Agroforestry systems with trees for biomass production in western Kenya

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Cover: Farmers’ fieldday at Ebukanga research site, Vihiga county in western Kenya. Improved fallow experiment with *Sesbania sesban* (photo: Hans Sjögren)

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Abstract

Low agricultural production and a decline in fuelwood resources are serious constraints for subsistence smallholder farmers in western Kenya in the sub-Saharan African region. Furthermore, low soil fertility and general environmental degradation has contributed to the build-up of the parasitic weed *Striga hermonthica.* Improved cropping systems have to be introduced to address the interrelated problems of declining soil fertility and *Striga* infestation. Two studies were performed in the highlands of western Kenya, one with improved fallows with *Sesbania sesban*, and one with hedgerow intercropping. Farmers can use *Sesbania* not only for soil improvement, but also for fuelwood, poles and fodder. Maize (*Zea mays* L.) yields and levels of *Striga* infestation on farm land were assessed after improved fallows with leguminous tree/shrub *Sesbania sesban*. Six experimental treatments were arranged in a phased entry, and randomized complete block design. The treatments were 6 and 18 month improved fallow, 6 and 18 month natural fallow consisting of regrowth of natural vegetation without cultivation, continuous maize cropping with and without fertilizer application. Results showed that improved fallows increased maize yield relative to continuous unfertilized maize. The results also indicated that a new rotation of *Sesbania* could be recommended after 2-3 seasons to improve maize production. Short-duration natural fallows were ineffective. The 6 and 18 month improved fallow produced 21 t ha^{-1} and 61 t ha^{-1} *Sesbania* biomass, respectively. The high production of *Sesbania* biomass was an added benefit to this type of improved fallow systems. *Striga* plant populations were not significantly affected. Effects of hedgerow intercropping on maize yields was assessed in a farmer-participatory trial. Results showed that farmers established dense hedgerows, but annual yields of hedgerow pruning of *Leucaena leucocephala* and *Calliandra calothyrsus* were low compared to potentials in the region. There were no significant differences in maize yields, but reduced slopes significantly from 7.2% to 4.5% between alleys. The results showed that improved fallow systems can produce both increased maize yields and wood biomass.

Keywords: agroforestry; crop yield; improved fallow; on-farm research, residual effect; *Sesbania sesban, Striga hermonthica*

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Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Sjögren, H., Shepherd, K.D., Karlsson, A. 2010. Effects of improved fallow with *Sesbania sesban* on maize productivity and *Striga hermonthica* infestation in western Kenya. *Journal of Forestry Research* 21: 379-386.

II Sjögren, H., Savadogo, P., Shepherd, K.D., Karlsson, A. 2015. Growth of *Sesbania sesban* and natural weed in an improved fallow system in western Kenya. (Manuscript)

III Shepherd, K.D., Ndufa, J.K. Ohlsson, E., Sjögren, H., Swinkels, R.A. 1997. Adoption potential of hedgerow intercropping in maize-based cropping systems in the highlands of western Kenya. I. Background and agronomic evaluation. *Experimental Agriculture* 33:197-209.

Papers I and III are reproduced with the permission of the publishers.

The contribution of Hans Sjögren to the papers included in this thesis was as follows:

I Planned most of the study. Carried out most of the data compilation and evaluation and wrote the major part of the manuscript.

II Planned most of the study. Carried out all data compilation and evaluation and wrote the major part of the manuscript.

III Participated in planning of the study as well as with data compilation, evaluation, and writing of the manuscript.

1 Introduction

1.1 Background

Close to 900 million people in the world were undernourished in 2010, the majority living in developing countries and are dependent on agriculture for their livelihoods. (Ahmed *et al.*, 2007; FAO 2012). In order to meet the global demand for food until 2050, agricultural production must increase by 70–100% and most of this will have to come from smallholder farms (FAO 2011). However, in Sub-Saharan Africa (SSA) agricultural productivity have been stagnant for many decades and production increases have been due to expanded areas under cultivation (Conway 2012). In Vihiga County, Kenya, the county where most of the field sites of this thesis are situated, the human population has doubled in the last three decades. Simultaneously, the area under agriculture has increased 27% and per capita crop production has been reduced by 28% indicating a higher dependency on off-farm activities for small-holder farmers. Maize crop productivity lingers around 1 ton/ha in the county (Mutoko *et al.*, 2014). A consequence of continuous agriculture without replenishment of organic material and nutrients is degradation of cultivated soils which presents a big challenge for sustainable crop production in smallholder farming systems of sub-Saharan Africa (Scherr, 2000; Muchena *et al.*, 2005). Since the 1980s Kenya has experienced a persistent decline in agricultural growth leading to low crop productivity, food shortages, and rising poverty levels (Scholes *et al.*, 1994). This has been attributed to low inherent soil fertility combined with inappropriate soil management practices (Sanchez *et al.*, 1997).

Despite high yield potential, continuous cropping with low levels of nutrient input has led to declining soil fertility and a high prevalence of related crop pests and diseases, resulting in low crop yields in the east African highlands (Buresh and Calhoun, 1997). The effects of soil fertility degradation do not only have impact on agricultural production. It also leads to a number of secondary problems: reduced vegetation cover, increased conversion of natural habitats, decreased water quality, increased risk from pests and diseases because of lowered biological control capacity, increased risk to human health for the same reason, and increased risks for landslides and floods etc. (Young, 1997).

Agroforestry is one of the potential options to increase yields, productivity, food security, and resilience. The role of agroforestry in improving and maintaining soil productivity and sustainability is well documented (Shibu 2009), as are the positive effects on nitrogen in the soils in the tropics (e.g. Nair and Latt, 1997; Young, 1997; Buck *et al.*, 1998; Schroth and Sinclair, 2003). and water infiltration into the soil (Nyamadzawo *et al.*, 2008). Globally the number of people practicing agroforestry is estimated at 1.2 billion (Dawson *et al.*, 2013).

1.2 Agroforestry

1.2.1 Concept and principles

Agroforestry can be described as a land use system that combines trees /shrubs and/or agricultural plants and/or animals on the same land area. There have been a number of attempts to define what agroforestry is. One of the principal definitions of agroforestry was proposed by Lundgren and Raintree (1982): "Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement, temporal sequence or combination of both. In agroforestry systems there are both ecological and economical interactions between the different components". Another definition suggested by Leakey (1996) is; "Agroforestry is a dynamic, ecologically based, natural resources management system, that through the integration of trees in farmland and rangeland, diversifies and sustains production for increased social, economic and environmental benefits". A structural classification of agroforestry into six simple categories is: crops under tree cover, agroforests, agroforestry in a linear arrangement, animal agroforestry, sequential agroforestry and minor agroforestry techniques (Torquebiau, 2000). Although an ancient practice, trees in farming systems began to gain more attention from institutions during the 1970s and 1980s, with the beginning of studies on "agroforestry systems" (Nair, 1993).

1.2.2 Approaches to agroforestry

Two agroforestry technologies used in east Africa, improved fallow and hedgerow intercropping (alley cropping), were the focus of this thesis work.

An improved fallow is a rotational system that uses preferred tree species as fallow species, as opposed to colonization by natural vegetation, in rotation with cultivated crops as in traditional shifting cultivation (Young, 1997). Improved fallows consist of deliberately planted species, usually legumes, with the primary purpose of improving soil fertility as part of a crop–fallow rotation (Young, 1997; Sanchez 1999). “Managed fallows” is a term that is also used in the literature to mean, e.g. improved fallows (Young, 1997). This is in contrast to “unmanaged fallow” that could mean e.g. natural weed fallow. In a meta-analysis of e.g. different agroforestry methodologies Silesh *et al.* (2008) showed that improved fallows with non-coppicing legume trees (e.g. *Sesbania sesban*) showed that improved maize yields with around 30-50% as compared to continuous maize cropping for 1-3 seasons after the fallow.

Hedgerow intercropping is a method of planting rows of trees combined with rows of agricultural crops (Young, 1997). Also here leguminous nitrogen fixing species may be used, and after pruning the obtained biomass can be incorporated in the soil to improve soil fertility (Mutegi *et al*., 2008). Hedges and vegetative barriers can also offer alternatives to control erosion, conserve soil and water resources and additionally provide fodder for livestock (Angima *et al.,* 2002; Guto *et al*., 2011).

These methods aim to improve soil fertility and thereby crop production, as with much of the agroforestry research did in the 1990’s. The hedgerow intercropping take place at the same time as crop production, whilst the improved fallow is sequential. In improved fallows substantial improvements are expected in the later part of the sequence at the cost of losing out some crop harvest during the fallow period. Improved fallows would give added benefits in the form of e.g. fodder and fuel wood production.

1.2.3 Tree-soil relations

The potential contribution of trees to soil improvement is one of the major assets of agroforestry. Some evidence on the effects of trees on soils comes from comparing soil properties under canopy of individual trees with those in the surrounds without tree cover (Young 1997). For *Faideherbia albida*, cases of increases in organic matter and nitrogen under canopy are known together with increased water-holding capacity. In many land use systems in the semi-arid regions it is common to find higher soil organic matter and nutrient content under tree canopy than in adjacent open land. The enhancement of soil fertility by trees is conspicuous in studies which compare productivity of crop grown on soils formed under tree canopies and on control soils in open sites. For instance,Verinumbe (1987) found that maize and sorghum produce higher dry matter on soils collected in tree plantation than on ordinary field soil. High crop yield were obtained on soil under *Azadiracta indica* followed by *Prosopis jubiliflora* and *Eucalyptus camaldulensis* (Boffa, 1999). The process by which trees improve soil fertility in agroforestry systems range between proven and quantitatively demonstrated effects at one extreme to plausible but unproven hypotheses. Garrity *et al.* (2010) exemplifies this by long term intercropping, i.e. cropping under the canopies of trees by *Fadherbia albida*, an traditional method of the Parklands in West Africa now intensified and spread over large areas of Eastern and Western Africa, and by shorter term tree species intercropped in crop fields, e.g. *Sesbania sesban*, *Tephrosia candida* and *Gliricidia sepium*. Many of those processes are summarized in Table 1.

Table 1. *Processes by which trees maintain or improve soil*

Processes that improve additions to the soil
• Maintenance or increase of soil organic matter through carbon fixation in photosynthesis and its transfer via litter and root decay • Nitrogen fixation by some leguminous and few non-leguminous trees • Nutrient uptake: the taking up of nutrients released by rock weathering in deeper layers of the soil • Atmospheric input: the provision by trees of favorable conditions for input of nutrients by rainfall and dust, including via throughfall and stemflow • Exudation of growth-promoting substances by the rhizosphere
Processes which reduce losses from the soil
• Protection from erosion and thereby from loss of organic matter and nutrients • Nutrient retrieval: trapping and recycling through the action of mycorrhizal systems associated with tree roots and through root exudation • Reduction of the rate of organic matter decomposition by shading
Processes which affect soil physical conditions
• Maintenance or improvement of soil physical properties (structure, porosity, moisture retention capacity or permeability) through a combination of maintenance of organic matter and effects of roots • Breaking up of compact or indurated layers by roots • Modification of extremes of soil temperature through a combination of shading by canopy and litter cover
Processes which affect soil chemical conditions
• Reduction of acidity, through addition of bases in tree litter • Reduction of salinity or sodicity
Soil biological processes and effects
• Production of a range of different qualities of plant litter through supply of mixture of woody and herbaceous material, including root residues • Timing of nutrient release: the potential to control litter decay through selection of tree species and management of pruning and thereby to synchronize nutrient release from litter decay with requirements of plants for nutrient uptake • Effects upon soil fauna • Transfer of assimilate between roots systems

1.2.4 Parasitic weed

One of the species that often invade maize based farming systems in east Africa is *Striga hermonthica* (Del) Benth (Figure 1). It is a prevalent parasitic weed of maize and other plants including sorghum, millet, rice and sugarcane (Parker and Riches, 1993; Berner *et al.*, 2003; Beed *et al.*, 2007) and constitutes one of the most important biotic constraints to the production of food crops for small-scale farmers in sub-Saharan Africa (Scholes and Malcolm, 2008; Kiwia *et al.*, 2009). This parasitic weed can cause crop losses of 30-90% (van Ast *et al.*, 2005; Khan *et al.*, 2008), mainly under low soil fertility and drought conditions (Stringer *et al.*, 2009, Kamara *et al.*, 2012). In Kenya, *Striga hermonthica* was estimated to infest about 75 000 ha of maize crop in the 1990s (Hassan *et al.*, 1995) and the rate of infestation, both in severity and spread, has been increasing over the years as depletion in soil fertility in smallholders' farms continues and is now the dominant parasitic weed in western Kenya, especially in areas such as Busia, Homa bay, Siaya and Vihiga counties (Khan *et al.*, 2008; Jamil, 2012; Avedi, 2013).

Figure 1. Striga hermonthica in a maize field at Ebukanga research site (Photo: Hans Sjögren).

The control of *Striga hermonthica* is difficult to achieve because of its high fecundity (Andrianjaka *et al.*, 2007), and asynchronous seed germination (Worsham and Egley, 1990). Furthermore, its roots grow into the crop roots and use the plants nutrients. Therefore, management of *Striga hermonthica* infestation needs an integrated approach including host plant resistance, management practices, and chemical and biological treatment (Andrianjaka *et al.*, 2007). Improved fallow systems, which involve the use of perennial legumes, are receiving increased research attention as a promising method for resource-poor farming communities to combat *Striga* (Pisanelli *et al.*, 2008).

1.3 Adoption of agroforestry

A major constraint to increasing crop production in East Africa is poor fertility status of the soil. In order to address this problem, improved fallow has been introduced as a sustainable option to replenish soil fertility within the shortest possible time (Kwesiga et al., 1999). Improved fallow involves planting of fast growing plant species that are (usually) nitrogen-fixing, produce easily decomposable biomass, compatible with cereal crops in rotation and are adapted to the climatic and edaphic conditions of the region (Kwesiga and Coe, 1994). The major species that have been found to be suitable for improved fallows are *Sesbania sesban* (L.) Merr., *Gliricidia sepium* (Jacq.)Walp., *Tephrosia vogelii* Hook. f. and *Cajanus cajan* (L.) Millsp. Farmers have been testing the technology and a number of empirical studies have been undertaken over the years to identify the factors influencing farmers' decisions to adopt the technology. In general adoption is a matrix of several hierarchies of different factors including household-specific characteristics, community-level factors, institutional arrangements and policies (Place and Deewes, 1999; Ajayi *et al*., 2003). Regarding improved fallow, it appears that lack of farmer awareness of the technology, inability of farmers to wait for two years before obtaining direct benefits from the technology were the major constraints to planting improved fallows (Matata et al., 2010). Farmer training through workshops and seminars, enforcement of village by-laws regarding animal grazing, and facilitation of farmers access to credit are being found as the major approaches to enhance the adoption of improved fallow technology (Matata et al., 2010). The extent of public agricultural extension services is declining (Kiptot and Franzel (2014). Farmers that have received some training may contribute to overcome part of this shortcoming by training other farmers. This volunteerism would be motivated by that the "teacher-farmers" would gain new knowledge and increased social status and respect by disseminating this knowledge to other farmers (Kiptot and Franzel, 2014).

1.4 Relevance of the studies

A constraint for subsistence smallholder farmers in western Kenya is low agriculture productivity due to declining soil fertility. Low soil fertility and overall environmental degradation has contributed to the build-up of parasitic weed infestation of *Striga hermontica*. Wood shortage is very evident in western Kenya, one of the most densely populated areas in Africa (Jama *et al.*, 2008). Farmlands in western Kenya are generally small, varying between 0.5 and 2.0 ha with a median of 1.2 ha, due to high population densities and the subdivision of farms for inheritance (David and Swinkels, 1994). When farmers cannot grow maize due to nutrient depletion in the soil and cannot afford fertilizer they leave the land for natural weed fallow (Bationo, 2004). However, the natural regeneration of vegetation during traditional fallow becomes insufficient to restore soil fertility as the duration of fallowing decrease. Despite of the small holding, short duration unmanaged fallows are common at Bunyore county in western Kenya (Swinkels *et al.*, 1997). As an example, a survey in western Kenya showed that 52% of the farmers periodically fallowed 10–50% of their total farmland at a time (Swinkels *et al.*, 1997). The lengths of the fallows varied between one growing season (24% of fallowers), one year (35%) and two or more years (42%).

2 Objectives

The overall objectives of the thesis was to assess two agroforestry technologies, improved fallow and hedgerow intercropping, for increased maize yields and biomass production in small holder subsistence farmers land in the highlands of western Kenya. The nitrogen fixing tree species *Sesbania sesban* was used in the improved fallow system, and *Leucaena leucocephala, Leucaena diversifolia, Calliandra calothyrsus* or *Gliricidia sepium* in the hedgerow intercropping. In study 1 the objective was to evaluate the effects of improved fallows on maize yields, and the prevalence of *Striga hermonthica* plants and soil seed bank, compared to continuous maize production. The objectives of study 2 were to determine *Sesbania sesban* tree growth and biomass production. In study 3 the objective was to assess the maize yields and biomass production in hedgerow intercropping, in an agroforestry system with farmer-participatory trials.

3 Material and Methods

3.1 Study sites

Study 1 and 2 was located at Ebukanga (00°06’N, 34°34’E) in Vihiga county (Figure 2). The study area in study 3 was located in the highlands of western Kenya in part of Siaya, Kisumu and Vihiga counties between lat 0°05'S and 0°10'N, and long 34°31'E to 34°40'E (Figure 2). These areas (study 1-3) have high agricultural potential but the land has become nutrient-depleted (Shepherd *et al.*, 1996b). The cropping seasons is bimodal: the long rains (LR) from March to July and the short rains (SR) can occur from August/September to November/January. The soils in the landscape are dominated by Acrisols, Ferralsols and Nitisols (Shepherd *et al.*, 1992). Annual precipitation is 1374-1730 mm. (Sjögren *et al.*, 2010).

Figure 2. Research area in western Kenya located within Vihiga, Siaya and Kisumu counties (Picture: Google Earth 2015).

3.2 Improved fallow

The experimental design in study 1 and 2 was a randomized complete block design with four replicates. Six treatments were applied; six months tree growth with *Sesbania* fallow (S6); 18 months tree growth with *Sesbania* fallow (S18); six months natural regrowth of vegetation fallow without cultivation (N6); 18 months natural regrowth of vegetation fallow without cultivation (N18); continuous maize cropping (M), and continuous maize cropping with fertilizer (60 kg P_2O_5 + 60 kg N ha^{-1}) application (MF) (Figure 3).

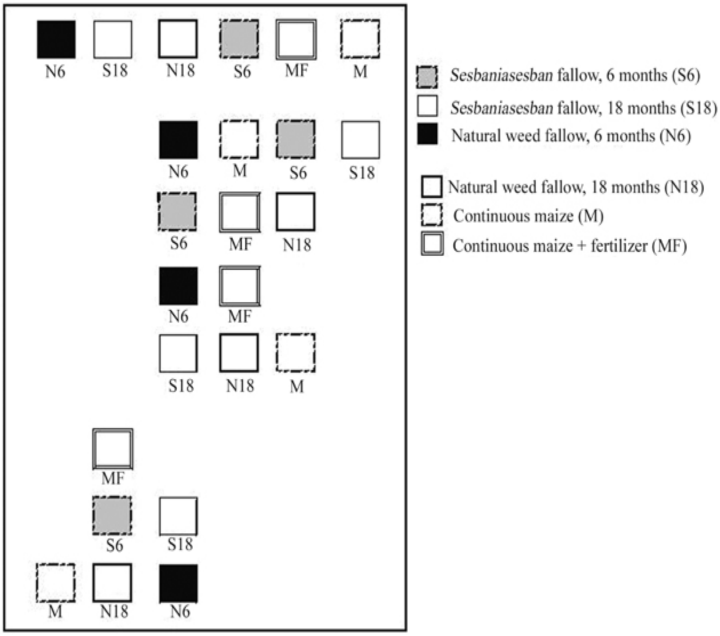

Figure 3. Layout of the experimental design – a randomised complete block design with four replicates (blocks).

The site was previously cropped with maize. The site was chosen to be P-sufficient for maize, but degraded from continuous cropping and with a high prevalence of *Striga hermonthica*. A phased entry design was applied to allow comparisons between crop yields within the same year after different lengths of fallows (Table 2).

Table 2. *Experimental treatments at each growing season during and after the fallow period*

Treatments	1994		1995		1996		1997		1998
	LR	SR	LR	SR	LR	SR	LR	SR	LR
S6	M	M	MS6	S6	M	M	M	M	M
S18	MS18	S18	S18	S18	M	M	M	M	M
N6	M	M	M	N6	M	M	M	M	M
N18	M	N18	N18	N18	M	M	M	M	M
M	M	M	M	M	M	M	M	M	M
MF	MF	MF	MF	MF	MF	MF	MF	MF	MF

LR=long rains period (March-July), SR=short rains period (August/September-January), S6=six months tree growth with *Sesbania sesban* fallow, S18=18 months tree growth with *Sesbania*, N6=six months natural re-growth of vegetation fallow without cultivation, N18=18 months natural re-growth of vegetation fallow without cultivation, M=continuous maize cropping, and MF=continuous maize cropping with fertilizer (60 kg P_2O_5 + 60 kg N ha^{-1}) application, MS=Maize and *Sesbania* intercropped

Gross plot size was 10 m × 10 m and the net plot was 6 m × 7 m. Borders around the gross plots of 1.5 m were used to allow trenching. Border trenching was done down to 1 m below the soil surface to minimize root competition between plots. The experiment was laid out down a slope and blocked according to slope. The plots were laid out to minimize within plot variation, on the basis of variation in previous maize growth and assessment of soil characteristics.

The experimental area was uniformly cropped with unfertilized maize during the growing season (short rain in 1993) preceding the start of the experiment to facilitate subdivision into blocks. Three maize seeds (Kenya Seed Company, hybrid 511 Zea mays L.) were sown at 0.75 m × 0.25 m spacing and thinned to one plant per hole after emergence which is the agricultural extension service recommendation. The above-ground maize biomass and weeds were removed from the plots at each harvest. The plots were kept weed-free throughout the growing seasons by hoe and two hand weeding operations. Weeding of S. hermonthica was carried out as part of the regular weeding practiced by farmer. Predominant weeds were Tephrosia holstii Taub. Vernonia lasiopus O. Hoffm., and Digitaria velutina P. Beauv.

At maturity, maize was harvested and the fresh weight of stover and cobs were recorded in the entire plot. Cobs were separated into core and grain. Subsamples of cobs and stover were taken from each plot and air-dried. At the end, maize grain yields were expressed on 15% water content. During each cropping season, S. hermonthica assessment was done once. Aboveground S. hermonthica biomass was collected within each plot from five randomly selected spots (0.75 m × 1.33 m) at the end of each cropping season. The location of these spots was chosen systematically to avoid selecting the same location in consecutive years. Weeds were harvested manually by cutting at the base and mixed together. Fresh weight of the weed mixture was taken and moisture content was determined on a subsample of 300 g oven-dried at 70°C until constant weight. Within each net plot of 6 m × 7 m, we also recorded the number of individuals of S. hermonthica a few weeks before the harvest. S. hermonthica plants were not uprooted but left to seed until maize was harvested. Further, quantification of seed bank dynamics of S. hermonthica was undertaken in all plots. Core samples were collected from nine spots at the centre of each plot, bulked and then placed in bags. These samples were air-dried and grounded to pass through a 2- mm sieve. From the sieved a sample of 500 g was separated to determine the S. hermonthica seed bank using the elutriation and column separation method (Ndung'u et al. 1993).

The Sesbania fallows were established through direct sowing together with maize in the long rains of 1994 and 1995 to allow establishment and survival of the trees. After soaking seeds overnight, Sesbania seeds were sown at a rate of five seeds per hole at 0.75 m × 0.25 m spacing in the middle of the maize inter-rows. The Sesbania was thinned to one plant per hole when 15 cm high. The Sesbania was inoculated at the time of sowing using compatible Rhizobium inoculants from Nairobi University. Maize and Sesbania were growing together for four months before the maize was harvested and the actual fallow period started. In the 6- and 18-month natural fallows we let the natural weed vegetation grow without interference. All the Sesbania and natural weed fallows were harvested in January 1996 and then five successive maize crops were grown.

Tree height (cm), root collar diameter (DRC, mm, just 10 cm above ground) and diameter (mm) at breast height (DBH) 1.3 m above ground) were measured on all the Sesbania trees in the net plot after each growing season. Height was measured with a telescopic measuring stick and diameters with a caliper. Three levels of tree injuries (undamaged, damaged, and dead) were determined. Damaged trees were either broken or showing a dead top. At harvest in January 1996 each tree in the net plot was cut down with a hand saw and put on a plastic sheet on the ground. Stem, branches, twigs, leaves and seeds were separated and fresh weight (g), for all fractions, was measured for all trees with a field scale (in gram). Samples from trees of different size were used to take nine bulk samples (300 g) per fraction and net plot to be sent to

Maseno lab, western Kenya to be oven-dried at 70°C until constant weight to determine dry weight (g).

At the establishment of the experiment pre-trial soil physical and chemical properties were assessed (Table 3). Soil sampling was done after tillage, when the soil had settled after early rain in the SR and LR season, by taking a composite of nine samples per plot at depths 0–15, 15–30, 30–50, 50–100, 100–150 and 150–200 cm. The 0–15 cm samples were taken with a core sampler with an internal diameter of 2.5 cm and the samples from below 15 cm were taken using a 5.28 cm diameter auger. The soil analyses were conducted by the ICRAF soil laboratory using standard methods, as reported by Shepherd *et al*. (1996a) and Shepherd and Walsh (2002).

Soil pH was determined at a soil:water ratio of 1:2.5 by volume. Soil organic C was analyzed using dichromate oxidation with external heat (Nelson and Sommers, 1982). Inorganic P was determined by extraction with 0.5 M sodium bicarbonate (Olsen *et al*., 1954). Bicarbonate- extractable organic P was estimated as the difference between total P in the bicarbonate extract, determined after digestion with ammonium persulphate for 1 h in an autoclave at 0.1 MPa and 121^{o} C and inorganic P in the bicarbonate extract. Exchangeable acidity, Ca, and Mg were determined in 1M KC1 extracts using a 1:10 soil:extract ratio. Exchangeable K was determined in 0.5 M sodium bicarbonate plus 0.01 M ethylene diaminetetraacetic acid extracts using a 1:10 soil:extract ratio.

Table 3. *Soil properties at the start of the experiment in 1994 at Ebukanga experimental site, Vihiga county, western Kenya*

Soil dept (cm)	Ph in water	Ca a)	Mg b)	K c)	P d)	Total organic C	Sand %	Silt %	Clay %
0–15	6.2	8.0	1.8	0.65	13	1.81	35	30	35
15–30	6.3	7.8	1.7	0.45	18	1.43	34	21	45
30–50	6.4	6.4	1.5	0.37	10	0.96	30	16	54
50–100	6.6	4.7	1.4	0.49	6	0.64	28	18	54
100–150	6.4	3.6	0.9	0.57	3	0.41	34	18	48

a) Exchangeable Ca cmole kg^{-1}, b) Exchangeable Mg cmole kg^{-1}, c) Exchangeable K cmole kg^{-1}, d) Extractable P kg^{-1}.

Fertilizer test strips (1 m^2), outside the plots, were laid out at the site prior to the experiment to determine maize response to fertilizer. Land preparation prior to the experiment consisted of slashing of the maize stover and weeds from the previous crop and removal of all organic residues except on the plots where natural weed fallow treatment was involved. Tillage was done using manual labour to limit biomass and *Striga hermonthica* seed carryover between plots.

3.3 Hedgerow intercropping

The experiment with hedgerow intercropping started out with 56 farmers from 16 farmer groups. The experimental design was a control plot without hedges and an adjacent plot with hedges on each farm and the groups were selected to represent the main variation in soils and ethnic groups in the area. The planted tree species were *Leucaena leucocephala*, *Leucaena diversifolia*, *Calliandra calothyrsus* or *Gliricidia sepium*, planted from inoculated seedlings, with 0.30 m between trees in contour-aligned rows of about 4 m apart. Maize crops were planted close to the trees to minimize crop loss due to trees. On each tree plot, the number of trees planted, the number surviving at six months, and the causes of plant death were recorded. On a subset of 12 farms with *Leucaena spp*. and 12 with *Calliandra calothyrsus*, tree height, basal shoot diameter at one and six months after planting and at the time of the first cut, and tree biomass and nutrient yields at each cut for the first two years after planting were recorded. The cut tree biomass was incorporated into the soil. Tree biomass was measured on four systematically located 2 m lengths of hedge from each plot and N, P, K, Ca and Mg concentrations in leaf, twig and woody stem components were determined on subsamples. The total length of hedge and the plot size were used to calculate tree biomass and nutrient yields per hectare. Crop harvest yields were measured on the whole area of test and control plots from the short rains in 1990 on the farms where annual crops were grown and the trial maintained. Farmer estimates of numbers of green maize cobs harvested earlier in the season were converted to dry grain weight on the basis of average cob weights. Crop plant populations were estimated from quadrat counts, and the incidence of pests, weeds, diseases, and other causes of crop damage were scored on each plot. Data on the use of labour were collected for each plot (Swinkels and Franzel, 1997). Plot sizes were varied seasonally by farmers and therefore they were measured each season. Soil properties were determined in each plot (Shepherd *et al.*, 1996b). Average slopes were measured in degrees on all farms using a clinometer. On eight of the steeper farms, the average slope of the hedgerow plot and the slope within each alley were determined in 1994 using a surveying level. Daily rainfall was recorded at Maseno Agroforestry Research Centre in the vicinity of the experimental sites.

3.4 Statistics

In the improved fallow study maize and *Striga* data was log transformed and analysis of variance (ANOVA) was performed separately for each parameter using the following model:

$$Y_{ij} = m + B_i + T_j + e_{ij}$$

where Y_{ij} is the response variable, μ is the overall mean, T_j is the effect of the treatment, B_i is the block effect and e_{ij} is the error term. Multiple comparisons were made with Tukey's test to detect differences between treatments at 5% level of significance. All statistical analyses were done using SPSS (2007) software package. For *Sesbania* biomass untransformed data was used in the same model. Statistical analyses were done using MINITAB (2013) software package.

In the hedgerow experiment treatment effects were assessed by ANOVA using farms as randomized blocks. Relationships between the measured variables were also examined graphically and by multiple regression analysis, using Statistical Analysis Systems procedures (SAS, 1990).

4 Results

4.1 Maize production

During the fallow there was no maize production for one season in the 6-month fallows (SR 1995) and for three seasons in the 18-month fallows (SR 1994, LR 1995 and SR 1995). When the *Sesbania* fallow was established and intercropped with maize (LR 1994 (S18) and LR 1995 (S6) (Figure 4) there was a loss in maize production during this season.

Figure 4. Sesbania sesban intercropped with maize during establishment of fallow (Photo: Hans Sjögren).

The loss in maize grain yield compared to continuous unfertilized maize (M) was 16% in S6 and 27% in S18. Throughout the experiment and for all treatments maize yields were lower in the short rain season than in the long rain season.

The first residual season after the fallow (LR 1996) grain yield increased significantly in the 18-month *Sesbania* fallow (239%) and the 6-month *Sesbania* fallow (170%) relative to continuous unfertilized maize plots (Figure 5). Grain production was also significantly higher in the second growing season (SR 1996) in the 18-month *Sesbania* fallow compared to continuous unfertilized maize. In the 6-month fallow the grain yield also tended to be higher than continuous unfertilized maize in the second season (SR 1996) but not statistically significant. To recover the loss in maize grain production during the fallow period one season in the residual period was needed for the 6-month *Sesbania* fallow (LR 1996) and two seasons for the 18 months *Sesbania*. The difference in total net maize yield between the treatments and continuous unfertilized maize over the entire experiment that lasted for nine growing seasons was: N18 -5.1 t ha^{-1}, N6 -1.2 t ha^{-1}, S6 +1.0 t ha^{-1}, S18 +1.5 t ha^{-1}, and MF +7.9 t ha^{-1} (Figure 5). Over six seasons (three fallow seasons + the three following crop seasons), S18 produced 12 ton of maize, i.e. 1.5 ton more than continuous maize. The S6 treatment produced 6.4 tons of maize over three seasons (fallow season + the two following crop seasons) as compared to 4.3 ton in the continuous maize without fertilizer for the same period (three cropping seasons).

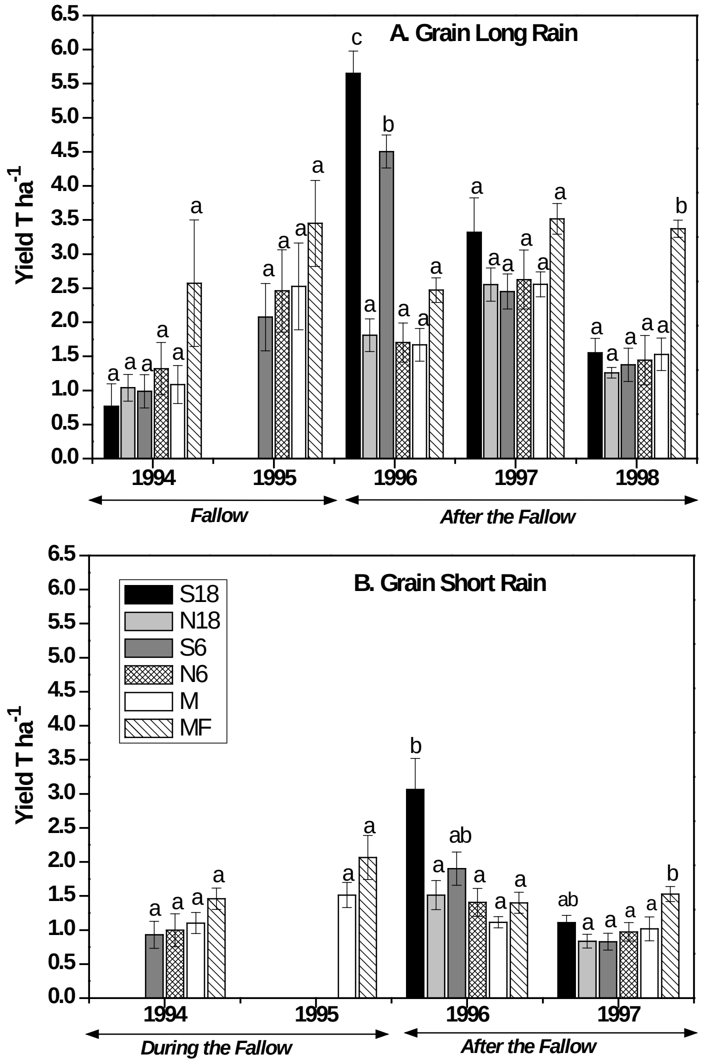

Figure 5. Yield of maize grain during the fallow (kg ha^{-1}) and the experimental period at Ebukanga, Vihiga county, western Kenya. Within the same year mean (±SE) with different letter are statistically different based on Tukey's test.

4.2 Prevalence of *Striga hermonthica*

No statistically significant difference was observed between the treatments. After the first cropping season (LR 1994) in SR 1994 the number of *Striga* plants was reduced in all treatments. *Striga* plant populations decreased in continuous maize between the first season (mean = 428 × 10^3 ha^{-1}) and second season (mean = 61 × 10^3 ha^{-1}). In the first residual cropping season (LR 1996) following the fallow period the number of *Striga* plants was statistically significantly higher in the N18 as compared with the other treatments. Lowest *Striga* plant numbers was at S18 first season after the fallow.

Striga hermonthica seed density in the soil at the beginning of the fallow period was 155 ± 16 seeds per kg of soil. Most of the *Striga* seeds in all treatment plots were found in the upper 0–15 cm of the soil profile. The total mean number of seeds found in all treatment plots at 0-30 cm soil depths levels were not significantly different from each other in any of the seasons. There was a decline in number of seeds per kg with depth at the end of both short and long rainy (LR) season for all treatments except for MF in the SR 1995 and SR 1996 and for M in the SR of 1996.

4.3 *Sesbania sesban* growth and biomass production

At harvest of the 18 month *Sesbania* fallow the total tree density (undamaged, damaged and dead trees) was 13 988 trees /ha. In the 6 months *Sesbania* fallow the tree mean density of 43 393 trees/ha. Tree density in the 18 month *Sesbania* fallow after 6 month was 22 440 trees/ha. The number of dead trees at harvest was higher in the 18 months *Sesbania* fallow compared with 6 months *Sesbania* fallow (Figure 6).

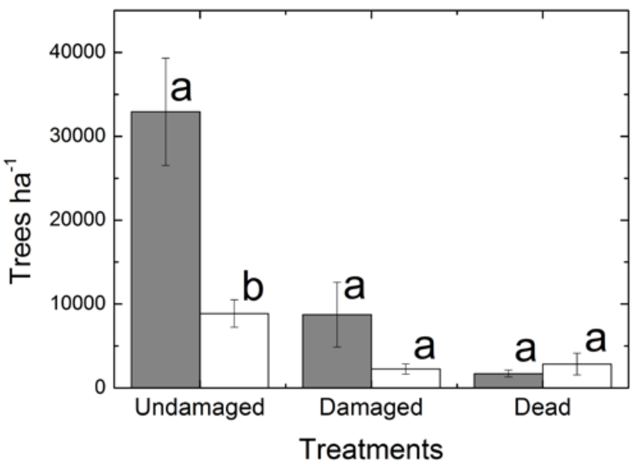

Figure 6. Sesbania sesban tree density ha^{-1} at harvest after 6 (6S) and 18 (18S) month fallow. Filled bars 6S and unfilled bars 18S. Different letters are statistically significant.

Mean tree height for the undamaged trees at harvest was 7.9 m and 4.4 m in the 18 and 6 month *Sesbania* fallow, respectively (Figure 7). Tree height after 6 months in the 18 month *Sesbania* fallow was 5.0 m. Breast height (1.3 m) diameter for the undamaged trees was 54 and 28 mm at harvest in the 18 and 6 months *Sesbania* fallow, respectively. The 18 month *Sesbania* fallow produced three times as much biomass compared to the 6 months fallow, i.e. 61 respective 21 t ha^{-1} (dry weight) (Table 4). Out of the total biomass ca 80% consisted of stem biomass in the 18 and 6 month *Sesbania* fallow respectively.

Table 4. *Sesbania sesban dry weight biomass production (t ha^{-1}), for whole tree, stem, branches, twigs, leafs and seeds) after six (S6) and 18 (S18) month of growth. Different letters between rows (fallow durations) in respective column show statistically significant differences based on Tukey's test ($p \leq 0.01$)*

Treatment	Dry weight biomass, ton/ha					
	Whole tree	Stem	Branches	Twigs	Leafs	Seeds
S6	20.7 b	16.4 b	2.4 b	0.2	1.7	0
S18	61.2 a	47.4 a	10.1 a	2.2	1.4	0.1

In the 18 and 6 month *Sesbania* fallow weed (dry weight) production at harvest was 1.1 and 0.5 t ha^{-1}, respectively. The weed biomass production (dry weight) from 18 month natural weed fallow was 2.9 t ha^{-1} and from the 6 month natural weed fallow 2.5 t ha^{-1}.

Figure 7. Sesbania sesban 18 month after establishment (Photo: Hans Sjögren).

4.4 Hedgerow intercropping

The trees used were mainly *Caliandra calothyrsus* and *Leucaena Leucephala*. Farmers made all crop and tree management decisions themselves but also received regular management advice from the project staff. The hedge plots size ranged from 270 to 2 010 m^2. The density within the hedges ranged from 3 660 to 10 040 trees ha^{-1}. Tree density decreased with increasing plot size. Damage from termites on 67% of the farms was the main cause of tree death. Comparing the early tree growth with a similar experiment run by researchers at Maseno Agroforestry Research Center, the growth was 40% higher at the research Center experiment. Due to farmers' free choice control plots consisted of a variety of tree plots, crop plots and natural fallows. This made it difficult to evaluate the effects of the hedgerows on yields. There were no significant differences in mean grain yields between the hedgerow and the control plots in any individual season. The average slopes for the plots in the farms ranged from 1 to 13% with a median of 5.8%. Due to the hedgerows there was a terracing (leveling) effect and the slopes were reduced from 7.2 to 4.5% within the rows of hedges.

5 Discussion

5.1 Hedgerow intercropping

Comparing the early growth rates of trees in the on-farm study with trees of the same provenances in a researcher managed on-station experiment (Maseno Agroforestry Research Center), the growth rate was about 40% lower for the on-farm study. A reason for this could have been that the on-station experiment had better weeding management and applied some fertilizer. It is not an unusual experience when taking on-station studies out to on-farm that the results for e.g. growth rate or biomass production become lower. The lower early growth rates on-farm compared with on-station may be due to competition effects between crops and weeds during early establishment of trees on farms. On the farms the annual amount of biomass returned to the soil ranged from 1.2 to 4.3 t ha^{-1} and was below on-station levels measured over the same growing phase. In other studies in the sub-humid and humid tropics with the same species and management, the yields of biomass returned through pruning were between 4-8 t ha^{-1} (Balasubramanian and Sekayange, 1991; Kang, 1993). Composts, green manure, and biomass from trees and shrubs already growing on farm borders are other potential sources of nutrients for cropped land. In our study, the main effect of the hedges on crops may have been through mulching and green manure. The results indicated that the hedges reduced the slopes.

Hedgerow intercropping as designed in the 1990’s and as used in this study, has never really been adopted in practice by farmers. Reasons to this could be the low (or no) productivity increases, the complexity of the system and/or that it is quite labour demanding. There are however several similar systems where lines of trees in crop fields are used to produce e.g. fuelwood or fodder, to reduce erosion or to act as windbreaks. Improved soil fertility can then be an added benefit (Ong, 1994).

5.2 Prevalence of *Striga hermonthica*

During the first season after the fallows, there was a tendency of lower *Striga hermonthica* emergence where the 6 and 18 month *Sesbania* trees had previously been standing. This may have contributed to the increased maize yield observed relative to continuous unfertilized maize. On the other hand, increased fertility after the fallow could have resulted in the maize being able to more effectively resist *Striga* infection, and resulting in increased maize yield. This interpretation is supported by the observation that there were less *Striga* also in the maize with fertilizer treatment, and is also consistent with other studies that have shown that nitrogen fertilizer decreases *Striga* populations (Odhiambo, 1998).

One of the reasons that S*triga* plant populations decreased in continuous maize cropping could be good weed management compared with farmer management before the experiment.

Legumes can reduce *Striga* infestation as trap crops or due to suppression of emerged *Striga* through the legumes shading effect. Combining legumes with improved weed management could be one strategy to combat *Striga*. The reduction of *Striga* seed bank in the soil can be done by consumption of seeds by insects and earthworms, suicidal germination, stimulation by root exudates and infestation by fungi (van Delft *et al.*, 2000; Oswald and Ransom, 2001). The relative increase in *Striga* following the 18 month natural weed fallow in the study conflicted with the pattern of reduction of *Striga* infection in maize following planted fallows, which is believed to be because of increased mineral N in the topsoil and/or depletion of *Striga* seed during the *Sesbania* fallow phase (Gacheru and Rao, 2005).

Parasitic weeds such as *Striga hermonthica* are difficult to control by conventional methods because of e.g. their fecundity (Andrianjaka *et al.*, 2007). Some difficulties that limit the development of successful control methods are the ability of the parasite to produce a very large number of seeds that may remain viable in the soil for more than 15 years (Pouvreau *et al.*, 2013). A factor to consider when studying *Striga* in a field experiment is the risk that the small seeds get airborne and contaminate neighbouring plots. In the experiment we minimized this risk by doing the weeding before the *Striga* set seed. To minimize the seasonal variations, the experiment had a phased entry design, so that all fallows ended the same season, and comparisons between maize crop yields after different lengths of fallow covered the same time periods. However, different durations of fallow were thus confounded with year to year differences in weather conditions during the fallow period, which may have affected *Sesbania* stand development. Seed germination can e.g. be sensitive to seasonal variations in weather conditions as well as seedbed conditions, e.g. rainfall and soil moisture (Harper, 1977). However, there is nothing in the data that suggest that differences in weather during the fallow period have confounded the results.

5.3 *Sesbania sesban* growth and biomass production

The *Sesbania* trees showed a very high growth potential. The total above-ground biomass production of *Sesbania* in this study, 21 t ha^{-1} after six month and 61 t ha^{-1} after 18 month, was considerably higher than the levels reported in some other studies. Torquebiau and Kwesiga (1996) reported about 18 t ha^{-1} for a 2-year *Sesbania* fallow in eastern Zambia (10 000 trees ha^{-1}, rainfall of 800-1 000 mm year^{-1} and one rainy season per year), and Ståhl *et al.* (2002) reported 31.5 t ha^{-1} after 22 month from a study in eastern Kenya (10 000 trees ha^{-1}, rainfall of 900 mm year^{-1}). However, the difference is probably explained by different site conditions. Better site conditions at the study sites in this study compared with the other studies may be one explanation for the higher mean heights. Niang *et al.* (2002) reported 40 t ha^{-1} after direct seeding and and 47 t ha^{-1} after planting seedlings, 12 month after plantation (ca 27 000 trees ha^{-1}) in a study located in the same area as this study.

When the *Sesbania* grew as fast as in this study, and the tree densities were high within the plots, there was a concern that some of the *Sesbania* roots would find its way to neighboring plots and take water and nutrients from there. This was addressed by only performing measurements in the net plots, and by trenching between all *Sesbania* plots, 30 cm wide and 1 m deep.

In most agroforestry experiments conducted with legume tree/shrubs the net plots are quite small. This creates problems in correctly delineating the plots in relation to the planted trees, and could have affected the calculated hectare figures.

Higher stand densities can increase biomass production initially and in pure even-aged stands, a site can only support a definite number of trees of a given size (Reineke, 1933). When trees continue to grow, self-thinning begins to occur when tree individuals compete for resources (Saville *et al.*, 1997). This was most likely the case in the 18 month fallow where the number of undamaged stems decreased from 22 440 ha^{-1} after six month to 8 870 ha^{-1} after 18 month.

Production of *Sesbania* biomass is a valuable added benefit to this type of improved fallow systems. The farmers can use *Sesbania* for fuelwood, fodder, poles and soil improvements. Agroforestry with trees in e.g. an improved fallow could have a significant impact to reduce wood harvest pressures in surrounding forests and woodlands by sustainably supplying farmers with trees.

5.4 Maize production

The residual benefit of improved fallow with *Sesbania* lasted for one to three cropping seasons which is in agreement with previous results (Kwesiga *et al.*, 1999; Ståhl *et al.*, 2002; Ndufa *et al.*, 2009; Liyama *et al.*, 2014). The favorable residual effect on maize yield can be attributed to a supply of plant available N from decomposing *Sesbania* biomass, increased soil organic matter, improved nutrient and water retention in the soil (Young 1997). The improved fallow system may improve water availability to the following maize crop by reducing runoff and increasing water infiltration, as suggested by Nyamadzawo *et al.* (2008). *Sesbania* can go down with its roots in the sub soil and capture water and nutrients (Hartemink *et al.,* 1996), and may also have contributed to weed suppression, and therefore increased nutrient availability for the maize. Thus, *Sesbania* fallow could offer an option for soil improvement, especially on the fields of subsistence farmers (Kwesiga *et al.*, 1999). Although not statistically significant, continuous maize cropping without fertilizer application was the least productive treatment over all seasons. This was in agreement with previous yield data from the same area (Jama *et al.*, 1998a), and corresponds to the low yields typical of subsistence agriculture in the tropics (Ståhl *et al.*, 2002). Lower yield in the short rainy season may be explained by the lower rainfall (Jama *et al.*, 1998b). Despite the generally higher rainfall in the short rainy season of 1997, the low yield observed could possibly be attributed to the uneven distribution of the rains, which has been suggested to result in severe crop stress (van Lauwe *et al.*, 2002).

A typical maize crop on many nutrient-depleted soils in western Kenya yields less than 1 ton ha^{-1} of grain per season and requires a plant accumulation of less than 40 kg N ha^{-1} (Sanchez, 1976), whereas a 7 t ha^{-1} maize crop requires 200 kg N ha^{-1}. In many areas in sub-Saharan Africa, farmyard manure is the main nutrient source of farmers, but the quantities available on farms are often insufficient to maintain soil fertility (Chivenge *et al.*, 2009).

The total duration of the experiment, nine seasons, was chosen in order to see the longevity of residual effects from the improved fallows. Comparing at the end of the final season the S6 and S18 treatments resulted in 7% and 10% higher total yield compared to the treatment maize without fertilizer, respectively. However, if S 6 was instead compared on a three season rotation basis, i.e. one season of improved fallow followed by two maize crop seasons, the S6 treatment resulted in 49% higher total maize yield compared to unfertilized maize. A similar comparison for the S18 treatment, improved fallow for three seasons followed by three seasons of maize cropping, resulted in 11% higher total maize yield compared to unfertilized maize. This do agree with the results of the meta-analyses by Sileshi *et al.* (2008) that concluded that maximum two crop harvests after the fallow period was recommendable. A simulation of rotational *Sesbania sesban* improved fallows under expected climate change scenarios suggested that *Sesbania* fallows with a minimal addition of inorganic N was the most sustainable and more productive in 2090 than conventional intensified maize agriculture (Folberth *et al.,* 2014).

In spite of the higher total yield, improved fallow systems have not been widely adopted. One explanation could be that poor small-scale farmers cannot afford to lose out on 1-3 crop harvests, even if they know that these harvests will be small compared to harvests after improved fallow. Fuelwood is a substantial output from improved fallow systems, especially in this study with high wood production, but is often of low economic value. Furthermore, fuelwood collection is often the responsibility of women and not seen as a scarce resource by male decision-making farmers. Should the value of fuelwood substantially increase, or some other markets for fallow wood develop, e.g. for small-scale bioenergy production, the use and adoption of improved fallows may increase. Improved soil fertility and higher total crop yield would then be a valuable “added benefit”.

6 Way forward/future research

This study and other improved fallow research follows tree biomass and maize production, and in some cases soil fertility, through one cycle of fallow-crop production. Some effects of the improved fallow could be more long-lived than others and hence the total effects on the second or third rotation of the system might be enhanced or different. However, to find out this, long term research over several improved fallow-crop cycles is needed.

If the value of the fallow product, e.g. in this case fuelwood, should change due to socio-economic changes, the economics and also the adoptability of e.g. improved fallows might dramatically change. If socio-economic contexts change, as they constantly do in rural Africa and elsewhere, agroforestry and agroforestry research needs to be innovative and adoptive *vis-à-vis* socio-economic drivers of change. On-farm trials may be one way to improve farmers' adoption of agroforestry methodologies. However, results from on-farm trials are often confounded by varying socio-economic preferences, conditions, and constraints of different farmers. This could be seen clearly in the hedgerow intercropping study. Still, on-farm trials are important for obtaining farmer feedback, for identifying constraints affecting the technology, and to define realistic conditions.

This may seem contradictory with a need for both long-term and adoptive research. This is however exactly what is needed for agroforestry research, in other words persistence and innovation. And from a researcher perspective; that makes it interesting to pursue.

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