income; nevertheless a fair proportion of farmers depended on three income. Farm households with lower food security depended more on tree income than farmers with a higher food-security status, suggesting that tree income could be more important for the poorest farm households. It was apparent that on-farm tree numbers were usually not proportional to the income they generate, indicating that farmers might be producing trees on-farm mainly for household use rather than for income generation. Though I did not quantify the fuelwood produced for household consumption, it is evident that farmers producing their own fuelwood are able to save money they would have otherwise needed for purchasing it.

Although trees in agroforestry may compete with the corresponding crops for growth resources such as water and nutrients, farmers still choose to grow on-farm trees to meet their households' fuelwood needs. Indeed, Rwandans have a proverb which says 'People with firewood eat cooked food', meaning that good things happen to self-sufficient people. To a Rwandan farm household, a bag of maize flour without firewood is less useful than half of the bag that comes with enough firewood to prepare it. In Chapter 2 we found that in the more densely-populated areas in the west of Rwanda, farmers tend to have more on-farm trees to meet their fuelwood need right on their small plots, as a strategy to cope with the limited access to the rare forests in the region.

6.6 Implications for management and policy

Unsustainable farming systems are partly responsible for the severe food shortage in East Africa. Agroforestry has the potential to provide a more resilient system that combines food and energy production and that provides extra income, thus helping rural households to improve food security and to absorb and cope with shocks. Considering the low potential for expanding afforestation in most agroecologies in East Africa (Ndayambaje 2013), the need to limit land degradation on cropland, and the desperate need for fuelwood and other tree products, agroforestry could be the system best suited to region's conditions.

Trees might be good and ecologically beneficial for the whole landscape but not for an individual farmer, because of the lower crop yield under trees. In this case, two options could provide a remedy: (i) growing high-value trees that can easily compensate for the yield loss, or (ii) the governments providing incentives or compensation to such farmers holding the lungs of the landscape. In all cases, in order to improve the food security situation by introducing more sustainable farming systems, a supportive policy environment is needed. Most of the tree products produced on-farm are cheaply sold or not sold at all, mainly due to the lack of good market value chains and of policies supporting their establishment. For instance, most fuelwood originates from agricultural land in Rwanda (Ndayambaje 2013), but no policies or planning for its production and commercialization exist at present. Better market access and the ownership of the means of transport could be the economic drivers and enabling conditions for the adoption of commercially valuable tree products (Mukuralinda et al. 2016).

Despite the potential of agroforestry to generate income, and despite the recent strong political will to scale it up, often it is still unclear to which ministry agroforestry belongs in East African countries. This creates confusion among institutions when it comes to the elaboration of agroforestry policies and to scaling-up efforts. For instance, in Rwanda the Ministry of Agriculture and Animal Resources is in charge of crop production while the Ministry of Land and Forestry is in charge of all tree planting. Extensionists (agronomist and forest officers) are under the Ministry of Local Government. Coordination among these ministries was ranked second among the weaknesses concerning agroforestry adoption (Mukuralinda et al. 2016). The scaling up of agroforestry will require cross-sectoral coordination and goodwill, with an 'all-in' spirit of collaboration of all stakeholders concerned.

6.7 Future research directions

The food security and income situation of farmers adopting agroforestry may depend on the value of tree products rather than on increased food production, as the latter is rare in agroforestry (Quinion et al. 2010). However, agroforestry can help to meet the needs of smallholder households, and improve their food security. It can also contribute to the ability of farmers to purchase food, provided that the market value of tree products remains stable or increases and enough food is available on markets. It is important to investigate how the adoption of agroforestry on a larger scale will impact the food-security situation of farmers. The production of more on-farm tree products at the expense of crop yields might lead to an unbalanced supply of food and tree products, with a potential negative impact on food security.

In the densely-populated areas of East Africa, land degradation, food insecurity and scarcity of firewood are serious problems, but agroforestry is taking root and can spread rapidly among smallholders. It will require further research to identify drivers and preconditions for the scaling up valuable tree species and better techniques of tree management (e.g. adequate pruning), crop management (e.g. the use of genotypes adapted to agroforestry conditions) and soil management (e.g. deep tillage to prune tree roots) that can help minimize tree-crop competition. The productivity of different on-farm tree species will need to be investigated, in order to allow a real value estimation of the on-farm trees. Also, the breeding for agroforestry is an area to be explored; in the breeding process shade-tolerance traits and traits influencing agroecological structure and function (e.g. the increase of arbuscular mycorrhizal fungi increased by crops only when associated with trees) ought to be targeted. Research to improve the market value chains for on-farm tree products will need to be conducted in different agroecologies of East Africa in order to increase the proportion of income farmers get from trees on-farm.

6.8 Concluding remarks

The central hypothesis of this study was: 'the benefits of on-farm trees outweigh their competition with crops for resources, as the trees provide valuable products and increase soil fertility'. My findings were that food security decreased with increasing tree income, and that households with lower food security depended more on tree income than households with a higher food-security status (Chapter 2); that trees on farm generally reduced crop yields in the sub-humid region of Rwanda (Chapter 3) and in the tropical savannah of both Rwanda and Ethiopia (Chapter 4 and 5). Compared to conventional tillage with trees (CTWT), conservation agriculture with trees (CAWT) likely exacerbates tree-crop competition for water and nutrients and consequently reduces crop yields in the tropical savannah of East Africa (Chapter 5). My hypothesis was partly supported: trees increased the household income of poor farmers, but crops mostly did not benefit from the fertility effects of trees because of their negative shade effects.

My study further showed that the presence of trees significantly reduced the incident solar radiation and air temperature, negatively affecting growth and yield of the associated maize crops, with the effect varying depending on the tree species and the distance from the tree trunk. Among five tree species evaluated in this study, only *A. acuminata* showed a positive interaction with maize at 3 m from tree trunk in seasons following higher litter fall. This suggests that the negative effect of shade was occasionally offset by extra N input from litter under low input conditions. This means that adequate pruning and high leaf litter recycling might help reduce the negative effect of shade in low-intensity farming systems.

While tree management has been exhaustively investigated in agroforestry systems, crop management studies have lagged behind. In my study, I investigated seeds and tillage options that minimize tree-crop competition. I found that maize hybrids yielded more than open-pollinated varieties (OPVs) under *G. robusta* and *S. spectabilis* in Bugesera, Rwanda but equally performed under *A. tortilis* in Meki, Ethiopia. In tropical savannah regions of Rwanda, farmers using agroforestry could benefit from cropping hybrids. In contrast, farmers practicing agroforestry in tropical savannah regions of Ethiopia would probably be better off using the current OPVs instead of expensive hybrid seeds that need to be purchased every year. I found that onservation agriculture with trees (CAWT) reduced maize emergence rate, LA, LAI, plant height and maize yields when compared to conventional tillage with trees (CTWT) in the tropical savannah areas of East Africa. Thus policies intending to scale up CAWT should be cautious.

My analysis provided evidence that mixing trees and crops produces a worthwhile, if somewhat reduced, crop yield, and that on-farm trees can provide substantial income for the poorest households of Rwanda. Better varieties and deep tillage to disturb tree roots will be necessary to optimize crop production in agroforestry systems. Detailed studies need to be carried out to assess the impact on food security of a large-scale adoption of agroforestry by farmers, taking into account the effects of the production of more on-farm tree products at the expense of crop yields. Furthermore, the market for on-farm tree products will need to be developed in order to provide substantial benefits to agroforestry farmers and thus help them cope with their yield losses.

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Summary

The East Africa region is confronted with a large and increasing population, low agriculture productivity and land degradation due to continuous cropping with little return of nutrients and soil erosion. Deforestation continues at a large scale due to the expansion of agriculture land. Achieving food security while preventing further expansion of agriculture is a major issue on the agenda of governments in East Africa. One option to alleviate the effects of deforestation and land degradation in Africa is agroforestry, combining crops and trees in the field. There is a current ambitious policy plan to scale up agroforestry in Africa: some East African countries have pledged to restore up to 100% of their arable land by the year 2020, mainly through agroforestry. It is therefore crucial to investigate the impact that on-farm trees would have on food security of farm households. The objective of this thesis was to understand the effect of trees in cropped fields on crop productivity and food security in East Africa through detailed studies in Rwanda and Ethiopia.

Chapter 2 details the value of on-farm trees in relation to food security and farm income in the six agroecologies of Rwanda. Data from a survey including 465 farmers that were selected across the six agroecologies was used. Farm size, crop and livestock income were related to the number of on-farm trees in most of the agroecologies and positively increased the household food security. Within the same agroecology, food security increased with increasing farm size. Overall, trees contributed the least proportion of income as compared to crop and livestock. In many agroecologies, on-farm tree numbers were not proportional to the tree income that the households get, suggesting that most trees are probably kept by farmers for other reasons (e.g. own fuel and fruit consumption) than for income. Households in agroecologies with less trees reported high tree-crop competition, suggesting that introducing agroforestry technologies to these farmers will not be effective, unless their perceptions on tree-crop interactions change. In general, households with low food security relied more on tree income than households with higher food security status, indicating that tree income can be seen as a ‘safety net” for the poorest households.

In Chapter 3, the effects of mature *Alnus acuminata* and *Markhamia lutea* on crops are investigated at different distances from tree trunk in the sub-humid environment of Rwanda. Nutrient availability was higher under *A. acuminata* compared with *M. lutea*, because of higher litter fall but maize nutrient uptake increased only under *A. acuminata* three meters from tree trunk during a wetter season. None of tree species affected water availability for maize in the topsoil. Both tree species reduced the amount of solar radiation that reached the associated maize crop. Maize plants were shorter under trees but had a similar number of leaves and leaf sizes when compared with plants in sole maize plots. Crop yield was in general more strongly reduced at 1 m than at 3 m from the tree trunk. A positive interaction in crop yield between *A. acuminata* and maize was only apparent at 3 m from the tree in one of the four seasons following higher litter fall. In a scenario modelled using the Agricultural Production Systems sIMulator (APSIM) crop model a larger N input from trees could compensate for yield loss caused by reduction in radiation and temperature in about 60% of the seasons, but only when N fertilization was limited. Yield losses were not compensated in a scenario with a high N fertilization rate. The findings of this study suggest that adequate pruning can reduce the negative effect of shade, and leaf litter recycling can compensate yield loss in some years but only in low intensity farming systems.

Chapter 4 presents the comparisons of the effects of trees on the performance of hybrids and open pollinated maize varieties (OPVs) in agroforestry systems of equatorial savannah of Rwanda and Ethiopia. In this study, performance of four maize hybrids and four OPVs was compared in sole crop and under mature *Grevillea robusta* and *Senna spectabilis* in Bugesera, Rwanda and under *Acacia tortilis* in Meki, Ethiopia. In Bugesera, the grain dry matter (DM) yield of hybrid maize (2 t DM ha^{-1}) was significantly better than OPVs (1.5 t DM ha^{-1}). Further, the presence of trees significantly reduced maize grain yield and total biomass in both hybrids and OPV crops. However, trees reduced the maize harvest index significantly more in OPVs than in hybrids, suggesting that competition had a larger impact on grain yield for OPVs. In the experiments in Meki, the grain yield of OPVs (2.08 t DM ha^{-1}) and hybrids (2.04 t DM ha^{-1}) did not significantly differ in the open field and the presence of trees also reduced their grain yields in a similar manner. It was concluded that in tropical savannah regions of Rwanda agroforestry farmers could benefit from cropping hybrids, both under trees and in the open field. In contrast, agroforestry farmers in tropical savannah regions of Ethiopia are better off using the current OPV varieties for which they can retain seed instead of purchasing more expensive hybrid seeds.

Chapter 5 presents the effect of conservation agriculture (CA) with trees (CAWT) on crop productivity as compared to conventional tillage (CT) with trees (CTWT) in the equatorial savannah of Rwanda and Ethiopia. The tree species considered in the study were mature *Grevillea robusta* and *Senna spectabilis* in Rwanda and mature *Acacia tortilis* in Ethiopia. Crop emergence was significantly reduced under CAWT compared with CTWT. Maize emergence rates in CAWT and CTWT were respectively 46.9 % and 70.1 %, compared with 74.7 % and 79.8 % in sole maize under CA and CT. Grain yields in CAWT and CTWT plots were respectively 0.37 t DM ha^{-1} and

1.18 t DM ha^{-1} as compared with 1.65 t DM ha^{-1} and 1.95 t DM ha^{-1} in CA and CT plots. It was concluded that CAWT is not a viable alternative to CTWT and that CA is not a viable alternative for CT in the equatorial savannah regions of East Africa. CAWT likely exacerbates tree-crop competition for water and nutrients and consequently reduces crop yields. Thus, CAWT should be strongly discouraged in the equatorial savannah of East Africa.

Chapter 6 presents discussion and some conclusions based on results detailed in Chapters 2 to 5. In this Chapter, the specific research objectives are revisited to offer key results and the implications for future research directions. Overall, the thesis provides substantial information on the effects of trees on crop productivity and possible crop management and tillage options that could improve crop productivity in the agroforestry systems of Rwanda and Ethiopia. It also provides information on the contribution of trees on household income and food security in Rwanda. Mixing trees and crops most often reduced crop yield. Agroforestry systems were both economically and ecologically worth retaining and scaling out to meet household needs and potentially improve food security through food purchase but may reduce food self-sufficiency. Nevertheless, tree management, better crop seeds and conventional tillage will be necessary to limit crop yield reductions in the studied agroforestry systems.

Future research should focus on assessing the impact of agroforestry adoption at larger scales (e.g. regional scales) on food security and food self-sufficiency of farm households, since the production of more on-farm tree products at the expense of crop yields could lead to unbalanced supply of food and tree products with the possible negative impact on food security in a wider area. The productivity of different on-farm tree species (e.g. tree growth and tree products in a given period) will need to be investigated to allow the evaluation and prediction of trade-offs involved in growing trees on-farm. It is suggestable that breeding crops for agroforestry conditions be explored for more shade tolerance and other traits.

Curriculum vitae

Alain Ndoli was born on July 21, 1985 in Gitega, Burundi. He finished his secondary education from Saint Aloys High School in 2003, Rwanda, where he obtained his high school certificate in biology and chemistry. Alain has obtained his BSc degree in Soil and Environment Management from the National University of Rwanda in 2010. From April 2010 to July 2010, he got a fellowship from the state department of the United States of America (USA) for a training in leadership and civic engagement at the University of Delaware. In the same period, he pursued a training in English for academics at the advanced level at the same university. In December 2010, he got a Volkswagen foundation fellowship for the Master program on Integrated Soil Fertility Management (ISFM) from Kenyatta University, Kenya. From 2012 to 2013, he has been involved in lecturing and supervising BSc dissertations at both the National University of Rwanda and High Learning Institute of Agriculture and Animal husbandry (ISAE). He was admitted as a PhD student in the Plant Production Systems Group of Wageningen University in 2014 under a fellowship from the International Maize and Wheat Improvement Centre (CIMMYT). His PhD research focused on tree-crop interactions in Rwanda and Ethiopia and the impacts of agroforestry on farm households' food security. Alain Ndoli is gladly married to Vivine Uwera and they are blessed with one daughter and one son. Email: ndolialain@gmail.com

List of Publications

1. Peer reviewed articles in scientific journals

Ndoli, A., Naramabuye, F., Diogo, R. V. C., Buerkert, A., & Nieder, R. (2013). Greenhouse experiments on soybean (Glycine max) growth on Technosol substrates from tantalum mining in Rwanda. *International Journal of Agricultural Science and Research*, *2*(5), 144-152.

Ndoli, A., Baudron, F., Schut, A. G. T, Mukuralinda, A., & Giller, K. E. (2017). Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crops Research*, 213, 1-11.

Ndoli, A., Baudron, F., Schut, A. G. T, Sida, T. S., van Heerwaarden, J., & Giller, K. E. Conservation agriculture with trees amplifies negative effects of reduced tillage on maize crops in East Africa. Submitted to *Field Crops Research*.

Ndoli, A., Baudron, F., Schut, A. G. T, Sida, T. S., van Heerwaarden, J., & Giller, K. E. Do open pollinated maize varieties perform better than hybrids in agroforestry systems? Submitted to *Experimental Agriculture*

2. Proceedings

Ndoli, A., Naramabuye, F., Mochoge, B., and Nieder, R. (2012) Growing Tithonia diversifoliafor for fertility restitution of technosols from coltan mined soils of Gatumba, Rwanda. *Third RUFORUM Biennial Conference* 24 - 28 September 2012, Kampala, Uganda.

Diogo, R. V. C., **Ndoli, A.,** Naramabuye, F., Nieder, R., Rukazambuga, Ntirushwa, D. T., and Buerkert, A. (2013): Nutrient uptake, biomass production and quality of soybean grown on Technosols of the Gatumba mining district, Western Rwanda, using different fertilizer combinations. *Tropentag "Agricultural development within the rural-urban continuum",* October 17–19, 2013, Stuttgart-Hohenheim, Germany.

Nieder, R., Knoblauch, C., Naramabuye, F., and **Ndoli, A**. (2013) Nitrogen mineralization and nitrification in soils of the Gatumba tin-tantalum mining district, Rwanda. *International Nitrogen Conference (N2013),* November 18-22, 2013, Kampala, Uganda.

Nieder, R., Knoblauch, C., Naramabuye, F., and **Ndoli, A**. (2014) Nitrogen Dynamics in soils of Central African Smallholder Farms. *18th Nitrogen Workshop,* June 30 to July 05, 2014, Lisbon, Portugal.

PE&RC PhD Education Certificate

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)

Review of literature (6 ECTS)

- Agroforestry – a compulsory pathway to meet food and fuelwood demand in East Africa?

Writing of project proposal (4.5 ECTS)

- Direct effects of trees on crop growth and drivers of tree adoption in smallholder farms

Post-graduate courses (5.7 ECTS)

- Farming systems and rural livelihoods: vulnerability and adaptation; PE&RC, WASS and WIAS (2013)
- Geostatistics; PE&RC, SENSE (2015)
- Generalized linear models; PE&RC, SENSE (2017)
- Generalized linear mixed models; PE&RC, SENSE (2017)

Laboratory training and working visits (4.5 ECTS)

- Working visit: training on data analysis; CIMMYT, Ethiopia (2015)
- Training on APSIM 7.8 and APSIM-X with agroforestry functionalities; ICRAF and SCIRO (2015)

Deficiency, refresh, brush-up courses (9 ECTS)

- Systems analysis, simulation and systems management; PE&RC (2014)
- Agroforestry; PE&RC (2014)

Competence strengthening / skills courses (1.8 ECTS)

- Training on project monitoring and evaluation in the framework of famer managed natural regeneration project, Kisumu (Kenya); World Vision and ICRAF (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Weekend for PhD candidates in their first year (2014)
- PE&RC Weekend for PhD candidates in their middle year (2015)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- Discussion group: Plant-Soil Interactions (2014, 2015)
- Project workshop "taking to scale tree based ecosystems approach in Rwanda"; presentation title: agroforestry scaling up pathways in Rwanda; ICRAF in Rwanda (2015)
- Seminar on taking to scale tree based ecosystems approach in Rwanda; ICRAF in Rwanda (2016)
- The 4th meeting of the National Technical Advisory Committee of the Landscape Approach to Forest Restoration and Conservation project (LAFREC); presentation: tools for agroforestry monitoring and evaluation; Rwanda Environment Management Authority (REMA) (2017)

- Conference: presentation title: products and services derived from on-farm trees; ICRAF-Rwanda in Gatsibo district (2017)

International symposia, workshops and conferences (3.9 ECTS)

- Meeting on the elaboration of "Agroforestry guidance tool for Rwanda"; presentation: characteristics of land use systems of Rwanda (2014)
- Famer Managed Natural Regeneration regional workshop in Kigali; presentation title: agroforestry provides an ideal land use practice for smallholder farmers in East Africa; World Vision (2015)
- Conference: presentation theme: tree-crop interactions in sub-humid region of Rwanda; World Agroforestry Centre (ICRAF-Rwanda) and Commonwealth Scientific and Industrial Research Organization (CSIRO) (2017)
- Forest Landscape Investment Forum (FLIF); poster presentation: investment opportunities in tree shade coffee for sustainable benefit; FAO (2017)

Supervision of a MSc student (3 ECTS)

- Miss. Elpida Theodosiadou: the SAFERNAC model: evaluation, calibration and application in Rwandan coffee farms

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