Chakula bila kulima?

Trade-offs concerning soil and water conservation in heterogeneous smallholder farms of Central Kenya

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This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology and Resource Conservation

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Thesis
Submitted in fulfilment of the requirements
for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Friday 15 April 2011
at 11 a.m. in the Aula

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Chakula bila kulima?† - Trade-offs concerning soil and water conservation in heterogeneous smallholder farms of Central Kenya. 136 pages.

Thesis, Wageningen University, Wageningen, NL (2011)

With references, with summaries in Dutch and English

ISBN: 978-90-8585-929-1

† Swahili for: ‘Food without tillage’ or ‘Food without farming’

This thesis is dedicated to my dear wife Pendo Sumai and my Father Joseph Guto who was sick to the point of death towards the end of my study.

ABSTRACT

Soil and water conservation practices need to be tailored to suit the diverse local conditions in smallholder farms. Using a combination of survey methods, field experimentation over several seasons and farm scale analysis, this research explored the targeting of recommended options to field and farm types. Smallholder farmers' in Mbeere and Meru South Districts of Central Kenya acknowledged the occurrence of soil erosion in their farms and understood the water erosion process. Trash lines were common in the low potential Mbeere area for the control of erosion, except for farmers with high resource endowment who instead preferred fanya juu and vegetation barriers. In Meru South, contour farming was popular for different farmers although the preference was for vegetative barriers with multiple benefits. Three field types on a relative scale of soil fertility were identified by the farmers: good, medium and poor. Physical and vegetative measures were more common and well maintained in good fields but rare and neglected in poor fields. Farming on sloping arable fields with no vegetative barriers lead to soil degradation and establishment of vegetative barriers curbed soil erosion. Napier grass barriers were efficient in conserving soil and water but competed with crops for available water. This competition was especially strong with minimum tillage even when the Napier was intensely harvested. Leucaena barriers had a complementary water use pattern with crops across tillage practices but were less efficient for soil and water conservation. Considering economic returns and the soil conserved, leucaena barriers had attractive and less risky economic returns across tillage practices but conserved less soil. Napier barriers with regular tillage presented a win-win scenario for farmers and environmental impacts because of simultaneous attractive economic returns and efficient soil conservation. Cumulative maize grain yields in the good fields were above 15 Mg ha^{-1} across cropping seasons and were not influenced by tillage and crop residue retention. The cumulative grain yields in the medium fields were above 10 Mg ha^{-1} across cropping seasons and were greater with crop residue retention. In the poor fields, cumulative grain yield was less than 10 Mg ha^{-1} across seasons and minimum tillage resulted in yield decrease while crop residue retention did not affect yields. For the poor fields, emphasis should be placed on the rehabilitation of soil physical and chemical attributes. At farm level, retention of crop residues was not viable due to use of crop residues for livestock feed. Minimum tillage was of interest to well-endowed farmers who had labour constraints. Poor farmers were interested but would not afford herbicides and had no access to sprayer pumps. Long term studies and farm scale modelling are necessary to unravel further the complexity in heterogeneous smallholder farming system for better fitting of recommended soil and water conservation options.

Key words: soil and water conservation, farming system; heterogeneity, smallholder; minimum tillage; vegetative barriers; crop residues; economic returns; tradeoffs; socio-ecological niches

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Chapter 1

General introduction

1.0 Introduction

Global food production defies the Malthusian theory except in sub-Saharan Africa where per capita food production has declined (Boserup, 1965; Hudson, 1993) due to decline in soil productivity. Efforts to sustain soil productivity are constrained by several challenges that include restricted use of inorganic fertilizers and manure, and continuous cultivation of cereals (Nandwa and Bekunda, 1998; Vanlauwe and Giller, 2006; Vanlauwe et al., 2010). Soil erosion is universally recognized as a major cause of soil degradation (Lal, 1987; Young, 1990; Bekunda et al., 2010) especially on arable lands in areas with high rainfall and mountainous terrain that are continuously cropped without attention to soil and water conservation (Gachene et al., 1997; Westerberg and Christiansson, 1999; Ovuka 2000a).

Three discourses around soil erosion control have evolved (Longley et al., 2006; Pretty et al., 1995; Shiferaw et al., 2009). The early efforts on soil and water conservation during the pre-independence period focused on top-down interventions, mainly using structural methods to control run-off (Anderson, 1984; Stocking, 1985). This top-down approach limited the farmers' participation in the design of the technologies and restricted innovations to suit the local farming system. Based on resistance and failure of the top-down policies to secure the co-operation of the farmers, a new paradigm – referred to as populist (Shiferaw et al., 2009) was formulated in the post-independence period. The farmer became central to design and implementation of control measures with emphasis on small-scale and bottom-up participatory interventions, often using indigenous technologies. The design did not stimulate wide scale adoption of technologies as anticipated due to failure to take into account prevailing economic, institutional and policy factors that influenced adoption and adaptation of soil and water conservation technologies. In the neo-liberal approach (Shiferaw et al., 2009), the appropriate role for farmer innovation was recognized while bringing into centre stage the role of markets, policies and institutions to stimulate and induce farmer interest.

Despite the success reported in some regions (Tiffen et al., 1994; Pretty et al., 1995) degradation of soil and water resources in East Africa (Tenge et al., 2004; de Graaff et al., 2008) remains widespread. In Kenya, the mountaineous Central region is among the areas affected by erosion (Ovuka, 2000b; Okoba and Sterk, 2006;). The uptake of recommended conservation practices (Thomas, 1989; Jaetzold et al., 2006))by smallholder farmers in the region is limited (Okoba and de Graaff, 2005). This in part because underlying the immediate causes of soil erosion are site specific socio-economic and bio-physical conditions that determine the priority given to soil conservation by smallholder farmers as well as the kinds of conservation practices in which they are likely to invest. The question in the title of this thesis is a direct quote from farmer's reaction in Central Kenya to the recommendation of zero tillage as an option for soil and water conservation. The farmers did not question the need for conservation, but rather the possibility of producing "chakula bila kulima" because this was against the local norm where farming is synonymous with tilling land. The uptake of zero tillage ultimately depended on local perceptions rather than its technical efficiency.

1.1 Soil and water conservation in Central Kenya

Soil and water conservation in Central Kenya has a long history dating to the colonial times (Anzagi and Bernard, 1977; Mackenzie, 1991). Conservation measures previously introduced include impermeable barriers such as bench terraces and fanya juu (digging a trench and throwing soil up-slope) to check run-off by enhancing infiltration. Impermeable barriers occupy land area for crops and require intensive labour for construction (Tenge et al., 2005; Sudishiri et al., 2008) and are not popular with local farmers who have to deal with land and labour constraints (Okoba and de Graaff, 2006; de Graaff, 2008). Vegetative barriers that involve growing rows of perennial vegetation (grass and trees) simultaneously with arable crops occupy less land and are easy to establish (van Rode, 2000; Tenge et al., 2005). The barriers offer a superior alternative for soil and water conservation in the region and have been recomended for uptake by local farmers (Angima et al., 2002; Mutegi et al., 2008). Recent research efforts in the area have also focused on zero tillage practices that require less labour (Gicheru et al., 2004). Farmer uptake of barriers and tillage technologies is however still minimal and soil erosion continues to be a problem in the area (Okoba et al., 2006).

Arable land in Central Kenya is privately owned and while the general population has increased, the land has not exacerbating fragmentation of landholdings (Hagerud, 1989; Downing, 1990; Oucho, 2007). A complex smallholder farming system has evolved with various types of crops and livestock (Herrero et al., 2010) and sources of off-farm income (Clay et al., 1997; Tittonell et al., 2010) across different sites and soils (Giller et al., 2010). The complexity in smallholder farming systems leads to a wide range of competing farming objectives necessitating some trade-offs when farmers decide whether to implement or reject soil and water conservation practices (Ellis-Jones and Tengberg, 2000; Tenge et al., 2005). Recommended soil and water conservation practices therefore need to be tailored to suit local farming system opportunities and problems (Fujisaka, 1994; Knowler and Bradshaw, 2007; Giller et al., 2009).

1.2 Rationale for the study

Farm scale studies have helped in generating better understanding of farming systems (Tittonell et al., 2005; Tittonell et al., 2010) that can facilitate better targeting of recomended soil and water conservation practices. Soil and water conservation practices therefore need to be analysed within this context necessitating focus, not only on the field scale, but also on the whole farm as suggested in the NUANCES (Nutrient Use in Animal and Cropping Systems – Efficiency and Scales - http://www.africanuances.nl) framework (Giller et al., 2006; van Wijk et al., 2009) hence the need for this study. The overall goal of this study was to understand how bio-physical conditions, farming objectives and endowments of different households affect their strategies towards conservation of soil and water resources. This would result in better understanding of the trade-offs farmers face in considering uptake of recommended conservation practices and formulate guidelines for their targeting into local farming conditions.

1.2.1 Objectives of the study

The overall aim was to contribute to better targeting of soil and water conservation technologies to socially diverse and spatially heterogeneous smallholder farms. The specific objectives were to:

1. Characterize the local farming systems and better understand conservation strategies for farmers under different bio-physical circumstances and varying resource endowment;
2. Assess the impact of recommended conservation practices on soil productivity and possible trade-offs for competing farm production objectives in diverse bio-physical conditions on smallholder farms;
3. Explore opportunities for improved soil productivity through the use of recommended soil and water conservation practices on bio-physically heterogeneous and socially diverse smallholder farms in Central Kenya.

1.3 Outline of the thesis

In Chapter 2, the local farming systems were characterized in relation to previously identified farm typologies. Farmer perception on the occurrence and effects of soil erosion were examined to allow better understanding of how farmer conservation strategies vary with household resource endowment. In Chapter 3-5, we focus on a basket of viable conservation options for the local farming conditions. In Chapter 3, the trade-offs between economic and the conservation benefits provided by tillage and vegetative barriers were evaluated to identify to what degree investment in soil conservation is acceptable to farmers while giving attractive economic returns. In Chapter 4, we examined competition for resources between anti-erosion barriers and crop system components. This work aimed to identify appropriate management strategies to reduce competition for light, nutrients and water when intra-seasonal dry spells are common and their impact on crop production severe as in Central Kenya. In Chapter 5, results of experiments studying effects of minimum tillage and mulching with crop residues on maize crop yield across heterogeneous smallholder farms are presented. In the concluding chapter, we revisit the targeting of recommended conservation options to the local farming systems through ex ante analysis at farm level using insights from the NUANCES approach and feedback from farmers.

Chapter 2

Soil and water conservation strategies in Central Kenya: Is there a need to target varied bio-physical and socio-economic circumstances in smallholder farms?

This article is to be submitted as:
Guto, S.N., Giller, K.E., Pypers, P., Vanlauwe, B., 2010. Soil and water conservation strategies in Central Kenya: Is there need to target varied bio-physical and socio-economic circumstances in smallholder farms? Land Degrad. Dev.

Abstract

Heterogeneity in smallholder farming systems demands the tailoring of conservation practices to suit local bio-physical conditions and socio-economic circumstances. A study was carried out in Mbeere and Meru South Districts in Eastern Kenya to assess the impact of bio-physical and socio-economic heterogeneity in smallholder farming systems on the soil and water conservation strategies by farmers. After reviewing secondary literature and carrying out reconnaissance farm visits, we randomly selected 24 farms per study area for detailed study. We formally collected information through a questionnaire to investigate farm-household attributes and current soil and water conservation strategies. Most households in Mbeere (78%) focused on production of food crops for domestic use, while those in Meru South (58%) had a market orientation due to proximity to urban markets with emphasis on production of commercial crops such as tea and coffee. Commercial milk production was also widespread in Meru South and Napier fodder was grown to feed dairy cows in zero-grazing units or for direct selling. In both areas, labour available within the household was inadequate to carry out all farming activities making a thriving local labour market for provision of casual labour a common feature in both areas. Four farm types were identified across the two areas: small farms reliant on substantial off-farm income, large wealthy farms less dependent on off-farm income, farms with medium resource endowment and small poor farms dependent on irregular off-farm income. Farmers were aware of the occurrence of soil erosion in their farms and showed appreciable knowledge of the water erosion processes independent of site and farm type. In Meru South, two or more conservation practices were observed in 67% of the farms compared with 33% in Mbeere. Trash lines were common in the low potential Mbeere area except for farmers with high resource endowment who instead preferred fanya juu and vegetation barriers. Stone lines were found in farms of medium and poor resource endowment. In Meru South, contour farming was popular across farm types but farmers preferred conservation measures with multiple benefits. Vegetation barriers were preferred by farmers who had small land holdings or experienced labour constraints. Fanya juu terraces were however favoured by rich farmers in Meru South. No single conservation practice suited the two diverse agro-ecological zones or met the needs of each type of farmer. For better uptake, future efforts should focus on targeting options to site-specific bio-physical and socio-economic conditions for effective soil and water conservation.

Keywords: farming system heterogeneity, farm type, soil erosion, trash lines, fanya juu.

1. Introduction

High population density leads to continuous cultivation and diminishing farm sizes in the East African highlands (Nandwa and Bekunda, 1998). The intense farming (Bekunda et al., 2010) on mountainous terrain leads to soil erosion (Zöbisch et al., 1995; Gachene et al., 1997; Angima et al., 2003). Many effective options to conserve soil and water have been developed (Thomas, 1997; Ellis-Jones and Tengberg, 2000; Biamah et al., 2003), but implementation by smallholder farmers is limited and not uniform (Tiffen et al., 1994; Ovuka, 2000). Thus the implementation of soil conservation measures is deemed unsatisfactory (Pretty et al., 1995; Tenge et al., 2004; Okoba and de Graaff, 2005). Various factors contribute to the lack of uptake, such as the absence of immediate financial benefits (de Graaff et al., 2008) and failure to address opportunities and constraints within the local farming system (Tenge et al., 2005; Knowler and Bradshaw, 2007).

Farming systems in sub-Saharan Africa are diverse, heterogeneous and dynamic (Giller et al., 2006; 2010). Within a particular locality, farm-households differ in resource endowment and livelihood strategies (Zingore et al., 2007; Tittonell et al., 2010). Wide ranges in soil fertility within a single farm result from inherent variability of soil types in the landscape (Ncube et al., 2009; Ebanyat et al., 2010) and differential management (Tittonell et al., 2005; Vanlauwe et al., 2006). For better uptake of soil and water conservation options, variability among and within farms should be acknowledged (Tengberg et al., 1998) and conservation practices rationally tailored to suit local bio-physical and socio-economic conditions (Giller et al., 2009) such as the slope and distance of cropping fields from the homestead (Clay et al., 1998) and household wealth status (Kiome and Stocking, 1995; Hardaker et al., 2004; Langyintuo and Mungoma, 2008). Farming system studies have improved understanding of the main drivers of household and farm diversity (Carter, 1997; Shepherd and Soule, 1998; Giller et al., 2010) and functional farm typologies developed for farming systems in Eastern Africa (Tittonell et al., 2005; Tittonell et al., 2010)

A study was initiated in Mbeere and Meru South Districts in Eastern Kenya to: (1) characterize the local farming systems in relation to previously identified farm typologies; (2) examine farmer perception on the occurrence and effects of soil erosion; (3) better understand conservation strategies for farmers with varying resource endowment; and (4) identify opportunities for improved soil and water management in smallholder farming systems.

2.2 MATERIALS AND METHODS

2.2.1 Site Description

Three representative villages; two in Meru South (Murugi: S 00º14’49.3”, E 037º39’45.5” and Kirege: S 00º47’26.8”, E 037º39’45.3”) at average altitude of 1500 m above sea level and one in Mbeere (Machang’a S 00º47’26.8”, E 037º39’45.3”) at 1000 m above sea level were selected for the study. The two study areas are located on the Eastern foot-slopes of Mount Kenya. Meru South is inhabited by the Chuka people who are a sub-tribe of the greater Meru tribe. The Mbeere people - split from the Embu after an inter-clan war - occupy the less fertile and drier Mbeere District. Rainfall is bimodal in both areas: long rains from March to May and the short rains from October to December. Meru South is classified as medium potential for agriculture with 1500 mm average annual rainfall but Mbeere District receives less rainfall (750 mm yr^{-1}) and has shorter cropping seasons (Jaetzold et al., 2006). The landscape in Meru South is hilly with a 12% average slope whereas Mbeere has a relatively flat terrain with average slope of 6%.

Agriculture in Meru South is predominantly mixed smallholder farming and manual labour has a prominent role in production. Farmers grow non-food crops (coffee (Coffea arabica L.), tea (Camellia sinensis L.), khat (Catha edulis L.) and pyrethrum (Chrysanthemum coccineum L.), and the food crops maize (Zea mays L.), common beans (Phaseolus vulgaris L.), bananas (Musa spp. (AAA group) and Irish potatoes (Solanum tuberosum L.). Farmers also keep livestock mainly improved dairy cattle in zero- and minimum grazing units and feed them on Napier grass, maize crop residues, banana pseudo-stems and indigenous fodder species. Nitisols predominate which are soils with medium to high fertility status (FAO, 1991).

In Mbeere, mixed smallholder farming also dominates although the farms are larger than in Meru South. The farmers keep oxen for land preparation and rely less on manual labour for food production. Common food crops include maize (Zea mays L.), sorghum (Sorghum bicolor L.), common bean (Phaseolus vulgaris L.), cowpea (Vigna unguiculata L.) and green gram (Vigna radiata (L.) R. Wilczek) with minor production of cash crops such as sunflower (Helianthus annuus L.) and tobacco (Nicotiana tabacum L.). The farms have local breeds of cattle and small ruminants (sheep and goats) that have access to open grazing. The majority of soils are Haplic Ferralsols which are poor in plant nutrients supply (FAO, 1991).

2.2.2 Survey methods and data analysis

After reviewing secondary data, holding discussions with key informants and carrying out reconnaissance farm visits, 24 farms were randomly selected from an initial list of 50 farmers from each study area. Information on household attributes (e.g. family size, age of household head, cultivated area and household labour supply) and soil and water conservation situation (occurrence of erosion, causes of erosion and existing conservation measures) were collected using a questionnaire. Categorical Principal Component Analysis, SPSS version 18 (Meulman and Heiser, 2005) was used to carry out PCA using some of the variables previously used by Tittonell et al. (2010) to classify farms in the same area. The variables used in both studies were: total area, age of household head, months of food deficit, total number of cattle, family labour, family size, production orientation, % of household income from off-farm activities. The extra variables included in this study were education level of the household head and market access. The excluded variables previously used were: total farmed area, total area with cash crops, number of years receiving off-farm income, number of local cattle, number of graded cattle and number of oxen and ox-ploughs. Variables that made up the first four principal components were selected by use of factor loadings obtained by varimax rotation. Retained variables were: Total area, age of household head, months of food deficit, total number of cattle, family size, % of household income from off-farm activities.

Variables that loaded into the same component were analysed to identify socio-economic indicators for use as proxies for farm categorization using criteria described by Tittonell et al. (2005) for Western Kenya. The farms were grouped into classes using individual farm factor scores for the first and second principal components.

Categorical regression (Meulman and Heiser, 2005) was used to explore relationships between conservation measures (predicted) and farm attributes (predictor) due to the categorical nature and non-linear relationships between the variables. The variables were scaled simultaneously while preserving characteristics of the original categories (optimal scaling). The transformed values were analysed at either nominal, ordinal or numerical scales to find the best fitting regression model for the variables. Standard coefficients (β) were determined and used to assess the impact of each farm attribute on presence or absence of conservation measures in smallholder farms. Regression analysis of variance was used in conjunction with the standard coefficient to explore fully the predictor effects. For nominally scaled predictor variables such as farm type, the value of the standard coefficient was not taken into consideration because it did not correspond to increase in original category values.

2.3 RESULTS AND DISCUSSION

2.3.1 General farm and household attributes

Households in Mbeere were larger with at least four family members, as opposed to Meru South where most households had less than four family members (Table 1). Consequently, more household labour was available for on-farm activities in Mbeere than in Meru South. Hiring of casual labour was reported in both areas implying that labour supplied by household members was inadequate for carrying out all farming activities. Local labour markets for provision of casual labour were a common feature in both areas.

Most households in Mbeere (78%) focused on production for household consumption whereas the households in Meru South (58%) had a commercial orientation due to

Table 1. Socio-economic and bio-physical attributes of the farms that participated in the characterization exercise (n=24 per site)

Variable	Categories	Relative distribution (%)	
		Mbeere	Meru South
Gender of household head	Male	83	75
	Female	17	25
Age of household head (years)	< 35	17	33
	36-50	42	29
	51-60	25	29
	61 >	17	8
Marital status of the household head	Single	8	11
	Widow	13	17
	Married (spouse away)	21	0
	Married (with spouse)	59	71
Family size (persons)	< 4	8	54
	4-5	79	29
	5 >	20	17
Farm labour sources (%)	Household	17	17
	Hiring casuals	67	50
	Fulltime worker	8	17
Household members working on farm (persons)	0	4	13
	1-2	67	74
	3-4	25	13
	5 >	4	0
Dependence on off-farm income (%)	< 30	8	25
	30-50	21	33
	51-80	46	25
	80 >	25	17
Food deficit (months)	< 2	21	13
	2-4	27	27
	5-7	42	21
	8 >	29	17
Production orientation	Subsistence	75	42
	Mixed	25	58
	Commercial	0	0
Education level	Illiterate	21	4
	Primary	30	58
	Secondary	33	33
	Post secondary	17	4

proximity to urban markets with emphasis on production of milk and commercial crops such as tea and coffee (Table 1).

Farmers in Mbeere regarded farming as a part-time activity and supplemented their income off-farm through either formal employment or informal income-generating activities. Off-farm income was thus more important in Mbeere where almost half

(48%) of the households interviewed earned more than 50% of their income outside the farm as opposed to 20% of the households in Meru South. Whilst off-farm activities may on the one hand constrain uptake of conservation options by reducing available household labour, on the other hand, extra income may be available for investment in the farm (Clay et al., 1998).

2.3.2 Farm types and farm specific attributes

Four principal components were extracted based on Kaiser's criterion of Eigen values above 1 by categorical principal component analysis (Figure 1).

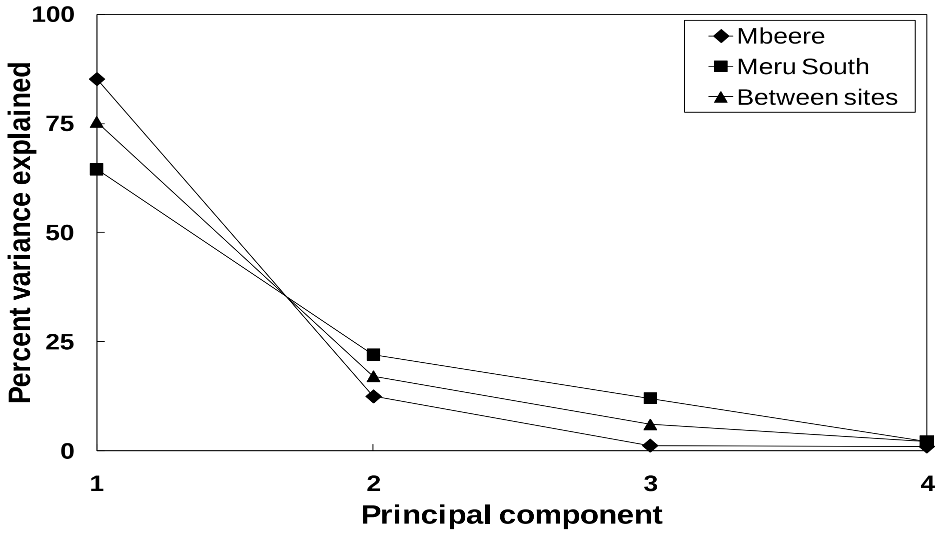

Figure 1. The sorted Eigen values in descending order for successive principal components extracted by categorical principal component analysis and varimax rotation for the two study areas

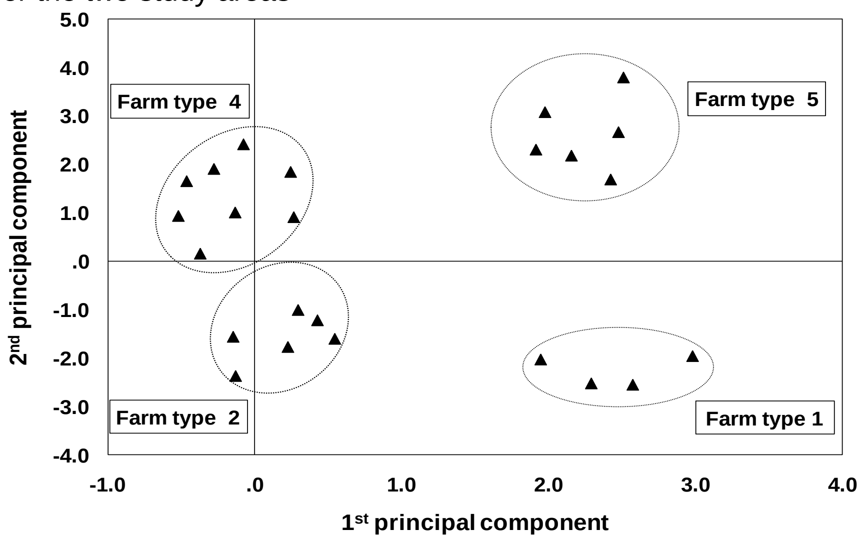

Figure 2. Distribution of farms according to the scores of the first two principal components for Meru South

Table 2. Absolute rotated loadings of the main socio-economic and biophysical farm-household attributes for the first four components extracted by categorical principal component analysis and varimax rotation for the two study areas

Variable	Mbeere				Meru South			
	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3	PC 4
Off-farm income	0.93	0.11	0.34	0.09	0.98	0.36	0.10	0.12
Food deficit	0.24	0.96	0.02	0.19	0.17	0.72	0.10	0.05
Livestock	0.44	0.45	0.69	0.35	0.36	0.34	0.12	0.12
Age	0.52	0.01	0.06	0.53	0.25	0.10	0.03	0.37
Family size	0.17	0.48	0.34	0.43	0.54	0.21	0.16	0.29
Total area	0.48	0.24	0.24	0.06	0.47	0.26	0.04	0.05

The first two components explained over 90% of the variation. Dependence on off-farm income loaded highly onto the first component while food self sufficiency loaded onto the second (Table 2). Other variables with moderate to high loadings were livestock ownership, age of household head, family size and cultivated area. Aggregated scores of the first two principal components for individual farms were used to identify farm types (Figure 2). Four farm types were identified: small farms reliant on substantial off-farm income, large wealthy farms less dependent on off-farm income, farms with medium resource endowment and small poor farms dependent on off-farm income from non-skilled activities (Table 3). Tittonell et al. (2010) identified five farm types across six districts in Uganda and Kenya which included the two districts studied in this paper.

2.3.3 Farmer knowledge of soil erosion and its effects

Across the two study areas, 88% of the farmers indicated that soil erosion occurred on their farms (χ^2=2.3, P = 0.32) despite the conservation measures in place. The farmers identified intense rainfall as the major cause of soil erosion in addition to field slope, soil characteristics and failure to establish or maintain soil conservation measures. Occurrence of soil erosion was inferred from presence of soil splashed onto field crops, presence of inter-rills and rills in cropping fields and exposure of tree or crop roots. The negative effects of soil erosion recognised by farmers included the loss of fertile topsoil (65%) and decline in soil productivity (73%). The farmers showed appreciable knowledge of the processes that lead to soil erosion by water, and of the impacts of erosion on soil productivity. Control of soil erosion in Kenya

Table 3. Comparison of socio-economic indicators between farms described by (A) Tittonell et al. (2010) and (B) in the current study for farm types in the two study areas

Farm Type	Source	House-Holds (%)	Total Area (ha)	Number of cows (TLU)	Off-farm income (%)	Food deficit (months)	Land: Family size (ha person^{-1})	Land: Labour (ha person^{-1})
Mbeere								
1	A	28	1.7	2.1	46	7.1	0.46	1.33
	B	None	-	-	-	-	-	-
2	A	10	8.8	4.5	22	11.3	1.62	3.74
	B	38	6.5 (2.5-10)	3.9 (1.8-9.5)	58 (20-69)	2.5 (0-6)	0.38 (0.1-1.2)	2.65 (0-3)
3	A	10	8.8	4.5	22	11.3	1.62	1.93
	B	None	-	-	-	-	-	-
4	A	25	1.5	0.6	47	6	0.31	0.48
	B	33	1.5 (0.5-2.0)	1.1 (0.3-2.3)	66 (30-95)	5.6 (2-8)	0.24 (0-1.1)	0.65 (1-4)
5	A	13	1.1	0.4	61	5.6	0.31	0.48
	B	28	1.3 (0.5-1.6)	0.5 (0-1.2)	74 (5-96)	6.3 (4-8)	0.19 (1-5)	0.47 (1-5)
Meru South								
1	A	23	1.3	2.4	33	7.7	0.45	0.99
	B	17	0.39 (0.1-0.4)	0.29 (0.1-0.4)	80 (70-90)	2.5 (1-4)	0.08 (0-0.13)	0.11 (0.1-0.4)
2	A	13	4	5.6	16	9.4	1.13	3.4
	B	25	1.99 (1.5-2.2)	0.59 (0.1-0.8)	26 (0-70)	3.5 (0-8)	0.34 (0-1.1)	0.85 (0.1-1.0)
3	A	20	2.3	2	18	8.9	0.46	1.93
	B	None	-	-	-	-	-	-
4	A	20	0.8	1.4	36	5.8	0.23	0.44
	B	33	0.40 (0.2-0.8)	0.77 (0.4-1.6)	40 (20-70)	5.5 (0-8)	0.12 (0-0.27)	0.44 (0.4-1.6)
5	A	25	0.7	0.9	40	7.3	0.15	0.43
	B	25	0.2 (0.1-0.5)	0.19 (0-1.0)	62 (20-90)	7.3 (3-12)	0.06 (0-0.15)	(0-1.0)

Table 4. Existing soil and water conservation practices in smallholder farms of Central Kenya

Practice	Features	[1]Current use by farmers	Potential/Opportunity
Contour farming	Planting hills and tillage operations across the slope	High	Combined with other measures
Trash lines/ barriers	Crop residues laid in lines within fields to impede run-off	Absent in Meru South but high in Mbeere	Effective if slopes are gentle and rainfall sparse
Cultivation with Panga	Panga used for planting and weeding to limit soil disturbance	High across the two sites	Compatible with improved tillage practices
Stubble grazing	Livestock allowed to graze in cropping fields after crop harvest	High in Mbeere but absent in Meru South (cropping fields fenced)	Hindrance to crop residue conservation in Mbeere
Mulching	Crop residue is left on the field to conserve water and reduce soil erosion	Low due to use of crop residues as feed in Meru South and stubble grazing in Mbeere	Some potential in Meru South if niches can be identified
Inter-cropping	Two or more crops grown on the same field	High for maize and beans	Other legumes can be introduced
Crop rotation	Particular combination of crops is rotated	Low to Moderate	Introduce new crops but guarantee food security
Vegetation strips	Perennial grasses planted in the cropping field to control run-off	High in Meru South especially for fodder production	Introduce legume fodder trees but assess conservation - returns trade-off
Stone lines	Row of stones lined across fields to control run-off	Absent in Meru South but high in Mbeere	Can be combined with trash lines to improve efficiency
Weeding ridges	Soil is heaped at the base of plants at weeding to conserve water	High for both areas	Effective in Meru South where soils are deeper and less prone to crusting
Fanya juu/chini	A trench is dug and soil is thrown up hill (juu) or down slope (chini)	Moderate to high but modified to suit local conditions	Potential integration with other options
Zero tillage	Weeds controlled by herbicides and soil inversion avoided	Low	Newly introduced to both areas and better targeting to local farming conditions required
Tied ridges	Contour ridges tied by regular cross to form depressions for water infiltration	Moderate and in Mbeere only	Labour intensive and not preferred

1High (>65%) Moderate (30-65%) Low (<30%)

including the central region has a long history and attracted attention of the colonial government as early as 1930s (Pretty et al., 1995; Ellis-Jones and Tengberg, 2000) and later by post colonial governments (Thomas, 1997; Ovuka, 2000). This might explain the good farmer understanding of their environment and occurrence of soil erosion crops and crop rotation), (ii) physical measures (including fanya juu terraces - made by digging a trench and throwing soil uphill, fanya chini - where a trench is dug and soil barrier made down slope, cut-off-drains, stone lines and ridging), (iii) biological measures (including grass strips, agroforestry), and (iv) bio-physical measures (including fanya juu/chini terraces reinforced with vegetative species). The farmers recognized all of the conservation practices except for zero tillage that was new to the area. Most farmers copied conservation practices from other farmers, although some indicated that they developed the ideas themselves or learned from agricultural extension officers. Agricultural extension services in Kenya have intensively promoted a composite strategy (Thomas, 1997) of physical measures (e.g. cut-off-drains, bench terraces and fanya juu) for both high and low potential agro-ecological zones, biological methods for high potential zones (e.g. grass strips, cover crops and contour earth bunds) and indigenous methods (e.g. trash lines, stone lines, tied ridges) for specific local conditions.

Different conservation practices were key in each study area: vegetation strips and fanya juu were widely used in Meru South and trash lines and stone lines in Mbeere. Vegetation strips consisted of narrow double bands of perennial vegetation (Napier grass, fodder trees, sugar cane or sweet potatoes) planted at several positions along the slope to impede run-off and retain soil sediments. The farmers rarely aligned the strips to the contours as recommended. Besides controlling erosion, vegetation strips provided fodder for livestock if appropriate species were used. Farmers reported that grass strips were easy to implement and could be easily relocated from one part of the farm or field to another based on soil erosion trends. Farmers complained that digging fanya juu was hard work due to the action of throwing the soil up-slope. Further, fanya juu occupied more space in the fields than vegetation strips, reducing the area available for cropping.

In Mbeere, farmers arranged crop residues in several positions across the fields in trash-lines to control run-off on gentle slopes. If the run-off concentrated and formed rills, some farmers re-enforced the trash-lines with wooden pegs to form trash barriers. Trash-lines were easy to establish but had a short life-span besides being susceptible to removal for fuel by women and children or removal by termites. Stone-lines were set up by arranging stones in 10-30 cm high barriers across the fields.

This was only done where the soil was stony and had the dual advantage of clearing stones from impeding tillage in the fields as well as construction of barriers to slow down run-off. Farmers regarded construction of stone lines to be labour intensive. Stone lines required little maintenance although farmers added more stones when they were encountered while tilling the fields.

2.3.5 Farmer soil and water conservation strategies

In Meru South, two or more conservation practices were observed in 67% of the farms compared with 33% in Mbeere. In Meru South which receives much more rainfall, and where the terrain is much hillier, intensive cultivation makes the area more prone to soil erosion. Households in Meru South were more dependent on farming as a source of income than in Mbeere. This may also explain the diversity of conservation practices that farmers of Meru South invested in. Longley et al. (2006) found dependence on agriculture strongly influenced uptake of soil and water conservation practices in Western Kenya.

The wide range of conservation practices (Table 4) and the small sample size makes it difficult to draw firm conclusions on farmers’ investment in soil and water conservation. Trash- and stone-lines were present in Mbeere only (Table 5). The low rainfall and relatively flat terrain made trash- and stone-lines effective run-off control measures in Mbeere as opposed to Meru South. The demand for crop residues as feed for livestock is also lower in Mbeere than in Meru South and less urgent in the former due to presence of communal grazing areas. In addition, stone lines required stones in the vicinity and would only be established in the marginal Mbeere area where soils are poorly developed and stony. Although fanya juu terraces were observed in farms across the two areas, their frequency in Mbeere was lower than that in Meru South (Table 5). Stony fields and presence of hard-pans near the soil surface in Mbeere made the construction of such physical structures difficult and labour intensive. Across the two areas however, unusual conservation practices were observed in the well endowed farms such as vegetative barriers in Mbeere and zero tillage in Meru South (Table 5). Well-endowed farmers easily experiment with and accept risk for new conservation practices (Kiome and Stocking, 1995).

Table 5. Current soil and water conservation measures (%) for different types of farmers in Mbeere and Meru South

Farm type	Fanya juu	Fanya juu with vegeta-tion	Vegeta-tion strips	Trash lines	Mulching	Contour farming	Stone lines	Zero tillage
Mbeere								
2	33	26	23	49	13	3	13	0
4	10	5	3	68	10	2	29	0
5	8	0	0	88	0	0	27	0
Meru South								
1	0	75	100	0	25	84	0	12
2	88	50	33	0	10	62	0	10
4	65	50	17	0	0	60	0	0
5	38	60	50	0	0	54	0	0

In the low potential Mbeere area, trash-lines were encountered in most farms (Table 5). The relatively flat terrain limited the need for physical conservation structures such as fanya juu. Stone lines were observed on the farms of medium (Farm type 4) and poor farms (Farm type 5) and this might reflect lack of access to better quality non-stony arable land. Rich farmers (Farm type 2) however had lower preference for trash lines because they used crop residues as livestock feed and to a lesser extent for mulching (Table 5). The rich farmers also favoured fanya juu terraces and this was significantly different between the farm types (Table 6). Rich farmers have extra financial resources that can be invested in acquiring more labour for the construction of fanya juu terraces. When imperfections in access to credit across different types of farms exist, greater farmer wealth and substantial off-farm income increase the likelihood of on-farm conservation investments (Clay et al., 1998). Farmers in Meru.

Table 6. Outputs of the categorical regression analysis between soil and water conservation practices (predicted) and characteristics of farms (predictor) in Mbeere and Meru South

Practice	Factor	Standard coefficient (β)	Regression F ratio
Mbeere			
Fanya juu	Farm type		4.07*
	Cultivated area	0.27	1.76
	Traditional cows	0.12	0.18
	Education level	0.15	0.39
	Maintenance	0.18	0.36
	Market access	0.05	0.05
Trash lines	Farm type		2.33*
	Market access	0.22	0.52
	Traditional cows	-0.17	0.40
	Cultivated area	0.18	0.77
	Maintenance	0.12	0.16
	Education level	0.18	0.73
Mulching	Farm type		0.21
	Market access	0.16	0.26
	Traditional cows	-0.14	0.11
	Cultivated area	0.43	2.25*
	Education level	0.23	0.57
Meru South			
Fanya juu	Farm type		3.39*
	Cultivated area	0.37	3.50*
	Improved cows	0.23	1.69
	Market access	0.27	1.72
	Maintenance	0.41	3.03*
	Education level	0.31	1.10
Vegetative strips	Farm type		2.44
	Cultivated area	-0.18	1.74
	Improved cows	0.22	0.51
	Market access	0.35	1.92*
	Maintenance	0.28	0.36
	Education level	0.32	1.23
Mulching	Farm type		0.21
	Cultivated area	0.43	2.25
	Improved cows	-0.14	0.11
	Market access	0.16	0.26
	Education level	0.23	0.57
Contour farming	Farm type		0.15
	Cultivated area	0.29	1.95
	Market access	0.28	0.57
	Maintenance	0.51	1.52
	Education level	0.40	3.47*

F ratio: *, **; significant at P≤ 0.05 and 0.01 respectively

Vegetation barriers were however common in intensively managed small farms with substantial off-farm income (Farm type 1) where arable land was scarce or in poor small farms (Farm type 5) where both farm size and labour were inadequate. Fanya juu terraces were found mainly in wealthy farms (Farm type 2) who hired in labour.

2.4 CONCLUSION

Farming systems in the Central Kenya region were heterogeneous and variability among smallholder farms was characterized in the two study areas. Four farm types were identified in Meru South and three in Mbeere District that differed in financial resources, cultivated area, food security and labour availability. The farmers were aware of the occurrence of soil erosion and showed appreciable knowledge of the water erosion processes independent of study area or farm type. Specific farm soil and water conservation strategies varied between study areas and farm type. In the low potential Mbeere area, trash lines were encountered in most farms because of the relatively flat terrain that limited the need for labour intensive physical conservation structures such as fanya juu. The rich farmers in Mbeere District however still invested on fanya juu while stone lines mainly occurred in medium and poor farms reflecting low quality arable land. Farmers in Meru South preferred measures with multiple uses such as vegetative barriers and reinforced fanya juu that conserved soil besides providing fodder. Vegetation barriers were however common in small farms where arable land was scarce while fanya juu was found in well-endowed farms with bigger farm size and access to labour for construction. No single conservation practice was suitable across the two regions or met the objectives of every farmer. In planning for effective soil and water conservation therefore, future efforts should focus on increased application of conservation techniques and practices already known by targeting them to site-specific bio-physical and socio-economic domains.

Tillage and vegetative barriers in a sub-humid region of Central Kenya: Soil conservation and economic benefits

This article has been accepted for publication as:
Guto, S.N., Pypers, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2011. Tillage and vegetative barrier effects on soil conservation and short-term economic benefits in the Central Kenya highlands. Field. Crop. Res.

ABSTRACT

Tillage and anti-erosion barriers can reduce the degradation of soil and water resources in the steeply sloping highlands of East Africa but adoption by smallholder farmers has been slow. Trade-offs between soil conservation efficiency and economic benefits for tillage and anti-erosion barriers were assessed over four cropping seasons to understand benefits of soil and water conservation strategies under local farming conditions. Minimum tillage was compared with regular tillage and vegetative barriers (leucaena and Napier) with no anti-erosion barriers. Between the tillage and anti-erosion barriers, grain yields were greater with than without vegetative barriers, except with Napier barriers when minimum tillage was practiced. Napier barriers with regular tillage conserved most soil (72%) followed by Napier with minimum tillage (53%) while minimum tillage without anti-erosion barriers conserved least soil (1%) with leucaena barriers having intermediate conservation efficiency. Across tillage practices, negative economic returns were realized in the first cropping season with vegetative barriers whereas without barriers, economic returns were also negative with minimum tillage but slightly positive with regular tillage. Considering economic returns and the soil conserved, minimum tillage without anti-erosion barriers or adequate soil cover was inefficient in soil conservation and had poor economic returns making it an unsuitable option for the local farming system. Leucaena barriers had attractive economic returns across tillage practices but conserved less soil. But for leucaena barriers with minimum tillage, labour price should be below US$ 0.36 $hour^{-1}$ and herbicide price below US$ 20 $litre^{-1}$ to guarantee attractive economic returns to the farmers. Napier barriers with regular tillage presented a win-win scenario for farmers and environmental impacts because of the simultaneous attractive economic returns and efficient soil conservation. However, the price of labour should be below US$ 0.30 $hour^{-1}$ for acceptable economic returns given current input-output prices. Further studies are necessary to ascertain the performance of minimum tillage without barriers due to the influence of one extreme rain season on its performance. Additionally, long-term multi-locational studies are neccessary to assess the feasibility of tillage and vegetative barriers across the diverse conditions that prevail on smallholder farms in the African highlands.

Keywords: minimum tillage, leucaena, Napier, soil erosion, trade-offs, marginal rate of returns

3.0 INTRODUCTION

Intensive land use on the sloping terrain of the East African Highlands accelerates soil erosion (Angima et al., 2000) reducing soil fertility and crop productivity (Ovuka 2000). Impermeable barriers such as ditch-and-bank structures which check run-off either by diversion or causing infiltration can control erosion but they occupy land area for crops besides requiring intensive labour and capital resources (Sudishiri et al., 2008). Vegetative barriers that involve inter-cropping perennial leguminous trees or grass strips with annual crops occupy less land (Young, 1990) and trap sediments while allowing some run-off to pass through hence offering a superior alternative for erosion control (Angima et al., 2003; Owino et al., 2006). The soil conservation efficiency of the vegetative barriers depends on vegetative development, crop performance and undergrowth (Spaan et al., 2005; Pansak et al., 2008; Blavet et al., 2009) as well as improved soil surface management practices such as minimum tillage that limit soil disturbance (Pansak et al., 2010).

Smallholder farmers' attraction to soil and water conservation measures can be enhanced if the options offer multiple benefits (de Graaff et al., 2008). Vegetative barriers give additional income from the sale of fodder (Angima et al., 2002) and, if planted with N_2-fixing trees, may improve soil fertility (Mureithi et al., 1994; Sanchez, 1995; Buresh and Tian, 1998) besides conserving soil and water. However, vegetative barriers may compete with crops for water, light and nutrients and, reduce the area available for crops leading to decreased crop yields (Kinama et al., 2007; Everson et al., 2009). Also, the process of natural terrace formation may sometimes expose infertile subsoil on the upper-slopes causing uneven row yields between the barrier rows (Agus et al., 1997; Dercon et al., 2003), although not as strongly as with physical measures. Further, economic benefits from vegetative barriers are delayed (Tenge et al., 2005; Bayard et al., 2007) because establishment costs incurred in the first season are recovered only after several seasons.

Although vegetative barriers (Mugendi et al., 1999; Angima 2003; Mutegi et al., 2008) and minimum tillage (Gicheru et al., 2004; Ngigi et al., 2006) technologies have received attention in central Kenya, they are not widely adopted by farmers (Okoba and de Graaff, 2005). Local bio-physical and socio-economic conditions (Knowler and Bradshaw, 2007) that affect the economic benefits and conservation efficiency of these options in the local farming systems have not been considered resulting in lack of fit with farmers' objectives. There is need for careful consideration of the trade-offs between economic and the conservation benefits provided by tillage and vegetative barriers to identify what degree of soil conservation is acceptable while giving attractive returns to farmers.

A study was initiated with the overall aim to assess the impact of tillage and vegetative barriers on soil conservation and crop yields in smallholder farming conditions in central Kenya. The specific objectives of the study were to: 1) determine tillage and vegetative barrier effects on maize and soybean yields in a maize-soybean rotation; 2) determine tillage effects on Napier and leucaena fodder biomass production; 3) determine vegetative barrier and tillage effects on soil loss; 4) determine economic benefits of tillage and vegetative barriers; and 5) analyse trade-offs between soil conservation and economic returns for tillage and vegetative barriers.

3.2 MATERIALS AND METHODS

3.2.1 Description of the study area

An on-farm, researcher-managed trial was set up in the sub-humid zone of central Kenya in Kirege Location, Chuka Division of Meru South District. Average annual temperatures vary between 18 and 20 ^{o}C while rainfall is bimodal with two seasons, short rains and long rains, and an annual rainfall average of 1500 mm (Jaetzold et al., 2006). Daily rainfall was recorded using a rain gauge adjacent to the experimental area. The long rains 2007 were the least while most rainfall was experienced in short rains 2007 (Figure 1). Dry spells of variable durations occurred at different stages during the study period.

The field selected (0.35^{o}S, 37.65^{o}E, 1429 m above sea level) was representative for the area in terms of slope (average 12%) and soil type (Humic Nitisols; FAO, 1991). Topsoil (0-15 cm) analyses using procedures described by Anderson and Ingram

(1993) gave: soil pH 6.48 (1:2.5 in H_2O), 2.01 % organic C, 36.23 mg kg^{-1} of bicarbonate extractable P, and 13.86, 2.64 and 0.88 $cmol_c$ kg^{-1} of exchangeable Ca, Mg and K, respectively.

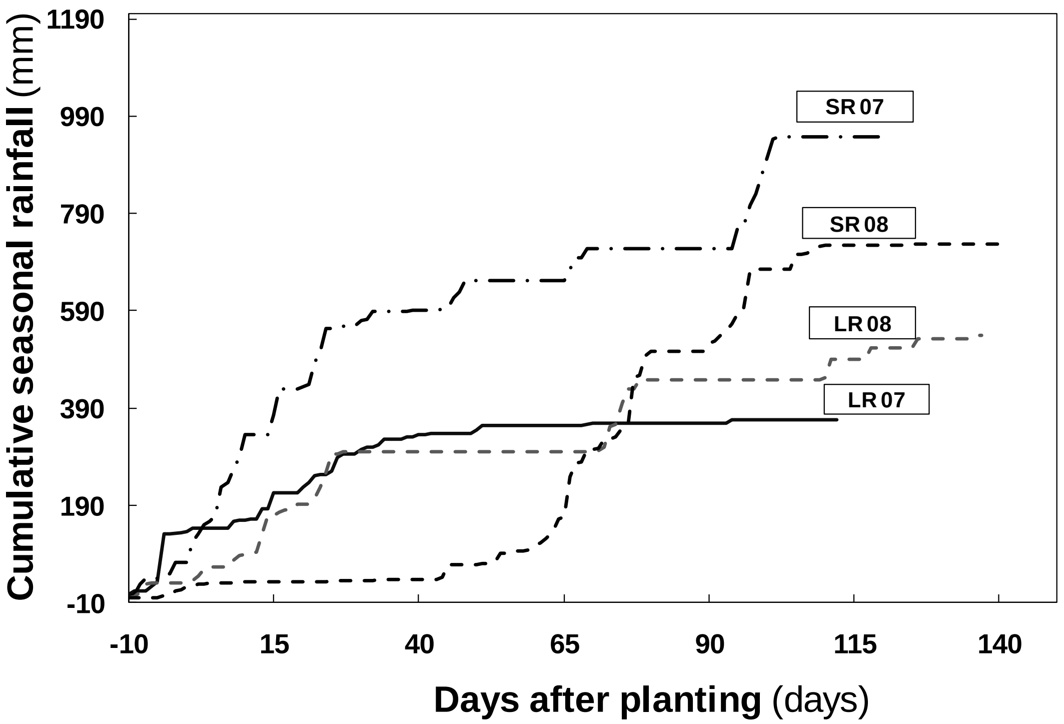

Figure 1. Cumulative rainfall for four consecutive cropping seasons (long rains 2007-short rains 2008) measured at the experimental site. In the graph, SR is for short rains and LR for long rains.

The selected field had no established vegetative barriers or physical conservation measures. Prior to trial establishment, the experimental area was uniformly cropped with unfertilized maize to reduce within-field variability related to cropping history. A retention ditch was established on the upper side across the experimental area to prevent run-on from the upper slope.

3.2.2 Experimental design

Farmers in the area commonly produce maize (Zea mays L.) and common beans (Phaseolus vulgaris L.). A maize-soybean rotation system was selected for testing because promiscuous soybean varieties produce more biomass than common beans and fit well in minimum tillage systems where crop residue for soil cover is fundamental. Leucaena (Leucaena trichandra Zucc. Urband) and Napier (Pennisetum purpureum Schumach. cv. cameroun) were selected for testing as vegetative barriers. Both are commonly known to farmers in the area.

The field trial was established in February 2007 following a full factorial design with two factors: (i) tillage practices and (ii) anti-erosion barriers. Minimum tillage was compared with the regular tillage practice in the area. Napier and leucaena barriers were compared with an open field without anti-erosion barriers. There were six tillage and anti-erosion barrier experimental combinations. The combination of regular tillage without anti-erosion barriers was considered as the control. The treatments were replicated in three separate blocks laid out across the slope.

Experimental plots were separated by creeping signal grass (Brachiaria humidicola L.), planted on 50 cm wide earth bunds to prevent lateral exchange of materials or run-on into adjacent plots. Each experimental plot was divided into three mini-plots designated as upper, middle and lower mini-plot and each mini-plot was 4 m wide while the length varied according to the spacing formula suggested by Thomas (1997). Double row vegetative barriers were established along the upper border of each mini-plot at an inter-row spacing of 50 cm and intra-row spacing of 20 cm in a staggered pattern. Napier barriers were established from mature stem cuttings about 50 cm long (two cuttings in each planning hole) and leucaena from seedlings (one seedling in every planting hole).

The upper mini-plot across all the experimental plots acted as a buffer zone. Trash-lines (maize stover) were set along their upper border to prevent movement of soil from the embankment of the retention ditch into the experimental area. Trenches about 1 m deep were dug at the end of each long rain season next to the leucaena barriers along the border in the middle mini-plots to inhibit lateral root extension into adjacent plots. Top-soil was kept separate from sub-soil and immediately returned in the proper order to re-fill the trenches.

3.2.3 Tillage and cropping practices

The regular tillage practice (as described by Thomas, 1997) involved soil inversion once at the beginning of the cropping season using a hand-hoe, and weed control thereafter twice or three times during the season. In minimum tillage, a post-emergent broad-spectrum herbicide (500 g litre^{-1} active ingredient of glyphosate) was applied just before planting, After planting, weeds were controlled manually while minimizing soil disturbance (annual weeds were slashed by panga while perennial weeds were pulled manually).

Maize and soybean were grown in a rotation system. During the long rainy seasons, soybean (Glycine max (L.) Merill, variety TGx1740-2F) was grown at an inter-row spacing of 50 cm and intra-row spacing of 5 cm (400,000 plants ha^{-1} for the plots without barriers and 350,000 plants ha^{-1} for those with barriers). During the short rainy seasons, maize (Zea mays L., Dekalb variety 8031) was grown at an inter-row spacing of 75 cm and intra-row spacing of 35 cm (38,000 plants ha^{-1} for the plots without barriers and 33,250 plants ha^{-1} for those with barriers). The soybean planting dates were 29th March 2007 for long rains 2007 and 16th March 2008 for long rains 2008 whereas those for maize were 16th October 2007 for short rains 2007 and 6th October 2008 for short rains 08. Maize and soybean were planted 25 cm away from the vegetative barriers. The vegetative barriers reduced the cultivatable area by 10%, equivalent to two soybean rows and one maize row.

Triple super phosphate and urea were applied to the maize at 30 kg P ha^{-1} and 50 kg N ha^{-1}, respectively. Urea was added in two split applications after the first and second weeding. No fertilizer was applied to the soybean crop. All crop residues from soybean were left in the plots after harvest. Maize stover was cut at 50 cm from the ground and removed from the plot to mimic the common crop residue management practice in the study area. The maize stumps and soybean residue were left on the soil surface for minimum tillage but incorporated into the soil under regular tillage.

3.2.4 Data collection

Labour used for various field activities was estimated during each cropping season by monitoring work rates on the trial field and corroborating them against estimates on neighbouring farms. Seed, fertilizer and herbicide prices were collected from the nearest local agro-input dealers (Chuka). Farm gate prices for farm inputs (leucaena seedlings and Napier stem cuttings), farm products (maize and soybean grains, maize stover, and leucaena and Napier fodder) were obtained through a price survey in 10 farms around the trial site (Table 1).

Fodder yield assessments were carried out on the vegetative barriers in the middle mini-plot. Napier grass was cut at 10 cm from the ground by a panga when 1 m tall while leucaena trees were pruned at 1.3-1.5 m height by secateurs so that the overall height was less than 1 m.

Table 1. Prevailing prices (April 2009) for inputs and outputs used for partial budgeting

	Item	Unit	Price (US$)
Inputs			
	Herbicide	litre	15
	Triple Super Phosphate	kg	0.96
	Urea	kg	0.63
	Maize seed	kg	2.00
	Labour	hour	0.29
	Leucaena seedling	seedling	0.04
	Napier cuttings	cutting (0.5 m long)	0.01
Outputs			
	Maize grain	kg	0.34
	Soybean grain	kg	0.50
	Maize crop residue	kg	0.02
	Leucaena fodder	kg (dry matter)	0.29
	Napier fodder	kg (dry matter)	0.12

On average fodder harvesting was carried out three times each season to minimize shading of the associated food crop. Fodder sub-samples were oven-dried (65°C) until constant weight and dry matter yields determined.

Maize and soybean yields were determined on the middle mini-plot from 22 and 24 m^2 net area for the treatments with and without anti-erosion barriers, respectively. Grain yields were corrected for moisture using a multi-grain moisture meter (Dickey John meter) and yield reported as dry weight. Fodder and crop yields were presented on the basis of the total area occupied by the vegetative barriers and food crops.

Sedimentation traps were installed at the lower end of the experimental plots (Figure 2) and lined with ultra-violet resistant polythene sheets to measure top soil loss. Water from the trapped surface run-off drained through fine holes in the sheet lining leaving behind top soil sediment, which was removed after every major erosion event. Top soil was lost from the plots predominantly by sheet erosion. Top soil sediment was weighed and 10% sub-sampled for dry weight determination. Top soil loss was expressed as the reduction in top-soil depth (Bakker et al., 2004) using the formula: RTSD=M/ (ρ_b x L x W) where RTSD is the reduction in top-soil depth (mm), M is the dry mass of soil sediments (kg), ρ_b is the soil bulk density (kg mm^{-3}), L is the length (mm) and W the width (mm) of the experimental plot.

3.2.5 Data analysis

Partial budgeting based on the guidelines by Alimi and Manyong (2000) was used for economic analysis. A discount rate of 8.8% was adopted and present total variable costs, net benefits and benefit-to-cost ratios calculated to assess economic viability of the tillage and anti-erosion barrier treatments. The treatment costs and benefits were cumulated sequentially over the study period. Marginal Rate of Return (MRR) analysis was carried out to show the economic effect of changing from one treatment to another taking 118% as the acceptable MRR and regular tillage without anti-erosion barriers as the baseline.

Dominance analysis was used to exclude treatments from further analysis that had greater present total variable costs but had also present net benefits equal or smaller value in comparison with other experimental treatments. Thereafter, sensitivity analysis was carried out to assess the changes in MRRs of the treatments not excluded by dominance analysis (non-dominated) for a range of prices for the key inputs. In addition, trade-off analysis between soil conservation and MRRs was carried out to identify scenarios in which various farming objectives can be met. Analysis of variance was conducted on present total variable costs, net benefits and benefit-to-cost ratios, forage and crop yields and soil loss using REML in Genstat version 12 with tillage and anti-erosion barriers as fixed effects and blocks as random effects. Means were compared using the standard error of difference (SED).

3.4 RESULTS

3.4.1 Cumulative soil loss

There were differences in soil loss amongst different cropping seasons and treatments (Figure 2). At the end of long rains 2007 and across tillage practices, leucaena barriers reduced soil loss by 27% (compared with no anti-erosion barriers) while Napier barriers resulted in 64% less loss. Across anti-erosion barriers for the next two cropping seasons (short rains 2007-long rains 2008), cumulative soil loss was smaller with minimum than regular tillage (Figure 2). In the same period but across tillage systems, soil losses were least under Napier barriers, intermediate under leucaena and greatest without anti-erosion barriers. By the last season of the study (short rains 2008), cumulative soil loss was greatest with both leucaena barriers and no anti-erosion barriers and was not affected by tillage practices.

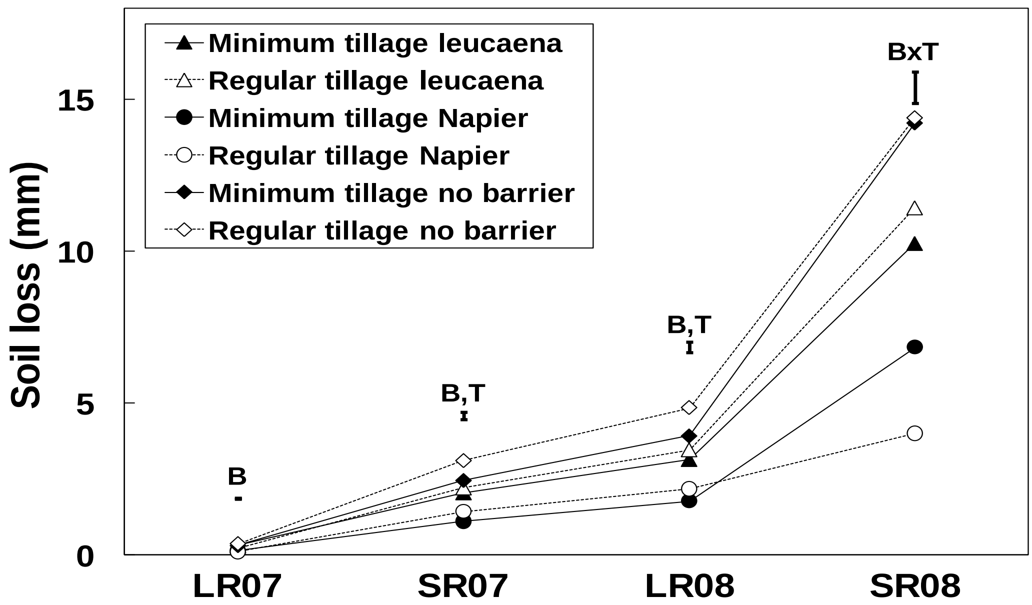

Figure 2. Cumulative soil loss for four consecutive seasons (long rains 2007–short rains 2008) as affected by tillage and barriers. Error bar represent SED for tillage (T) x barrier

interaction. In the graph, LR is for long rains and SR for short rains.
Note: A soil loss of 1 mm is equivalent to 10 Mg ha^{-1} if the bulk density is 1 Mg m^{-3}

3.4.2 Fodder yields

Napier stem-cuttings and leucaena seedlings grew rapidly after planting and fodder biomass was ready for harvesting one season after establishment.

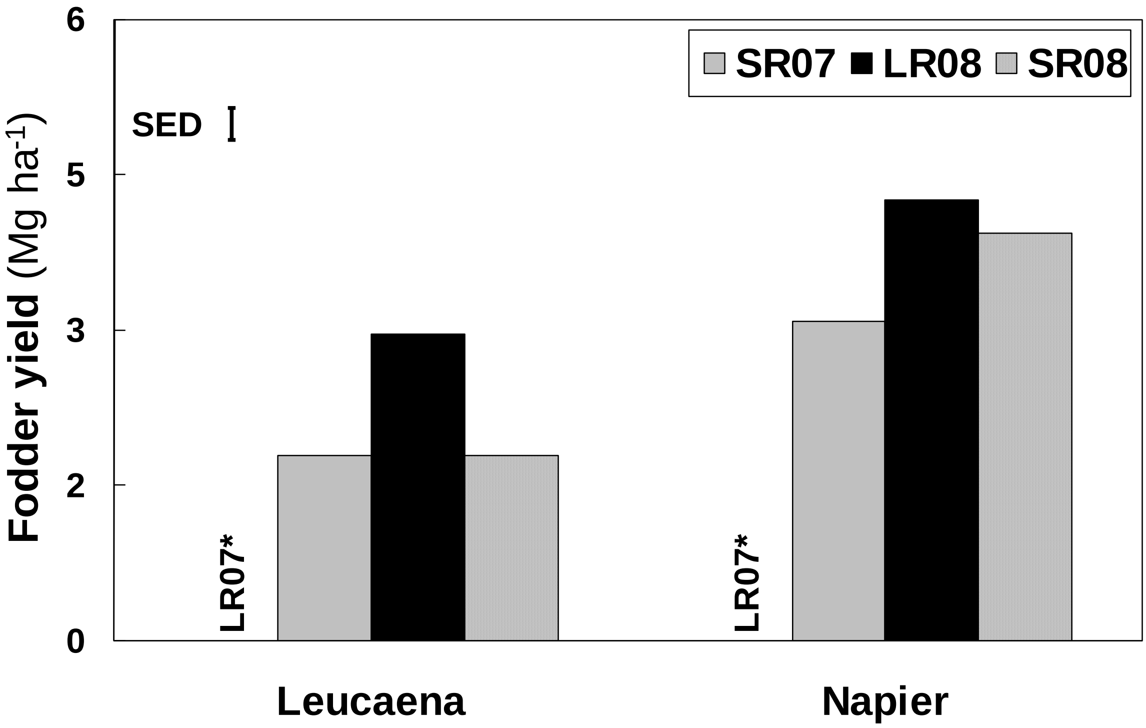

Figure 3. Fodder dry matter yields from Napier and leucaena barriers during three consecutive cropping seasons (short rains 2007-2008). The fodder yields were calculated on a hectare basis, of which 90% was occupied by the crop and 10% by the barrier. The error bar represents SED for cropping season x barrier interaction. In the graph, SR is for short rains and LR for long rains.

*Fodder was not harvested in the first season after establishment of vegetative barriers.

Despite the intense harvesting regime adopted, re-sprouting of the Napier grass and leucaena trees was not affected and less than 2% plant mortality was observed during the study period.

Biomass production from Napier grass and leucaena trees varied between the barriers and cropping seasons (Fig. 3). Across the cropping seasons, a smaller quantity of fodder biomass was obtained from leucaena than from Napier barriers.

Tillage practices had no effect on fodder production. Napier biomass production was smaller in long rains 2007 compared with the other cropping seasons while leucaena biomass was greater for the long than short cropping seasons.

3.4.3 Soybean and maize grain yields

Due to the variations in crop yields between seasons, maize and soybean grain yields are described separately for each season before overall trends in grain yields are considered. In the first season (long rains 2007), soybean grain yields were 0.59 Mg ha^{-1} across tillage and anti-erosion barriers. The soybean grain yields were least under Napier barriers but greater for regular than minimum tillage (Table 2). Soybean grain yields in long rains 2008 averaged 0.38 Mg ha^{-1} across tillage and anti-erosion barriers. Between the different tillage and anti-erosion barriers, soybean grain yields with leucaena barriers were greatest and independent of tillage. Grain yields under Napier barriers were intermediate but greater for regular than minimum tillage. The grain yields were smallest without anti-erosion barriers and minimum tillage out yielded regular tillage.

In short rains 2007, a mean maize grain yield of 4.95 t ha^{-1} was attained across tillage and anti-erosion barriers. Across tillage practices, the maize grain yields were greater under both leucaena and no anti-erosion barriers than under Napier barriers (Table 2). Between tillage and anti-erosion barriers, tillage practices did not affect maize grain yields in leucaena barriers but the yields were greater with regular than minimum tillage under Napier barriers. Without anti-erosion barriers, greater maize yields were obtained with minimum than regular tillage. The average maize grain yield in short rains 2008 across tillage and anti-erosion barriers was 3.56 Mg ha^{-1}. Across tillage practices, grain yields were greatest without anti-erosion barriers followed by leucaena and Napier barriers (Table 2). Across anti-erosion barriers, regular tillage gave better maize yields than minimum tillage.

In general, without anti-erosion barriers, minimum tillage had 18% yield advantage over the control for soybean and maize across the four cropping seasons. With vegetative barriers, the greatest crop yield reduction occurred with Napier barriers for minimum tillage and was 19% and 30% relative to the control for soybean and maize respectively across the four cropping seasons.

Table 2. Maize and soybean grain yields as affected by tillage and anti-erosion barriers for four consecutive seasons (long rains 2007 – short rains 2008). In plots with vegetative barriers, yields were calculated on a hectare basis, of which 90% was occupied by the crop and 10% by the barrier

Barrier	Tillage	Grain yield (Mg ha^{-1})			
		Soybean		Maize	
		Long rains 2007	Long rains 2008	Short rains 2007	Short rains 2008
Napier	Minimum	0.50	0.33	4.0	2.1
	Regular	0.62	0.37	4.9	3.3
Leucaena	Minimum	0.60	0.39	5.4	3.6
	Regular	0.64	0.40	5.6	4.1
None	Minimum	0.62	0.35	5.9	4.1
	Regular	0.64	0.26	4.7	4.0
Treatment means					
Leucaena		0.56	0.35	4.4	2.7
Napier		0.62	0.40	5.5	3.8
None		0.63	0.30	5.3	4.0
Minimum		0.57	0.36	5.1	3.3
Regular		0.63	0.34	5.1	3.8
SED					
barrier (B)		**0.03***	**0.01^{ns}**	**0.21*****	**0.30****
tillage (T)		**0.03***	**0.02*****	**0.17^{ns}**	**0.23***
B x T		**0.04^{ns}**	**0.02*****	**0.30****	**0.43^{ns}**

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

3.4.4 Economic benefits

The total cumulative variable costs for the different cropping seasons varied between tillage and anti-erosion barriers (Table 3). In the first three cropping seasons (long rains 2007 to long rains 2008) and across tillage practices, the cumulative total variable costs were greatest in leucaena followed by Napier and least with no anti-erosion barriers (Table 3). Across all anti-erosion barrier treatments, the cumulative costs were greater with minimum than regular tillage. In the last season and for minimum tillage, the cumulative total costs incurred (above the control) were US$ 800, 650 and 240 for leucaena, Napier and no anti-erosion barriers, respectively. With regular tillage, the cumulative costs were US$ 670 for leucaena and US$ 460 for Napier barriers.

Table 3. Total variable costs (TVC), Net benefits (NB), Benefit to cost (B:C) ratio and Marginal rate of return (MRR) as affected by tillage and barrier practices cumulatively for four consecutive seasons (LR 07–SR 8)

Barrier /Tillage	LR 07			SR 07			LR 08			SR 08			MRR
	TVC US$ ha^{-1}	NB US$ ha^{-1}	B:C ratio	TVC US$ ha^{-1}	NB US$ ha^{-1}	B:C ratio	TVC US$ ha^{-1}	NB US$ ha^{-1}	B:C ratio	TVC US$ ha^{-1}	NB US$ ha^{-1}	B:C ratio	
Leucaena													
Minimum	905	-620	-0.68	1163	1293	0.82	1651	1866	1.13	2046	2990	1.46	1.18
Regular	864	-556	-0.64	1345	1351	1.00	1545	2074	1.34	1917	3450	1.80	2.09
Napier													
Minimum	806	-567	-0.70	1284	614	0.48	1507	986	0.65	1892	1654	0.87	-0.61
Regular	720	-422	-0.59	1171	1130	0.97	1352	1550	1.15	1701	2650	1.56	1.32
None													
Mini-mum	356	-56	-0.16	872	1425	1.63	1082	1369	1.26	1484	2256	1.52	0.08
Regular	257	48	0.18	738	1184	1.60	902	1133	1.26	1244	2047	1.65	-
Treatment means:													
Leucaena	884	-588	-0.66	1380	1257	0.91	1598	1970	1.24	1981	3220	1.63	
Napier	763	-494	-0.64	1228	872	0.72	1429	1268	0.90	1797	2152	1.22	
None	307	-4	-0.01	805	1304	1.62	992	1251	1.26	1364	2151	1.58	
Minimum	689	-414	-0.52	1190	1067	0.98	1413	1407	1.02	1807	2300	1.29	
Regular	614	-310	-0.35	1085	1222	1.19	1266	1586	1.25	1621	2716	1.67	
SED													
barrier (B)	**15***	**24***	**0.056***	**15***	**101***	**0.096***	**15***	**115***	**0.088***	**15***	**251***	**0.140**	
tillage (T)	**12***	**20***	**0.045**	**12***	**82ns**	**0.078**	**12***	**94ns**	**0.072**	**12***	**204***	**0.110**	
B x T	**21ns**	**34ns**	**0.079***	**21ns**	**142**	**0.136***	**21ns**	**163**	**0.124***	**21**	**354***	**0.190ns**	

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

In the first cropping season the net benefits were negative for all the tillage and anti-erosion barriers with the exception of the control (Table 3). The benefits were most depressed with than without barriers and also for minimum than regular tillage. In the following two consecutive seasons and across tillage practices, the cumulative net benefits were positive and largest under leucaena, followed by Napier and least without anti-erosion barriers. But within the anti-erosion barrier treatments, the cumulative net benefits were independent of tillage under leucaena, greater for regular than minimum tillage in Napier and greater for minimum than regular tillage without barriers. In the last season, and for minimum tillage, the cumulative net benefits (compared with the control) were US$ +940, -390 and +210 ha^{-1} for leucaena, Napier and no anti-erosion barriers, respectively. With regular tillage, the net benefits were US$ +1,400 ha^{-1} for leucaena and US$ +600 ha^{-1} for Napier barriers.

The benefit-to-cost ratios for the tillage and anti-erosion barriers were generally negative in the first season but were all positive in the second cropping season (Table 3). For the treatments with barriers, only leucaena barriers under regular tillage had ratios above parity in the second season. In the third and fourth season, all tillage and anti-erosion barriers had ratios above parity, except for Napier barriers under minimum tillage. By the end of the study and across tillage practices, the benefits to cost ratios were largest with leucaena followed by no anti-erosion barriers and least under Napier barriers. Across the anti-erosion barriers, regular tillage had a greater benefit-to-cost ratio (1.67) than minimum tillage (1.29).

Between tillage and anti-erosion barriers, the MRR were positive for all treatments, except under Napier barriers for minimum tillage (Table 3)**.** The highest positive MRR were realized under leucaena barriers with regular tillage followed by Napier with regular tillage while minimum tillage without barriers had the lowest returns.

3.5 DISCUSSION

3.5.1 Tillage and vegetative barrier effects on crop and fodder yields

Maize grain yields in short rains 2007 were greater than those in the control for all the tillage and anti-erosion barrier treatments, except with Napier barriers when minimum tillage was practiced (Table 2). The grain yield increase was probably due to soil and water conservation effects of the tillage and vegetative barriers (Figure 2) that compensated for the loss of land plus any reduction in crop yield in the barrier-crop interface. Maize crop yield trends coupled with the yield advantage in the minimum tillage without anti-erosion barrier treatment supported the interpretation that varying degrees of complementary and competitive resource may have occurred between maize and the vegetative barriers. Further studies on profile water dynamics and individual row crop yields between the barrier rows would explore the occurrence and intensity of such interactions.

Leucaena barriers had smaller average fodder yields (2.18 Mg ha^{-1} $season^{-1}$) compared with Napier (3.76 Mg ha^{-1} $season^{-1}$) because in the latter, grass was cut close to ground level in contrast to the former where leucaena trees were maintained at 1 m height. Fodder yields are an added benefit to farmers who establish vegetative barriers for soil conservation (Angima et al., 2002). The leucaena fodder can supplement and in some cases substitute for purchased concentrates for livestock and Napier grass supplies roughage and carbohydrates required by animals.

3.5.2 Tillage and vegetative barrier effects on soil loss

Leucaena and Napier vegetative barriers intercepted soil sediments effectively and reduced soil loss. One season after establishment and compared with no anti-erosion barriers, soil loss was 15% lower for leucaena barriers and 69% lower for Napier. Angima et al. (2002) however observed less soil loss reduction in the region of study but their treatments combined a different vegetative (calliandra-Napier) barrier on steeper slopes. Across tillage practices, Napier barriers were more efficient and reduced soil loss by 65% (compared with no anti-erosion barriers) as opposed to leucaena barriers (27%) showing that grass barriers were superior to those of woody species in soil conservation. Species with a dense system of tillers and fibrous roots near the soil surface conserve soil and water better than those with only a few stems (Chaowen et al., 2007; Sudishiri et al., 2008).

For leucaena barriers, cumulative soil loss was less under minimum than regular tillage whereas a reverse trend was observed between the tillage practices with Napier barriers. The efficiency of vegetative barriers in soil conservation depends on the vegetative development, natural undergrowth, soil surface management and performance of the associated crop (Spaan et al., 2005; Pansak et al., 2010). The increased conservation capacity of leucaena barriers with minimum tillage may be related to less soil disturbance since crop performance was similar across tillage practices (Table 2). However, with Napier barriers more soil was lost with minimum tillage than with regular tillage due to poor crop performance that reduced soil cover, coupled with sparse development of natural undergrowth due to use of herbicides. Pansak et al. (2008) found that reduced run-off and soil loss from arable fields depended not only on the presence of vegetative barriers, but also on improved crop performance. Across the four cropping seasons and compared with the control, Napier barriers with regular tillage conserved most soil (72%) followed by Napier under minimum tillage (53%) while minimum tillage without anti-erosion barriers conserved least soil (1%) with leucaena barriers being intermediate. The soil conservation efficiency of the different anti-erosion barriers therefore depended both on which species formed the barrier and soil surface management between the barriers. Minimum tillage without anti-erosion barriers was inefficient for erosion control because most of the maize crop residue was cut and removed from the field. Crop residue from soybean did not provide adequate soil surface cover due to poor soybean crop performance (Table 2) and rapid decomposition of residue of narrow C-to-N ratio. Minimum tillage therefore should only be practiced if there is crop residue that provides adequate soil cover (preferably with wide C-to-N ratio) and supportive soil and water conservation measures are established.

3.5.3 Economic benefits for tillage and anti-erosion barriers

There were no positive net benefits realized in the first season (long rains 2007) under leucaena and Napier barriers (Table 3) due to barrier establishment costs (purchase and planting of tree seedlings/stems cuttings) coupled with the relatively poor yield of soybean due to inadequate rainfall as well as the lack of extra benefits from fodder. Further, the minimum tillage systems did not increase net returns over regular tillage because the added expense associated with herbicide purchase was not offset by the value of the soybean yield. The high investment costs and initial negative returns can be major hindrances to the adoption of soil and water conservation measures by smallholder farmers. This is in agreement with the findings of Tenge et al. (2005) who suggest gradual establishment of vegetative barriers and promotion of intensively managed dairy cattle as options to offset the initial negative returns.

Greater maize yields in the second season (short rains 2007) with adequate rainfall together with extra benefits from fodder increased cumulative net benefits (Table 3). The corresponding benefit-to-cost ratios were also positive for all tillage and anti-erosion barriers with the exception of Napier barriers with minimum tillage where crop yields were depressed. The cumulative benefit-to-cost ratios increased gradually and were greater than parity by the last season for all tillage and anti-erosion barriers, except for Napier barriers with minimum tillage. Napier barriers with minimum tillage also had negative marginal rates of return making both the recovery of investment costs and profit generation unlikely. The benefit-to-cost ratios in this study were less than those reported by Ngambeki (1985) and Tonye and Titi-Nwel (1995) for studies involving leucaena barriers in the humid regions of Africa. The fodder yields from vegetative barriers in the humid regions are double those realized in the sub-humid regions (Mugendi et al., 1999) and this is likely to increase the benefits that accrue from vegetative barriers in the humid regions.

3.5.4 Soil conservation and economic return trade-offs

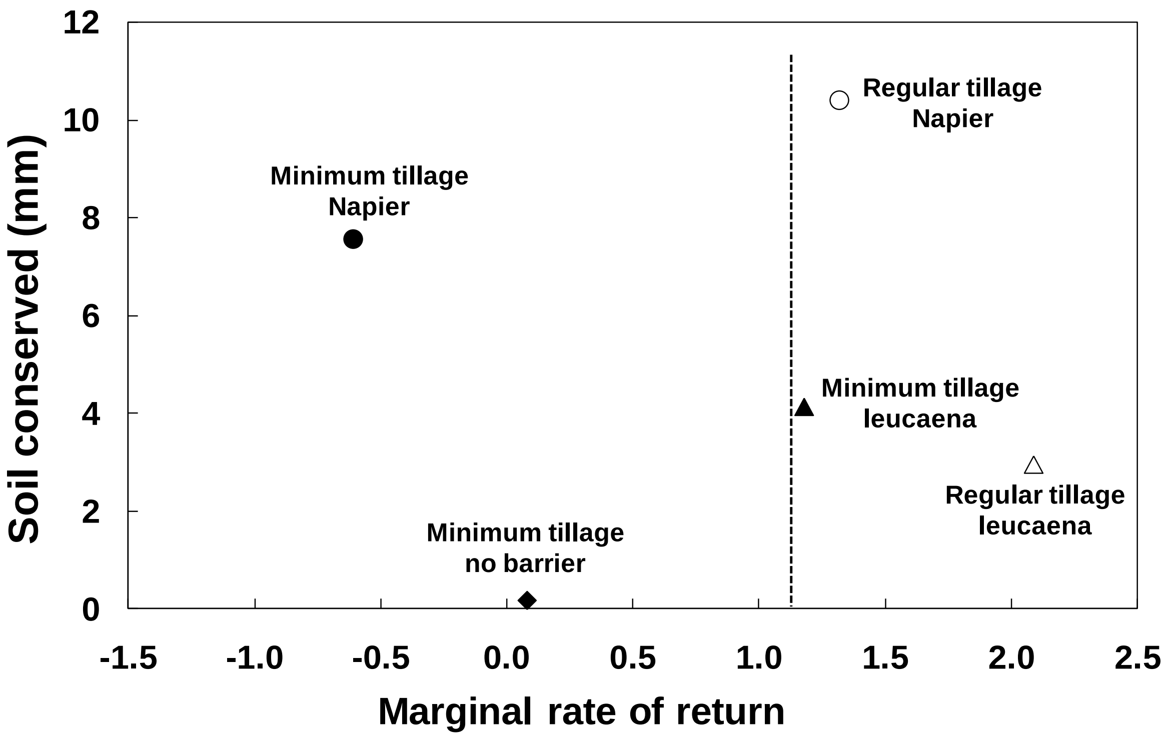

Figure 4. Trade-offs between cumulative soil conserved and marginal rate of return during four cropping seasons (long rains 2007 – short rains 2008) for the tillage and barriers. The dotted vertical line represents the minimum acceptable return (1.18).
Note: A soil conservation level of 1 mm for the top-soil is equivalent to 10 Mg ha^{-1} of soil conserved if the bulk density is 1 Mg m^{-3}

Considering marginal rates of return and soil conservation, the Napier barriers with regular tillage presented a win-win scenario for farmer production and environmental impacts because of the attractive MRRs and efficient soil conservation (Figure 4). Minimum tillage however depressed MRRs from Napier barriers and reduced the soil conservation efficiency slightly making this option less attractive depending on the minimum acceptable degree of soil conservation assumed. For leucaena barriers, the MRRs were attractive across the tillage systems but a smaller amount of soil was conserved compared with Napier barriers. Smallholder farmers can therefore adopt leucaena barriers provided they are willing to trade-off the reduced effect on soil conservation. Without vegetative barriers, minimum tillage conserved the least soil and MRRs were small making this option unattractive.

Since MRRs from Napier barriers with regular tillage and leucaena with minimum tillage were just above the acceptable rate (Figure 4), sensitivity analysis was needed to show the effect of changes in the price of labour and herbicide on MRRs (Figure 5). If the price of labour was below US$ 0.30 $hour^{-1}$, acceptable MRRs were feasible from Napier barriers with regular tillage. For leucaena barriers under minimum tillage, labour price should be below US$ 0.36 $hour^{-1}$ and herbicide price below US$ 20 $litre^{-1}$ for attractive returns.

Tree seedlings are key inputs whose price affects establishment and profitability of tree barriers due to intrinsic supply constraints (Young, 1990). Leucaena tree seedling prices should be below US$ 0.065 and 0.04 for regular and minimum tillage respectively to have acceptable MRRs. For Napier barriers under regular tillage, the price of a stem cutting should be below US$ 0.014 for acceptable MRRs.

3.6 CONCLUSION

This study demonstrates that vegetative barriers can be used to reduce soil loss making these barriers suitable conservation farming options for erosion control and restoration of soil productivity. The crop area occupied by vegetative barriers was compensated by crop yield gains from the remaining arable area coupled with.

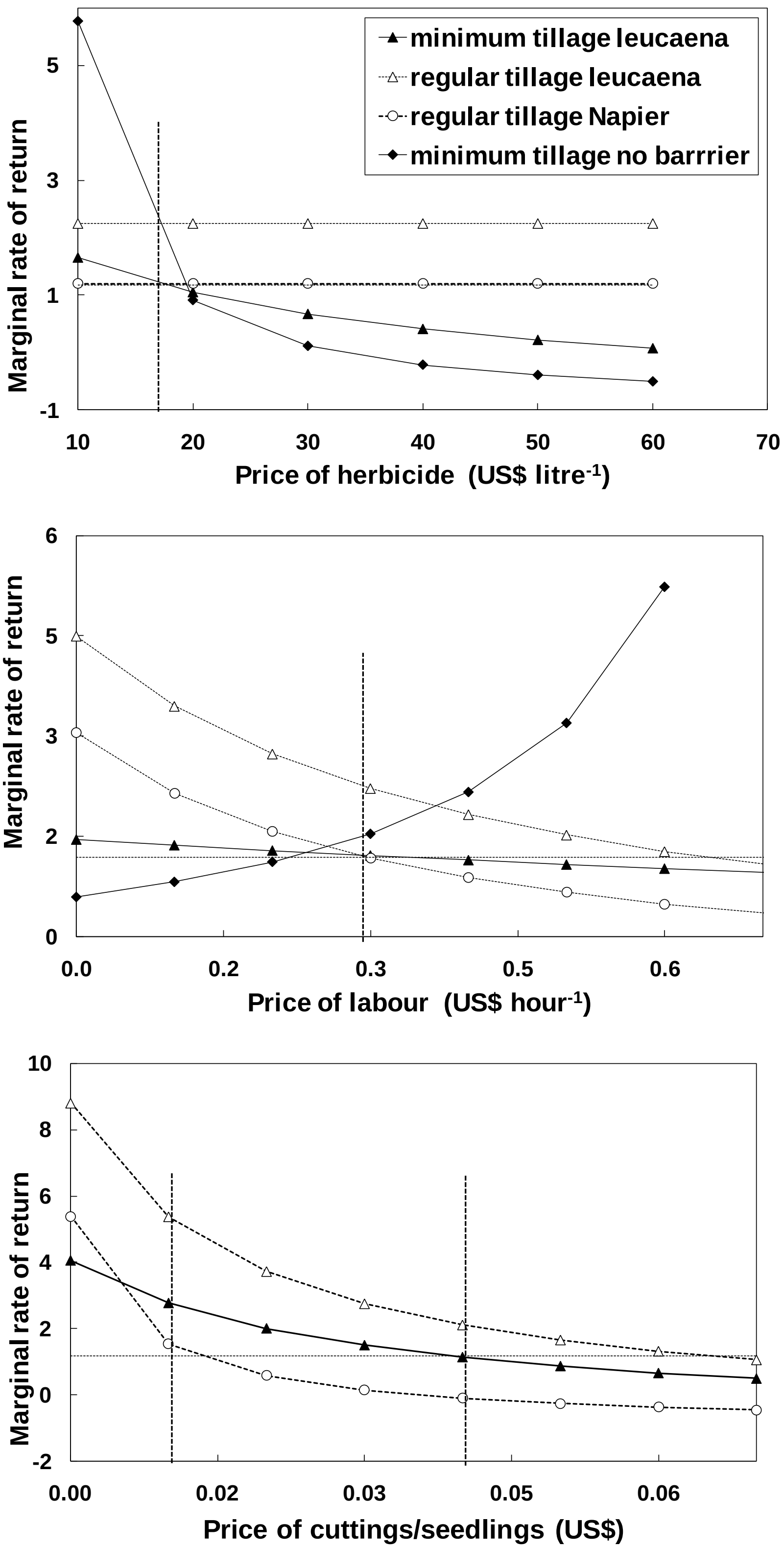

Figure 5. Sensitivity of marginal rate of return to herbicide (above), labour (middle) and cutting/seedling (below) prices for the non-dominated treatments. The dotted vertical lines represent the prevailing prices of herbicide (US$ 15 litre^{-1}) labour (US$ 0.29 hour^{-1}) and Napier stem cuttings/leucaena tree seedlings (US$ 0.01/0.04) while the dotted horizontal lines represent the minimum acceptable rate of return (1.18).

income from fodder. The only exception was for Napier barriers with minimum tillage probably due to increased crop-barrier competition. Leucaena barriers had attractive economic returns but were less efficient in soil conservation and maybe suitable for farmers willing to trade-off soil conservation efficiency in favour of economic returns. However, minimum tillage without anti-erosion barriers or adequate soil cover might not be suitable for the study area due to inefficient soil conservation and poor economic returns. Napier barriers with regular tillage presented a win-win scenario for farmers and environmental policymakers due to efficient soil conservation and attractive economic returns but labour and stem cutting prices should not increase if profitability is to be maintained. Further studies are necessary to ascertain the performance of minimum tillage without barriers due to the influence of one extreme rain season on its performance. Additionally, the performance of tillage and barriers in heterogeneous smallholder farms needs to be investigated to allow extrapolation of the results.

ACKNOWLEDGEMENTS

We thank the Netherlands Universities Fund For International Cooperation (NUFFIC) for funding through a PhD scholarship to S.N. Guto and the Kenya Ministry of Agriculture for logistical support. We thank Oliver Njue (the farmer) who provided the field for conducting this study and Bernard Gitonga for technical support in the field.

Chapter 4

Tillage and vegetative barrier effects on soil water relations and crop yields

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This chapter is to be submitted for publication as: Guto, S.N., Pypers, P., de Ridder, N., Giller, K.E. Vanlauwe, B., 2010. Tillage and vegetative barrier effects on soil water relations and crop yields. Field Crop. Res.

ABSTRACT

A study was initiated in a sub-Humid region of Central Kenya where intra-seasonal dry spells are common to explore soil water relationships and crop production. The objective was to examine the impact of tillage practices and vegetative barriers on soil water and crop performance. There were two tillage practices; minimum and regular tillage and two vegetative barriers; leucaena and Napier grass as well as a control without barriers. Maize and soybean were planted in rotation between the barriers. We measured crop yields separately for each row and soil loss after every major erosive rainfall event. Soil moisture was measured near (0.45 m) and away (3.5 m) from the barriers. Vegetative barriers influenced soil water content during wet and dry periods. In wet periods, more run-off was conserved with than without vegetative barriers. Across tillage practices, more water accumulated near the barriers with Napier than leucaena. In the dry period, reduction of conserved water commenced early and at a faster rate near than away from barriers. The rate of water reduction near barriers was higher with Napier than leucaena, particularly if minimum tillage was practiced. With Napier barriers, row crop yields were significantly reduced up to 3 m away from the barriers if minimum tillage was practiced, and up to 1.5 m with regular tillage. Such yield reductions were less pronounced with deep-rooted leucaena barriers. Napier barriers therefore competed for water and nutrients with companion crops whilst leucaena had a more complementary resource use pattern. Establishment of vegetative barriers can curb soil erosion. Napier grass barriers are efficient in conserving soil and water but compete with crops for available water especially with minimum tillage even when intensely pruned. Leucaena barriers have complementary water use pattern with crops independent of tillage practice but are less efficient for soil and water conservation.

Keywords: Napier and leucaena, yield suppression, accumulation, competition, complementation

1.0 INTRODUCTION

Food production and rural livelihoods in smallholder farming systems of sub-Saharan Africa depend on rain fed agriculture. Erratic rainfall patterns and soil water loss through surface run-off and deep percolation constrain agricultural production, particularly on steeply-sloping land. Improved soil and water management to optimize production is necessary for long-term sustainability of the smallholder farm production system. Impermeable barriers such as fanya juu (digging a trench and throwing soil up-slope) which check run-off by enhancing infiltration, can control surface run-off but they occupy land area for crops and require intensive labour for construction (Tenge et al., 2005; Sudishiri et al., 2008). Vegetative barriers that involve growing rows of perennial vegetation (grass and trees) simultaneously with arable crops occupy less land and are easy to establish (Young, 1990: van Roode, 2000), offering a superior alternative for soil and water conservation (Garrity, 1996; Angima et al., 2003; Kinama et al., 2007).

Vegetative barriers reduce soil and water loss (Angima et al., 2002), improve soil fertility (Buresh and Tian, 1998) and increase crop yields (Mutegi et al., 2008). Above- and below-ground competition for resources between the barrier and crop system components can occur (Duguma et al., 1988; Mugendi et al., 1999) and may depress crop yields (Huxley et al., 1994; Dercon et al., 2006). Pruning the vegetative barriers controls both the above-ground competition for solar radiation (Lawson and Kang, 1990; Kang, 1993; Everson et al., 2009) and below-ground competition for water and nutrients (Livesley et al., 2004; Kang et al., 2008). In addition, deep rooted vegetative barriers compete less with crops for water and nutrients (Garitty et al., 1995; van Roode, 2000) due to niche differentiation in resource use and capture of leached nutrients (McIntyre et al., 1997; Jama et al., 1998).

Intensive soil preparation by hoe or plough combined with removal of crop residues leaves the soil surface exposed to degradation (Lal, 1989; Chivenge et al., 2007)). In minimum tillage, soil inversion is minimal and this reduces soil degradation (Hobbs et al 2008; Guzha, 2004). Minimum tillage enhances soil and water conservation (Fuentes et al., 2003; Bescansa et al., 2006; Carof et al., 2007). Run-off of surface water is reduced (Biamah et al., 1993; Thierfelder and Wall, 2009) through improved soil structure and stable soil pore system (Govaerts et al., 2009) that lead to increased infiltration and available water for crop production (Six et al., 2002). The beneficial effects of permanent soil cover by crop residues alongside minimum tillage on soil and water conservation are well recognized (Monneveux et al., 2006; Schwartz et al., 2010). But the difficulty in producing or procuring the mulch material makes permanent soil cover a practically difficult innovation (Rockstrom et al., 2009), particularly in smallholder farming systems such as those in Central Kenya with stall-fed dairy cows (Tittonell et al, 2010). Feed shortage is common (Bebe et al., 2002), resulting in a huge demand for crop residues as fodder (Rufino et al., 2009). Emphasis is needed on practicing minimum tillage less dependent on maize residues for soil cover.

The strategy for successful introduction of tillage and vegetative barriers in water deficient farming environments is to manipulate system components to ensure facilitative or complementary resource use while limiting competition (Wallace, 1996; Teixera et al., 2003). The measurement of profile soil water contents allows understanding of the success of such strategies (Hauser et al., 2005). Studies on the effects of tillage (Gicheru 2004) and vegetative barriers (Kiepe 1996; McIntyre et al., 1997; Kinama et al., 2007) on soil water relations and crop performance in Kenya have mainly been carried out in the semi-arid tropics where strong water deficits prevail. Further studies are necessary to explore the water relations in tillage and barrier-intercrop systems in the sub-humid regions where intra-seasonal dry spells are common and their impact on crop production severe, particularly when they coincide with critical stages in crop development (Jaetzold et al., 2006). A study was therefore initiated to explore the impact of tillage practices and vegetative barriers on soil water and crop yields in the sub-humid region of Central Kenya. The specific objectives of the study were to determine effects of tillage practices and barriers on: (1) soil water accumulation, (2) soil conservation, (3) soil water depletion, and (4) row crop yields.

4.2 MATERIALS AND METHODS

4.2.1 The study area

The study was conducted from February 2007 to February 2009 at Kirege Location of Central Division in Meru South District of Central Kenya about 70 km East of Mt. Kenya and (0.35°S, 37.65°E, 1429 metres above sea level). The rainfall is bimodal with two rain seasons of almost equal duration; long rains from mid March to June and short rains from mid October to December. The mean annual rainfall is 1500 mm and the mean annual temperature is 19°C. The site was representative of the predominant soils in the Central Kenya region (Humic Nitisols: FAO, 1991) and slope (average 12%).

4.2.2 Experimental design

The experiment tested two main factors: tillage and barriers. Tillage had two treatments: (1) minimum tillage where soil disturbance was limited and (2) the regular tillage practice in the area where land preparation and weed control involved soil manipulation. There were three barrier treatments: (1) ‘leucaena’ consisting of leguminous trees (Leucaena trichandra Zucc. Urband), (2) ‘Napier’ consisting of Napier grass (Pennisetum purpureum Schumach), and (3) a control without barriers. The six experimental treatments (2 tillage x 3 barriers) were laid out in a randomized complete block design in three replicate blocks. Regular tillage without barriers was taken as the baseline for assessment of tillage and barrier effects on soil and water conservation.

4.2.3 Plot design and management

Experimental plots were separated by 50 cm wide boundaries of creeping signal grass (Brachiaria humidicola L.). Each experimental plot had three terraces on the upper, central and lower end. The upper and lower terraces were guard zones while the central terraces were used for experimental measurement. Each terrace was 4 m wide but the length varied from 7 to 8 m depending on the slope, with the length greater for smaller slopes based on the formula proposed by Thomas (1997) where a vertical interval of 1.6 m is used for steep slopes and 1.8 m for gentle slopes.

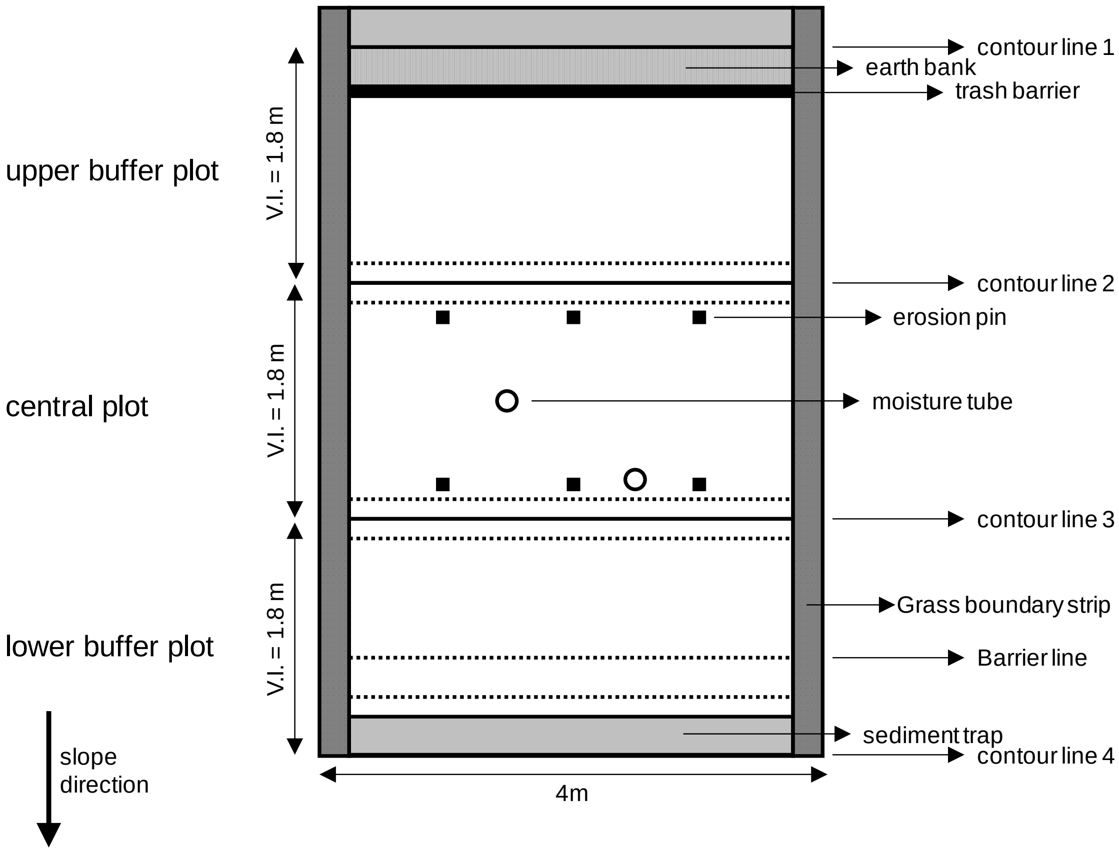

Figure 1. The design of the central terrace for a plot with vegetative barriers showing the position of two PVC access tubes for moisture measurement. The two barriers rows at the upper end of the terrace replaced one row of maize or two rows of soybean.

In plots with vegetative barriers, double rows of either Napier grass or leucaena trees were planted on the upper end of each terrace (Figure 1) at 50 and 20 cm inter and intra-row spacing respectively. A staggered planting pattern was used. For experimental plots under regular tillage, the land was tilled at the beginning of the cropping season and weeds controlled thereafter with a hand-hoe. In minimum tillage, a post-emergent broad-spectrum herbicide (glyphosate based, 500 g litre^{-1} active ingredient) was used to control weeds before planting. Thereafter, weeds were controlled while limiting soil disturbance by uprooting perennial weeds and slashing annual weeds. Maize (Zea mays L., Dekalb variety 8031) in short rain season and soybean (Glycine max L., Merill, variety TGx1740-2F) in long rain season were planted in the experimental plots. The distance between each vegetative barrier row and the nearest crop was 25 cm. The plots without barriers had either ten rows of maize (planted at 75 cm between rows and 25 cm within row) or fifteen rows of soybean (planted at 50 cm between rows and 10 cm within row) in every terrace. With vegetative barriers, a barrier row replaced either one row of maize or two rows soybean (Figure 1). All the plots received the same rate of N and P fertilizer (50 kg of N in two splits and 30 kg P ha^{-1}) in the short rain season only. At maize crop harvest, maize stover was cut at about 50 cm from the ground and crop residues removed from the field to mimic a common practice in the study area. For soybean, all crop residues (leaf fall and harvest residues) were left in the field for soil cover.

Napier grass was cut at 10 cm from the ground when 1 m high and leucaena trees pruned to maintain overall 1 m height at a frequency of 6-8 weeks. All biomass from the vegetative barriers was removed from the plots, as farmers commonly use this as animal feed (or firewood for leucaena). To prevent interference between treatments, trenches about 1 m deep were dug at the end of each long rain season along plot boundaries adjacent to barriers in the central terrace area.

4.2.4 Soil water measurements

Access channels were established and PVC access tubes (150 cm length and 23 cm diameter) with a water-tight lid at the bottom were installed in the central terrace during the third week of September '07. Precautions were taken to ensure that there were no air gaps by carefully re-filling the access channels to ensure tight contact between the access tubes and the soil. In plots with vegetative barriers two sets of access tubes were set up at the central terrace: near the barrier (0.45 m from the lower barrier) and 3.5 m from the barrier (away from the barrier) (Figure 1). In plots without barriers, there was a single set of access tubes at the middle of the terrace. Six additional access tubes were installed in the guard zone of the experimental area for calibration purposes. Two of the calibration tubes were set up next to Napier vegetative barrier. To prevent entry of surface run-off to the access tubes, 20 cm of the tubes projected above the soil surface. Installation of access tubes was completed three weeks prior to the onset of rains.

Soil moisture measurements commenced in the short rains ’07. A three week period elapsed before the measurements started to allow the access tubes to equilibrate in the soil. Measurements were taken three times every week between planting and harvest of the field crops using a portable Diviner 2000 model (Evett et al., 2009) moisture monitoring equipment at regular intervals of 10 cm down through the soil profile to a maximum depth of 130 cm. In the last season, soil samples were taken adjacent to six access tubes installed in the guard zone of the experimental area (two in wet soil artificially ponded with water for two days continuously before soil sampling, two in moist soil and two in a soil profile dried by Napier grass) for calibration. Some access tubes were also dug out in the last season and the growth patterns of crop and barrier roots along access tubes checked. There was no preferential growth of roots along the tubes that would have interfered with soil water measurements. Regression curves were developed between scaled frequency and actual soil volumetric water content. Calibration equations were linear (0-60 cm) and exponential (70-130 cm) for the different depths of the profile. Regression coefficients of scaled frequency against actual volumetric soil water content explained more than 90% of the variation.

4.2.5 Data collection

All the individual rows of soybean and maize in the central terrace were harvested separately to assess the impact of tillage practices and vegetative barriers on spatial crop performance. The net row length was 3 m. Row grain yields were corrected for moisture using a moisture meter (Dickey John multi-grain moisture metre) and yields reported as dry weight.

Sedimentation traps were installed at the bottom end of the lower terraces and lined with ultra-violet resistant polythene sheets before the onset of rains in the first cropping season. Water in trapped run-off drained through fine holes in the sheet lining leaving behind soil sediments. The soil sediments were removed after every major erosion event, weighed and 10% sub-sampled for dry weight determination. The sediment traps were regularly repaired and the polythene linings replaced every season.

4.2.6 Data analysis

Analysis of variance (ANOVA) was conducted on row crop yields, soil loss and soil water using Genstat 12th edition with tillage practice and barriers as factors. For soil profile moisture, ANOVA was carried out separately for each depth and profile position. In analysis of total soil moisture, ANOVA with repeated measures was used. A square root transformation was used to normalize skewed moisture data. Means were compared using the standard error of difference (SED). The variability associated with differences in row grain yield was estimated by calculating the coefficient of variation (CV).

4.3 RESULTS

4.3.1 Soil water during wet periods

A large amount of data was collected which cannot be presented in its entirety. Instead, selected data representing key trends relevant to study objectives are presented. In the short rains 2007, about 650 mm of rain fell in the first six weeks of the season (Figure 2 c) and soil water content increased simultaneously in all treatments for the first four weeks (Figure 2 a, b). After the fourth week, soil water content increased slightly for treatments without barriers while with vegetative barriers, there was continued soil water build up until the 6th week.

In long rains 2008, less rainfall was experienced (Figure 3) and the magnitude of soil water build up reduced but the trends (not shown) were similar to those observed in short rains 2007. For the last season (short rains ’08), rainfall (not shown) increased soil water in the pre-seasonal period. A dry period followed until November 2008 when heavy rainfall totalling 690 mm fell (Figure 4 c). Soil water increased concurrently in all treatments peaking at the end of January following trends similar to those in short rains 2007 (Figure 4 a, b). Taking regular tillage without barriers as the baseline, more water accumulated near than way from barriers, particularly with Napier barriers than with leucaena across the three seasons (Table 1). Away from barriers and in the control (without barriers), more water accumulated with regular than minimum tillage.

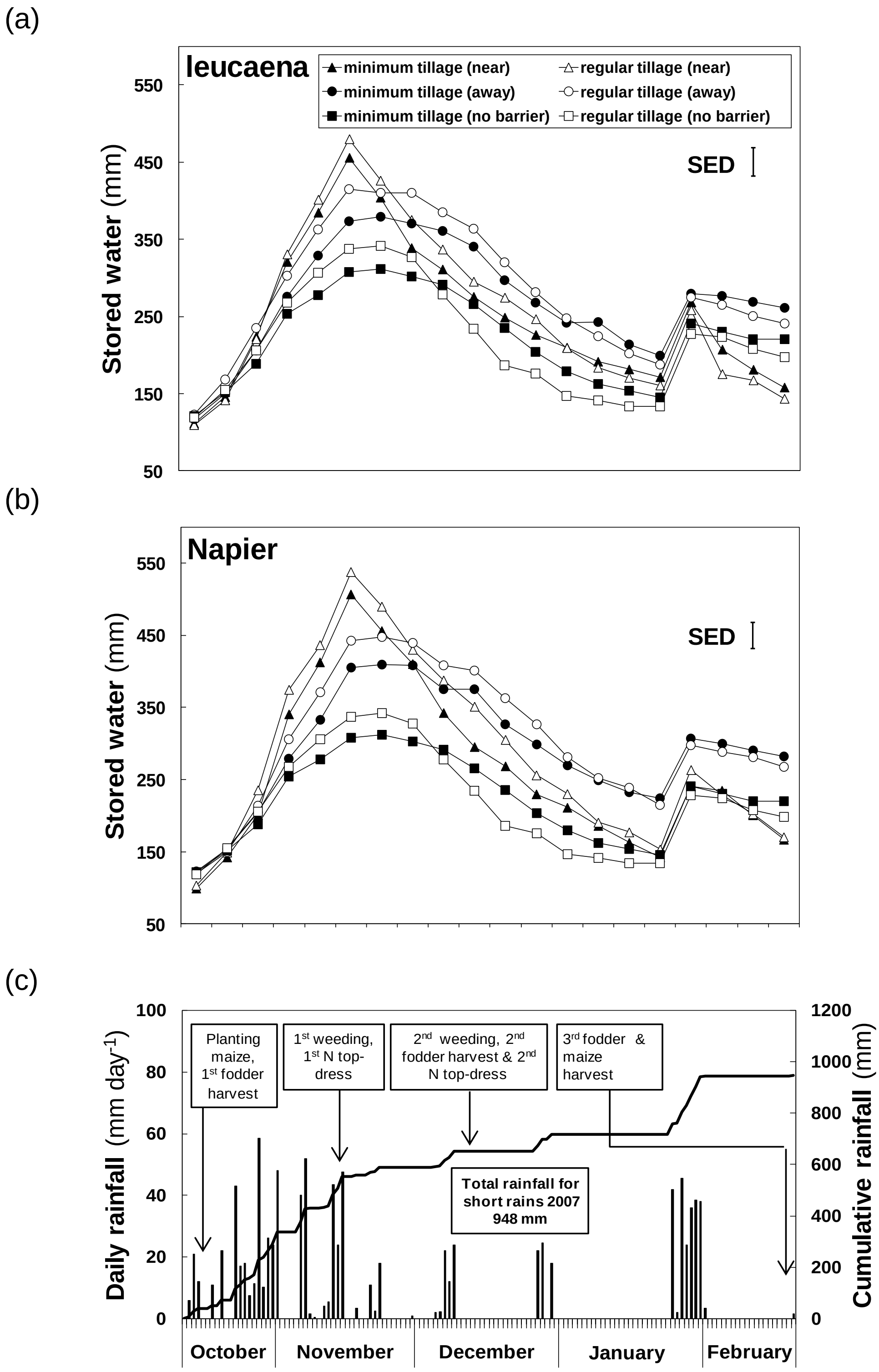

Figure 2. Stored soil water in the top 130 cm soil profile for (a) leucaena (b) Napier barriers along with control for minimum and regular tillage and (c) daily and cumulative rainfall for the short rains '07. Error bars represent pooled SED for time, tillage and barrier interaction.

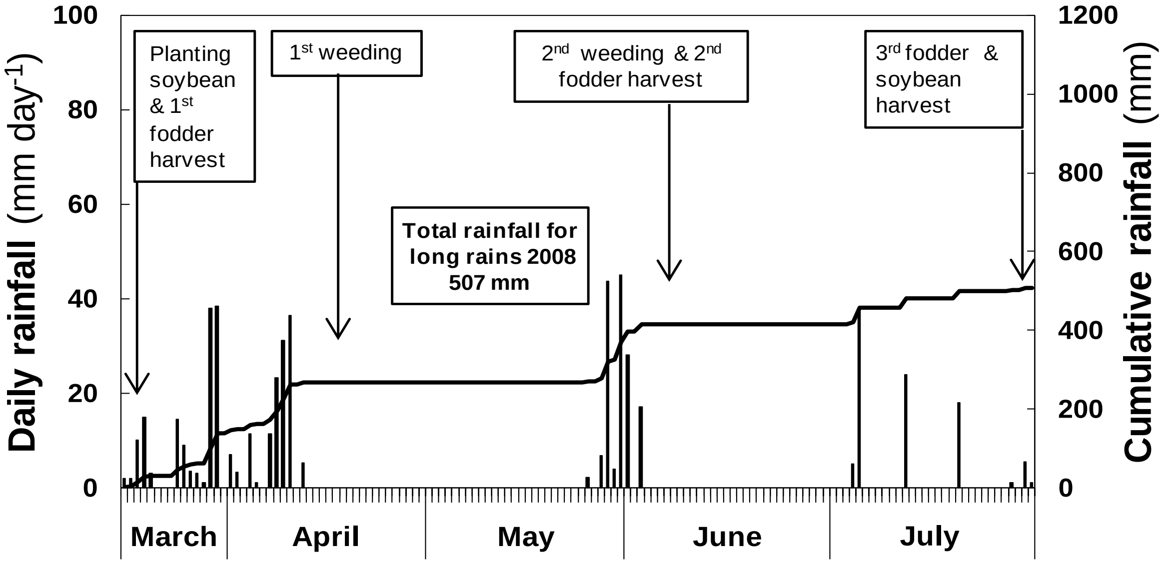

Figure 3. Daily and cumulative rainfall for long rains ’08 at the experimental site.

Table 1. Soil water accumulation (mm) during the wet period in short rains 2007 to short rains 2008 as affected by barriers, tillage and profile position with regular tillage and no barriers as the baseline

Barrier	Minimum tillage		Regular tillage	
	Near	Far	Near	Far
Leucaena	107	27	128	46
Napier	182	63	187	76
None	-13		0	
SED				
Barrier (B)				**11****
Tillage (T)				**9***
B x T x Position				**15***

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

4.3.2 Soil loss

Rainfall events in the long rains 2007 were below 40 mm day^{-1} (Figure 5) while in the short rains 2007 and the long rains 2008, rainfall events between 20-60 mm were frequent (Figure 2c and 3). In the short rains 2008, rainfall was most intense and events above 60 mm were recorded in three days (Figure 4c). The least seasonal rainfall fell in the long rains ’07 causing least soil loss (Table 2). The greatest number of erosion events was experienced in the short rains ’08 when storms were heaviest.

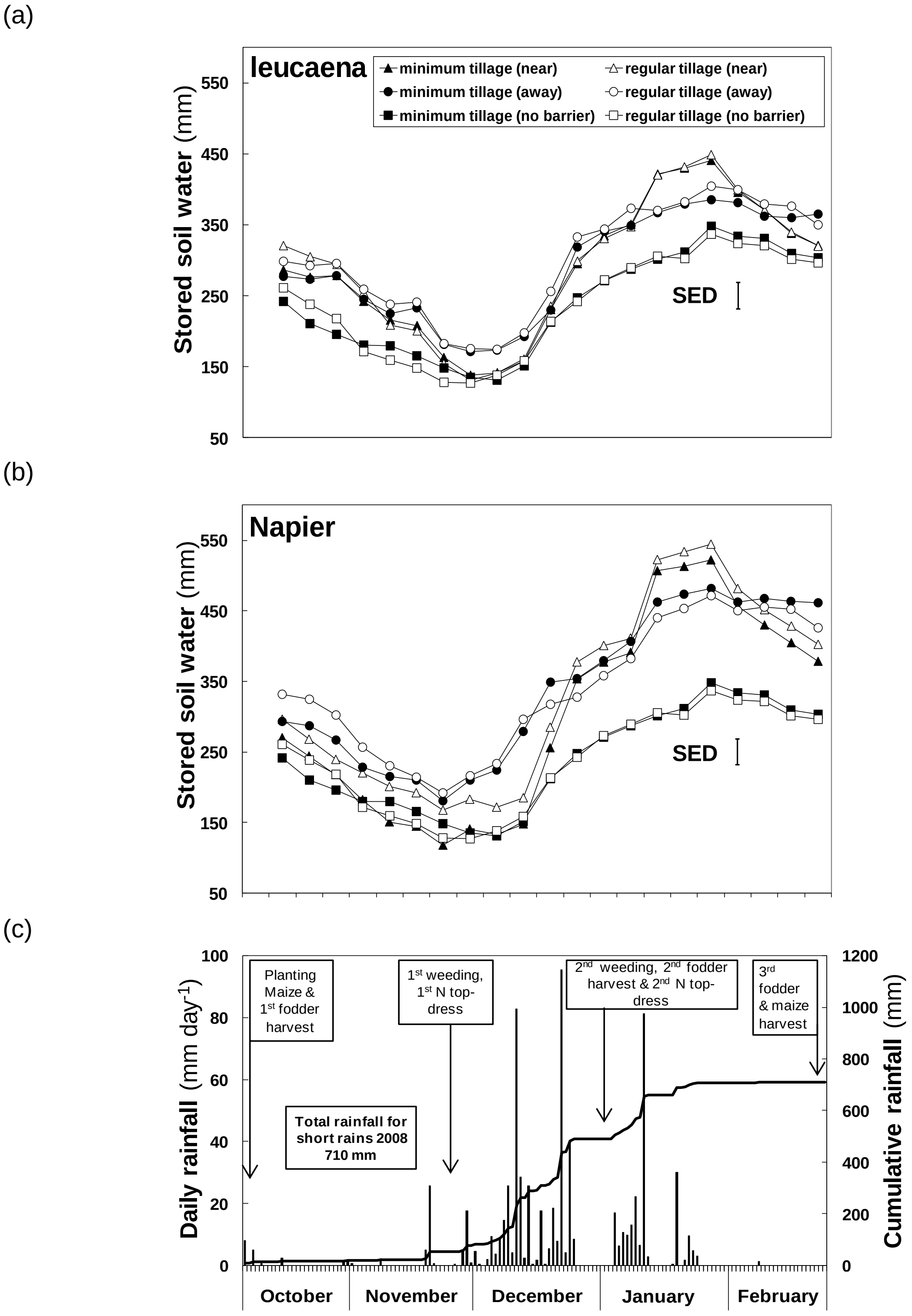

Figure 4. Stored soil water in the top 130 cm soil profile for (a) leucaena (b) Napier barriers along with control for minimum and regular tillage and (c) daily and cumulative rainfall for the short rains '08. Error bars represent pooled SED for time, tillage and barrier interaction.

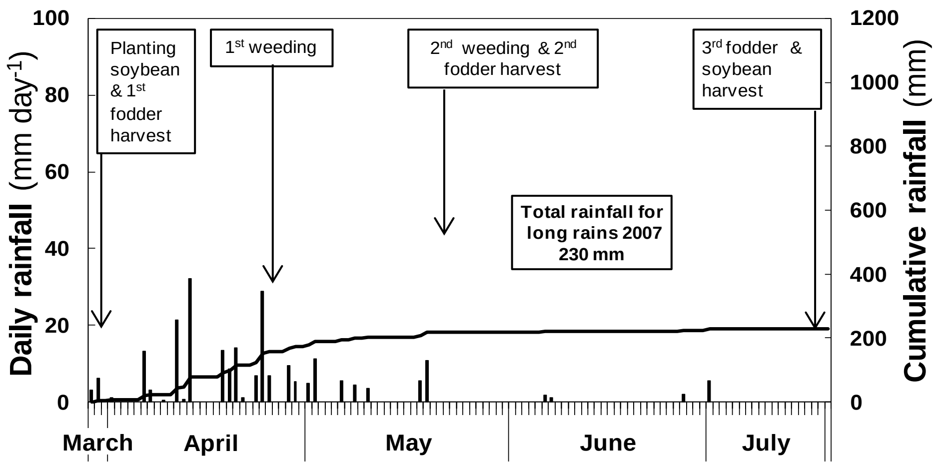

Figure 5. Daily and cumulative rainfall for long rains ’08 at the experimental site.

Table 2. Total seasonal rainfall, number of erosion events and soil loss in long rains 2007 through short rains 2008

Season	Rainfall (mm)	Number of erosion events	Seasonal soil loss (Mg ha^{-1})
LR 07	228	2	2
SR 07	947	3	20
LR 08	506	2	30
SR 08	710	6	100
SED			**5*** **

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively
Note: A soil loss of 10 Mg ha-1 is equivalent to a 1mm reduction in top-soil depth if the bulk density is 1 Mg m^{-3}

The relationship between rainfall and soil loss was linear for Napier barriers (Figure 6). For the control and leucaena barriers, the relationship between precipitation and soil loss was a 2nd order polynomial. For small to moderate rainfall events, the relationship was linear but as rainfall increased, some points were scattered away from the regression line making the relationship positive but skewed (Figure 6).

4.3.3 Soil water during a dry period

The short rains 2007 season had a distinct within season dry period that commenced after the 6th week (Figure 2 c). Soil water in the profile reduced simultaneously in all treatments although the reduction occurred earlier and at a faster rate near than away from the barriers (Figure 2 a, b).

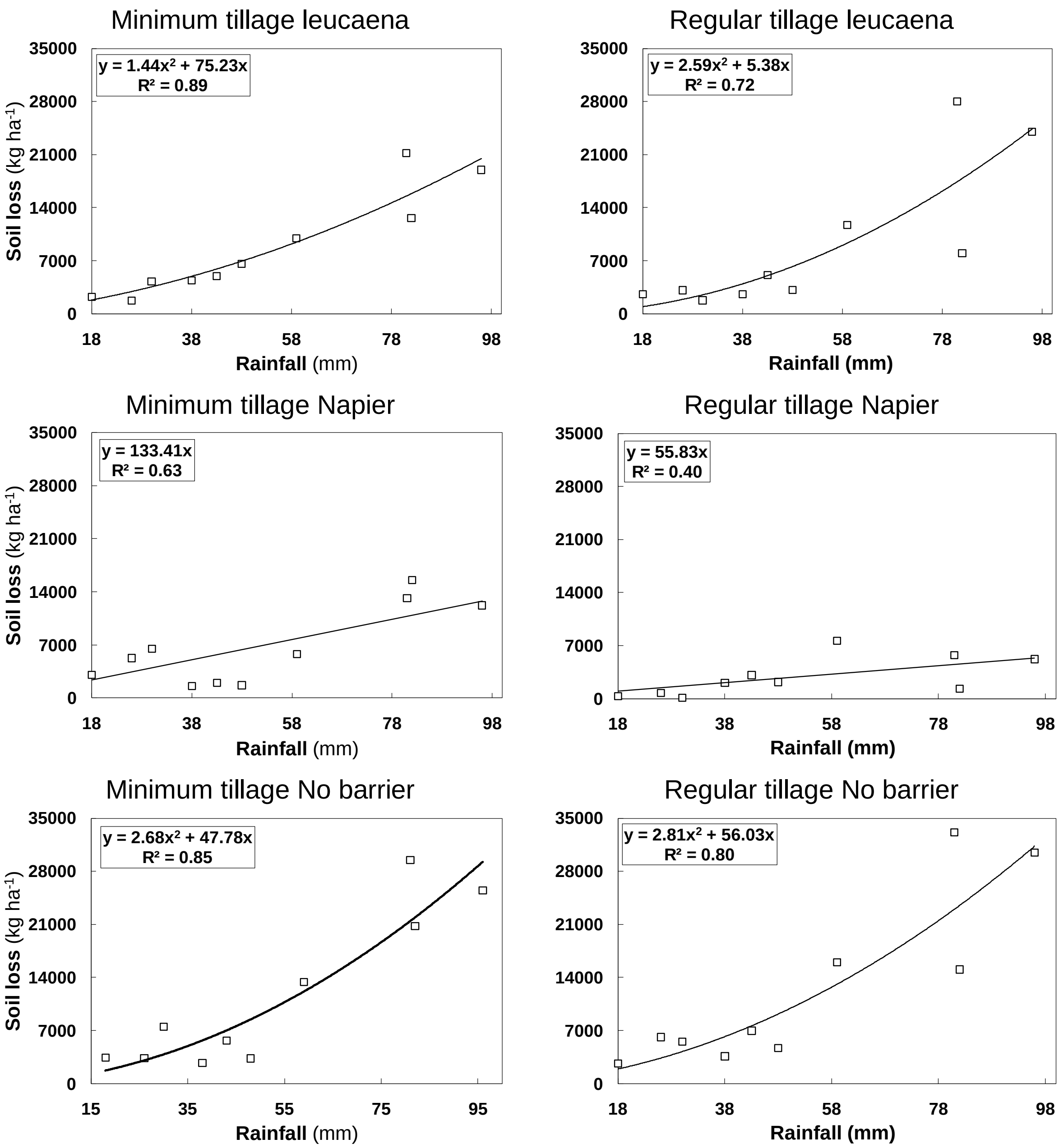

Figure 6. Relationship between soil loss and rainfall as affected by vegetative barrier and tillage systems across four consecutive seasons (LR 07 – SR 08).
Note A soil loss of 1 kg ha^{-1} is equivalent to $1x10^{-4}$ mm reduction in the top soil depth if the soil bulk density is 1000 kg m^{-3}.

Taking regular tillage without barriers as the baseline and across barriers, there was less water reduction away from the barriers with minimum than regular tillage (Table 3). Near the barriers, there was less water reduction with minimum than with regular tillage for leucaena barriers. With Napier barriers, there was a higher degree of water reduction if minimum rather than regular tillage was practiced. Away from the barriers, the upper soil layers had more water with minimum than regular tillage

(Figure 7). Near barriers and across tillage practice, leucaena barriers extracted more water from deeper soil layers (>60 cm) as opposed to Napier (Figure 7).

Table 3. Soil water depletion (mm) during a dry period in short rains 2007 as affected by barriers, tillage and profile position with regular tillage and no barriers as the baseline

Barrier	Minimum tillage		Regular tillage	
	Near	Far	Near	Far
Leucaena	76	-28	112	20
Napier	156	-22	176	25
None	-41		0	
SED				
Barrier (B)				**11****
Tillage (T)				**9***
B x T x Position				**15***

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

(a) (b)

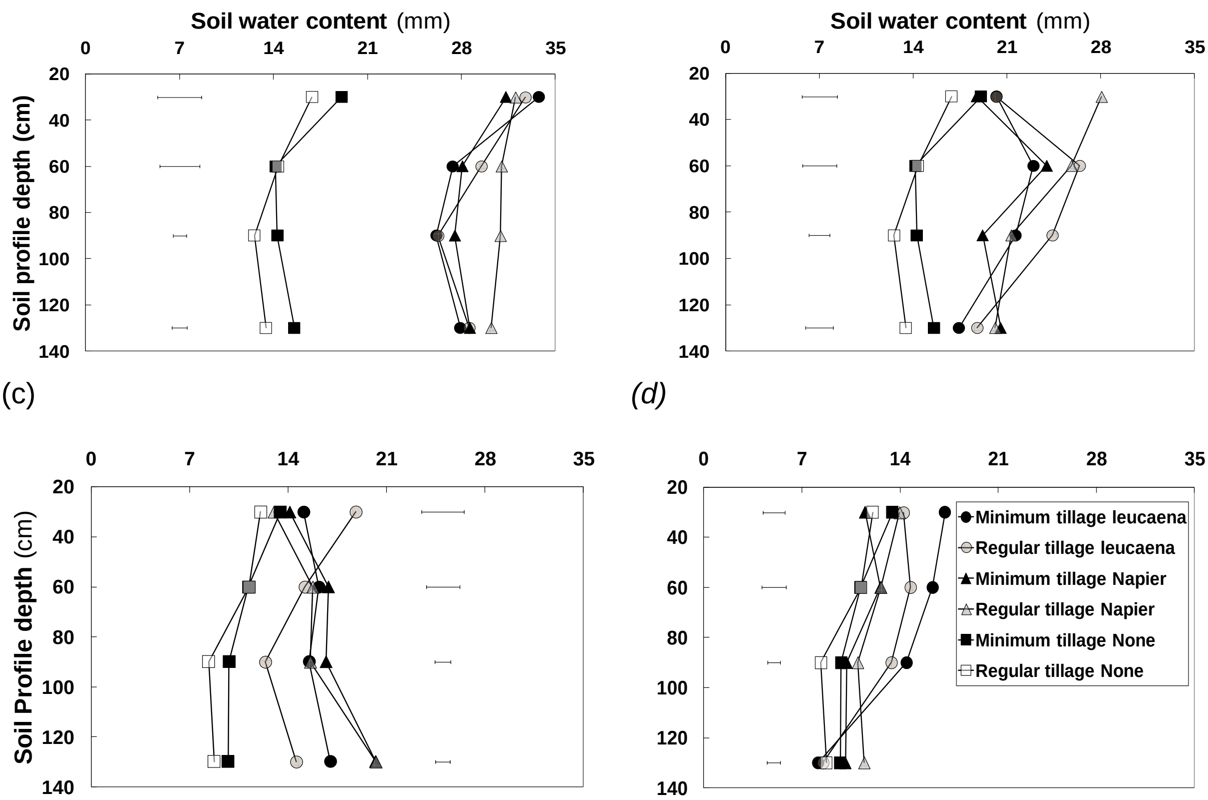

Figure 7. Soil water content at different depths mid-way through the dry period away (a) and near (b) the barriers and at the end of the dry period away (c) and near (d) the barriers as affected by tillage and barriers in short rains 2007. The error bars represent tillage and barrier interaction.

Near Napier barriers and between tillage practices, there was greater water extraction from the upper end of the profile (<60 cm) with minimum than with regular tillage.

4.3.4 Crop yields

The average row grain soybean yield in long rains ’07 was 40 g m^{-1} with 16% coefficient of variation across rows, tillage and barriers. The long rains ’08 season average soybean yield was 20 g m^{-1} with a 26% coefficient of variation across rows, tillage and barriers. Between tillage and barriers, row yields were greatest with leucaena barriers (20 g m^{-1}) independent of tillage. Grain yields were greater with regular than minimum tillage with Napier barriers, and vice versa without barriers.

Soybean yields with Napier barriers were suppressed up to about 0.8 m away from barriers across both seasons (Figure 8). Such yield reductions were minimal with leucaena barriers. In the short rains ‘07 cropping season, average row maize grain yield was 430 g m^{-1} with a 26% coefficient of variation across rows, tillage and barriers. With Napier barriers, row crop yields were significantly reduced by 28-78% up to 3 m away from the barriers if minimum tillage was practiced, and up to 1.5 m with regular tillage (Figure 8). Such yield reductions were less pronounced with leucaena barriers. The average row maize yield in short rains ’08 was less than that in short rains 2007 (300 g m^{-1}) with 28% coefficient of variation across rows, tillage and barriers. Trends in tillage and barrier effects on row grain yields were similar to those in short rains ‘07 though with smaller magnitudes (Figure 8). No grain yield was realized from maize rows near Napier barriers at the lower edge of the plot.

4.5 DISCUSSION

4.5.1 Tillage and vegetative barrier effects on soil and water conservation

Each season was characterized by a period of water accumulation and a period of water depletion in the soil profile. In the water accumulation period, soil water content increased due to the influence of rainfall and high values of soil water content were recorded in all treatments following rainfall events (Figure 2 and 4). There was better rainfall capture with than without barriers. Vegetative barriers reduce soil loss (Figure 6) by impeding run-off hence reducing the velocity of overland flow

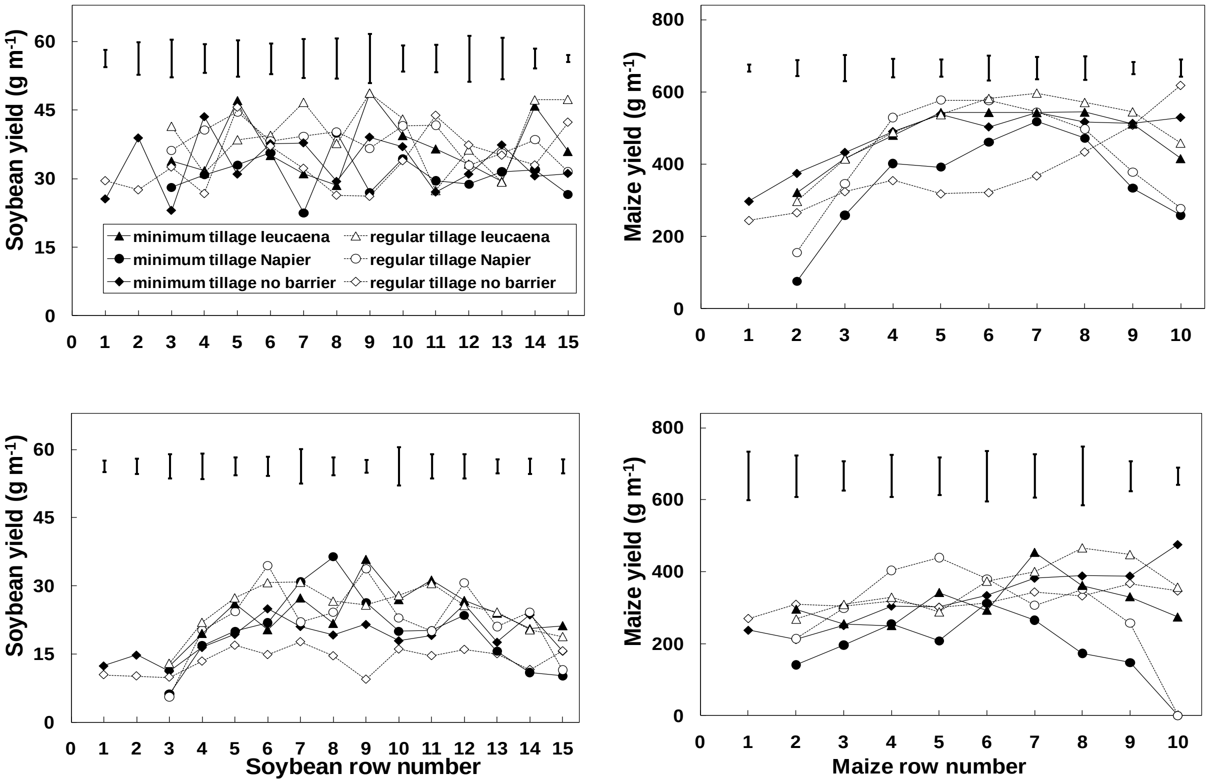

Figure 8. Soybean and maize row grain yields as affected by tillage and vegetative barrier systems for four seasons (LR 07 - SR 08). Net row length was 3 m and row numbering is from the upper end. Plots without barriers had 10 maize rows or 15 soybean rows, while those with barriers had 9 maize rows or 13 soybean rows. Error bars represent SED for tillage (T) and vegetative barrier (B) interaction.

(Sudishiri et al., 2008; Dass et al., 2010). Reduced run-off velocities and improved soil structure due to the presence of vegetative barriers contribute to better capture and infiltration of surface run-off (van Noordwijk et al., 1996; Udawatta et al., 2006).

Soil and water conservation efficiency was greater with Napier barriers than with leucaena (Table 1 and 2). Napier grass roots spread out superficially over a large area and bind soil particles, thereby enhancing cohesion and soil shear strength, which limits soil and water losses even if heavy rainfall events occur. Minimum tillage with soybean mulch was effective in controlling soil loss for small to moderate rainfall events only (Figure 6). This tallies with the findings of Kiepe (1996) and Pansak et al. (2008) who found minimum tillage and mulch to remarkably reduce soil loss but only on gentle slopes for small to moderate rainfall events.

4.5.2 Tillage and vegetative barrier effects on soil water during dry periods

In dry periods, rainfall did not influence soil water patterns, and the amount of water in the soil reduced gradually (Figure 2 and 4). Across tillage and barrier treatments, reduction in soil water content was greater near than away from barriers (Table 3). Water uptake in the presence of vegetative barriers in cropping fields depends on total leaf surface area and root density (for barriers and crops) and this decrease with increasing distance from the barrier drip line (Jackson et al., 2000; Ghazavi et al., 2008). Away from barriers, however, soil water was greater with regular than with minimum tillage across barriers (Table 3). Soil disturbance with regular tillage enhances direct evaporation of water from the soil surface. Increased evaporation of water with tillage has also been attributed to enhanced vapour flow near the surface and greater absorption of radiation by a tilled surface (Schwartz et al., 2010). Soil disturbance can also lead to a less stable soil pore system and poor aggregate development that reduce soil water holding capacity (Six et al., 2002).

More water was extracted from deeper soil layers by leucaena than Napier barriers (Figure 7). Napier grass has a shallower fibrous root system while leucaena trees have a root system with a long tap root that can extend up to 3 m depth (Mureithi et al., 1995) allowing utilization of water reserves from the deep. Water abstraction from the upper soil layers by Napier barriers was greater with minimum than with regular tillage. During regular tillage, superficial fibrous Napier grass roots are cut, reducing water depletion in the upper soil layers. Differential profile water depletion in barrier-intercrop systems under conditions of soil water limitation has been reported elsewhere (Hulugalle and Ndi, 1993; Everson et al., 2009).

4.5.3 Tillage and barrier effects on crop yields

The row grain yields in the absence of barriers gradually reduced from the lower to the upper plot end. Greater soil loss has been reported at the upper plot end (Chaowen et al., 2007) and attributed to soil scouring (Turkelboom et al., 1997). Eroded soil sediments are deposited at the lower plot end enhancing its relative fertility status. Despite of Napier barrier’s greater soil and water conservation efficiency (Table 2 and Figure 6), row grain yields in the Napier barrier-crop interface were depressed. Superficial Napier grass roots exploit the same soil layers as annual crops and directly compete for soil water and nutrients, hence suppressing crop yields. In short rains ‘08 with a dry spell longer than that in short rains ‘07 (Figure 4c), greater competition for water between maize and Napier barriers occurred and rows at the lower plot end were completely suppressed. The row yield suppression was less severe with regular than minimum tillage (Figure 8). The root density of shallow rooted barriers such as Napier grass is greater near barriers (Jackson et al., 2000; Ghazavi et al., 2008) and such superficial roots are cut during normal tillage operations reducing inter-specific competition for soil water (Hulugalle and Ndi, 1993). Competition in barrier-crop systems is common (Odhiambo et al., 2001; Livesley et al., 2004) especially for soil water and nutrients (Verinumbe and Okali, 1985; Singh et al., 1989; Miller and Pallardy, 2001).

The row yield suppression was less pronounced with leucaena than with Napier barriers (Figure 8). Also, improved crop performance for crop rows at the centre of plots with leucaena barriers compensated for yield suppression and reduction in crop area. The resource use pattern in leucaena barriers implies complementary relationship between crops and leucaena barriers. Leucaena barriers have deep roots (Hauser and Gichuru, 1994; Mureithi et al., 1995; Mugendi et al., 2003) that exploit different soil layers from shallow rooted crops thereby competing less for limited water and nutrients. Leucaena trees can in addition fix nitrogen and spare soil N (Giller, 2001) and restrict nutrient leaching by capturing and transporting leached nutrients from deep soil horizons to topsoil hence improving nutrient use efficiency.

4.6 CONCLUSION

The establishment of vegetative barriers in cropping fields reduced soil and water losses. Enhancement of soil and water conservation was greater with Napier than leucaena barriers due to its superior root and shoot structure. Accumulated soil water in the dry season was depleted early and faster near Napier grass barriers leading to competition for water between shallow rooted Napier grass and companion crops. Pruning and regular tillage controlled the competitiveness of Napier barriers. Leguminous leucaena barriers however had a complementary water uptake pattern due to different water use niches between deep rooted leucaena barriers and shallow rooted companion crops. The degree of row crop yield depression was related to vegetative barrier water use pattern and was therefore more severe with Napier than with leucaena barriers, particularly with minimum tillage. Farming without installation of barriers leads to soil degradation due to intense soil and water losses regardless of the tillage practice. Napier or leucaena vegetative barriers can reverse this trend. The strategy for their successful introduction into water deficient farming environments is to ensure complementary water use while limiting competition. Minimum tillage with soybean crop residues can only be viable in cropping fields with established vegetative barriers taking into consideration the slope and rainfall intensity of the area. Leucaena tree barriers have a complementary water use pattern with crops and can be incorporated into the smallholder farming systems. However, they are less efficient for capturing rainwater. Napier barriers on the other hand are efficient in capturing rainwater but compete with crops for available water even when intensely harvested.

ACKNOWLEDGEMENTS

We thank the Netherlands Universities Fund For International Cooperation (NUFFIC) for funding through a PhD scholarship to S.N. Guto and the Kenyan Ministry of Agriculture for providing logistical support. We thank Oliver Njue who provided the field for the study and Bernard Gitonga for the technical support in the field.

Chapter 5

Socio-ecological niches for minimum tillage and crop residue retention in continuous maize cropping systems in smallholder farms of Central Kenya

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This article is published as:
Guto, S.N., Pypers, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2010. Socio-ecological niches for minimum tillage and crop residue retention in continuous maize cropping systems in smallholder farms of Central Kenya. Agronomy Journal.

ABSTRACT

Soil fertility gradients develop on smallholder farms due to preferential allocation of inputs. A multi-location on-farm trial was conducted in Meru South, Central Kenya whose overall aim was to test minimum tillage and crop residue retention practices in socio-ecological niches across heterogeneous smallholder farms. We identified three soil fertility classes together with the farmers, namely: good, medium and poor. In each soil fertility class, two tillage (minimum or regular) and two crop residue (removed or retained) practices were tested for four consecutive seasons. Maize grain yields in the good fields were above 2.5 Mg ha^{-1} across cropping seasons and cumulated yields were not influenced by tillage or crop residue management. The grain yields in the medium fields ranged between 1.3 and 5.4 Mg ha^{-1} and were greater with crop residue retention. In the poor fields, grain yield was less than 3.6 Mg ha^{-1} and minimum tillage resulted in yield decrease while crop residue addition did not affect yields. Regular tillage and crop residue removal resulted in largest gross benefits in the good fields (US$ 5376 ha^{-1}) while in the medium fields, minimum tillage with residue retention was most profitable (US$ 3214 ha^{-1}). Retention of crop residues will give improved maize performance in the medium fields and the prevailing prices favour minimum tillage and crop residue retention. In the poor fields, the emphasis should be on the rehabilitation of soil physical and chemical attributes because none of the tillage and crop residue practices was profitable.

Keywords: Soil fertility gradients, spatial variability, net benefits, variable costs, Central Kenya

5.1 INTRODUCTION

Continuous cropping and use of inappropriate farming practices has led to decline in soil fertility, accelerated soil erosion and degradation of arable lands in East Africa. Minimum tillage and maintaining permanent soil cover are two approaches that can mitigate the effects of soil degradation (Fowler and Rockstrom, 2001; Monneveux et al., 2006; Thierfelder and Wall, 2009). Minimum tillage can improve soil surface conditions (Govaerts et al., 2009; Blanco-Canqui et al., 2010), improve crop yields (Bescansa et al., 2006) and increase net farm benefits due to reduced production costs (Nielsen et al., 2005; Chikoye et al., 2006; Sánchez-Girón et al., 2007). With permanent soil cover, diurnal soil temperature variations are dampened (O'Connell et al., 2004), surface runoff controlled (Biamah et al., 1993), soil drying slowed (Chakraborty et al., 2008) and crop rooting enhanced (Gill et al., 1996). Smallholder farmers can generate soil cover by growing cover crops, but foregoing food crops may not be attractive to the farmers (Giller, 2001). Crop residues from annual crops such as maize provide alternative sources of mulch but competing demands for their use as fodder provides a ready market for maize stover as feed (Bebe et al., 2002). This is particularly true in high rainfall areas of Kenya due to the dynamic and expanding smallholder dairy milk sector (Ndambi et al., 2007). Smallholder farmers thus face the challenge of producing sufficient crop residue biomass to cater for all of the competing demands on the farm.

The need to mitigate soil degradation while addressing on farm production constraints such as shortage of labour in smallholder farms open windows of opportunity for new approaches such as minimum tillage and permanent soil cover. But local conditions in smallholder farming systems that affect the performance of such technologies (Erenstein, 2003; Vanlauwe et al., 2006; Zingore et al., 2008) need to be considered (Knowler and Bradshaw, 2007) and deliberate adaptation efforts made. Local conditions are site-specific and depend on either the bio-physical environment such as seasonal variability in rainfall, and inherent soil fertility status or socio-economic environments (labour and capital constraints). Giller et al. (2009) stressed the need to identify specific local conditions based on the concept of the socio-ecological niche (Ojiem et al., 2006) where such practices may be feasible within the diverse and heterogeneous smallholder farming systems of sub-Saharan Africa.

The effect of tillage and crop residue practices on maize performance on smallholder farms in Kenya is poorly studied. Previous investigations have focused on erosion control (Fox and Bryan, 1992), mitigation of greenhouse gases (Baggs et al., 2006) and water conservation in the marginal rainfall zones (Gicheru et al., 2004; Ngigi et al., 2006). We studied the effects of minimum tillage and mulching with crop residues on maize crop yield across heterogeneous smallholder farms within the sub-humid agro-ecological zone of central Kenya. Our guiding hypothesis was that properly targeted tillage and crop residue practices can improve soil productivity but are feasible only in some socio-ecological niches within heterogeneous smallholder farms. The specific objectives were to: (1) identify different soil fertility classes for the assessment of tillage and crop residue practices in smallholder farms, (2) assess the impact of tillage and crop residue practices on soil productivity in different soil fertility classes and cropping seasons, (3) determine cumulative costs and benefits from tillage and crop residue practices for the different soil fertility classes, and (4) match tillage and crop residue management options to socio-ecological niches in the smallholder farming systems.

5.2 MATERIALS AND METHODS

5.2.1 The study area

The study was conducted in Murugi Location, Meru South District in Central Kenya. The area has a high population density (800 people km^{-2}) and small farm sizes averaging between 0.5 and 3 ha per household (Jaetzold et al., 2006). Land is individually owned and smallholder mixed farming predominates. Maize (Zea mays L.) and beans (Phaseolus vulgaris L.) are the most common food crops while coffee (Coffea arabica L.) or tea (Camellia sinensis L.) are the major cash crops. Majority of the farmers keep cattle, sheep, goats and poultry. There is no communal grazing for livestock and stall-feeding (zero-grazing) is common (Tittonell et al., 2010).

The soils are deep, well-drained Humic Nitisols with moderate to good inherent soil fertility (FAO, 1991) and a clayey texture (de Meester and Legger, 1988) whose estimated water holding capacity is 175 mm m^{-1} depth for the upper 1.5 m of the soil

(Landon, 1994). Mean annual rainfall is 1500 mm with a bimodal distribution: the long rains commence in mid March and end in May, while the short rains start in mid-October and end in late November (Jaetzold et al., 2006). Mid-season drought spells commonly occur in both seasons and pose a risk to crop production. Daily rainfall was measured in farmers' fields next to the experimental areas using rain gauges.

5.2.2 Experimental design and management

To understand spatial variability in soil fertility within smallholder farms in the study area and identify farmers to be involved in the experiment, we carried out exploratory visits, reviewed secondary literature and interviewed key informants. An initial group of 30 farms was randomly drawn from a list of 100 farmers identified by the key informants. Farms were visited to assess suitability of the 30 pre-selected farms based on their willingness to participate in setting up, monitoring and eventual evaluation of experiments. Subsequently, we identified 21 farms and revisited them to gather specific information on management of different fields within the farm to allow identification of fields for further experimentation. We deliberately timed the second farm visits to coincide with maize crop harvesting in the long rains 2007 season to observe crop performance in the different fields and discuss the cause(s) to the variations in crop performance with the farmers.

Three soil classes based on crop performance were delineated in consultation with the farmers that represented the spatial variability in soil fertility, namely: good, medium and poor (Table 1). Good fields were closest to the homestead (< 35 m), hence well-managed and most fertile as they received the bulk of the farm inputs. On the contrary, poor fields were furthest from the homestead (> 70 m) and least fertile due to poor past management. The medium fields were intermediate in both distance from the homestead and management status. Fields in the good class had substantial amounts of soil organic matter, available P, favourable soil pH and CEC (Table 2). The fields in the poor class had the least soil organic C, available P, CEC and were more acid.

Farm fields representing the identified soil fertility classes distributed across 16 farms were selected for setting up the experiments. A two-by-two-by-three full factorial experiment was established comparing two tillage (minimum or regular) and two crop residue (removed or retained) practices across three soil fertility classes (good, medium and poor).

Table 1. Characteristics of the different soil fertility classes in smallholder farms of Meru South District, Murugi Location of Central Kenya

Field characteristics	Fertility class		
	Good	Medium	Poor
Distance from homestead (m)	< 35	35-70	> 70
Field slope (%)	< 5	5-12	> 12
Average maize yield for last 2 seasons (Mg ha^{-1})	Large (> 3)	Medium (2-3)	Small (< 2)
Cultivation intensity (last 5 years)	High (fallow <2 seasons)	Medium (fallow 2-3 seasons)	Low (fallow 3> seasons)
Weed infestation (% area)	≤ 10%	10-20%	≥ 20%
Planting date	Early (before rains)	Expected (1 week after rains)	Delayed (1> week after rains)
Manure use (kg ha^{-1})	High (> 100)	Low (< 100)	None
Basal fertilizer use (kg ha^{-1})	High (> 45)	Low (< 45)	None
Anti stalk borer dust use (kg ha^{-1})	High (> 5)	Low (1-5)	None

A split-plot design was used whereby the soil fertility classes were replicated six times in main plots while tillage and crop residue practices were replicated four times in sub-plots within each of the main plots. A field within a farm was the main plot while plots demarcated within the field were sub-plots. The trial was maintained for four consecutive seasons (short rains 2007 to long rains 2009) but crop residue practices were only compared after the first season when residues had been generated. The trials were established jointly with farmers in the short rains '07 to expose farmers to the technology for their evaluation. Thereafter, the only operation performed by the farmers was tillage using a hand hoe on the tillage treatment plots.

A field assistant and three casual workers carried out all other field operations (herbicide application, planting, weeding and top-dressing) across the different fields to ensure consistent management across the experiment.

At the onset of each season, in the plots under minimum tillage, a post-emergent application of glyphosate (500 g l^{-1} active ingredient) at the rate of 1.5-2 l ha^{-1} was used to control early season weeds. Control of mid- to late-season weeds was done manually with minimal soil disturbance and weeds left on the soil surface. Land preparation in plots with tillage was by forked hoe (10-15 cm depth). Maize (Dekalb variety 8031) was grown at an inter-row spacing of 75 cm and an intra-row spacing of 25 cm (5.3 x 10^4 plants ha^{-1}).

Weeding was done twice with a machete (5-7 cm depth). Fertilizer was applied in all plots [30 kg P ha^{-1} as triple super phosphate (TSP) at planting and 50 kg N ha^{-1} as urea in two equal splits after the first and second weeding].

Table 2. Initial selected soil chemical properties of the topsoil (0-15 cm) for the three soil fertility classes (n=6)

Fertility class	Organic C (%)	Total N (%)	Available P (mg P kg^{-1})	Soil pH	CEC ($cmol_c$ kg^{-1})	Texture (%)		
						Clay	Silt	Sand
Good	2.18	0.22	31.9	5.94	15.50	37.0	41.0	22.0
Medium	2.06	0.21	17.3	5.59	13.17	35.5	42.1	22.4
Poor	1.54	0.17	10.8	4.85	11.00	36.3	41.0	22.7
SED	**0.15***	**0.01***	**3****	**0.09***	**0.7***	**0.7^{ns}**	**1.4^{ns}**	**0.4^{ns}**

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

Soil analysis based on the methods and procedures by Anderson and Ingram (1993)

5.2.3 Data collection

Prior to trial establishment, composite soil samples were taken from 0-15 cm depth in all experimental fields for field characterization. In the last season soil samples were taken separately from each treatment in the 0-6 cm depth and soil C measured (corrected for bulk density). Bulk density, penetration resistance and infiltration rate were determined in the last season of the trial (long rains 2009) in four fields selected randomly from the six fields in each class. Topsoil bulk density (0-10 cm depth) was determined by clearing plant residues and weeds from the soil surface, and gently pushing duplicate cores (5.7 cm depth, 121 cm^3) into the soil in each plot. The soil samples were dried for 48 h at 105°C and bulk density calculated.

Soil water infiltration was determined in the last season (long rains 2009) in triplicate for each plot using a single plastic ring (19 cm diameter and 29 cm height), inserted 2 cm into the soil. Fresh water (3 l) was released into the plastic ring and infiltration time measured at 1 cm (water column) intervals initially, and at 0.5 cm intervals later (subject to intensity of infiltration). Measurements were repeated until all the water had infiltrated or a steady-state rate was reached.

Topsoil (0-10 cm depth) penetration resistance was measured in the last season (long rains 2009) using a hand ring cone penetrometer (Type 1b) (0.05 cm cone diameter and 1.0 kg cm^{-2} spring) in three positions within each plot. The moveable penetrometer ring was adjusted to zero and the cone pushed at a constant speed in to the soil. A reading was taken showing maximum compression of the spring and penetration resistance determined using the equation PR = D x F / d where PR = penetration resistance (kg cm^{-2}), D = Penetrometer sliding distance (cm), F = Spring kilogram force (kg cm^{-2}) and d = Cone diameter (cm). Gravimetric soil water content was measured simultaneously when the penetration distance measurements were carried out to the same depth (0-10 cm) and used to adjust the soil strength measurements in case the two parameters were significantly correlated.

Maize grain was harvested in each plot, weighed and corrected for moisture content by a multi-grain moisture meter (Dickey John multi-grain moisture tester, Dickey John Corporation, Illinois, USA). Yield is reported on a dry matter basis. Maize stover was harvested in each plot and weighed and sub-samples oven-dried (65°C) for 48 hours to correct stover yields for moisture content.

In experimental plots with crop residues retained, residue cover was determined every two weeks in the short rains 2008 and long rains 2009 using the line transect method (Laflen et al., 1981) modified to suit the small plots. A 5 m long non-elastic cord with marks at intervals of 25 cm was randomly placed across the plots thrice.

The number of cord marks that touched crop residue on the soil was counted each time. Residue cover was calculated as the ratio between the counted cord marks and total markings.

Farm gate input and output prices were obtained from a survey of twenty five farmers in the experimental area (Table 3). For labour (non-purchased input), estimates were based on direct observations on work rates by casual workers in the fields,

Table 3. Input and output items, amounts used and prevailing average item prices (standard error of the mean in brackets)

Products	Item	Purpose	Unit	Amount (ha^{-1})	Price (US$)
Inputs					
	Touch-down	Weed control	litre	1-3	17 (4.5)
	Bull-dock powder	Anti-stalk borer Dust	kg	8-12	1.13 (0.01)
	Triple super phosphate	Basic fertilizer	kg	30	0.96 (0.21)
	Urea	Top dress Fertilizer	kg	60	0.63 (0.06)
	Dekalb 8031	Maize planting Seed	kg	20-25	2.00 (0.50)
	Labour		hour		0.29 (0.11)
		Tillage		94-126	
		Spraying		34-44	
		Planting		220-252	
		1st Weeding		90-157	
		2nd weeding		50-75	
		1st top-dress		63-94	
		2nd top-dress		63-94	
		Harvesting		152-214	
		Crop residue cutting/collection		157-180	
		Crop residue chopping		126-150	
Outputs					
	Maize grain	Food	kg		0.32 (0.12)
	Maize residue	Feed	kg		0.02 (0.003)

but corroborated with information gathered from neighbouring farmers and confirmed with key informants before use in economic analysis. Field costs of labour for specified field operations were based on the prevailing field labour price (Table 3). Labour and non-labour input costs were summed up to obtain treatment total variable costs. Treatment gross benefits were calculated by multiplying the market prices with corresponding treatment yields.

5.2.4 Data analysis

Effects of soil fertility class, tillage and crop residue practice on maize grain and stover yield, residue cover, soil physical attributes and the economic parameters (total variable costs, gross benefits and benefit-to-cost ratio) were determined by ANOVA using the linear mixed model in Genstat Discovery 3 statistical package. Soil fertility class, tillage and crop residue practices were the fixed parameters and plots nested within fields were random parameters. The protected SED mean separation procedure at $P \leq 0.05$ was used to compare treatment means. The benefit-to-cost ratio analysis (CIMMYT, 1988) was used to assess the profitability of the tillage and crop residue practices (ratios > 2 were profitable).

5.3 RESULTS

5.3.1 Grain yields

The maize crop stand ranged between 80-95% of the targeted maize population (5.3 x 10^4 plants ha^{-1}) for all the experimental fields and was satisfactory across the four cropping seasons. There was effective early season control of most annual and perennial weeds in minimum tillage plots following post-emergent application of the herbicide (glyphosate). Some tolerant perennial weeds (e.g., Commelina sp.) were controlled manually.

The first season (short rain 2007) was the wettest season (Figure 1) and the rainfall distribution even without periods of drought. Mean seasonal grain yields were 2.6 Mg ha^{-1} across soil fertility classes, tillage and residue practices and decreased steadily from the good to poor fields (Table 4). The harvest index ranged from 36 to 39% across soil fertility classes and tillage and crop residue practices (data not shown). Being the first season, there were no crop residue effects to test. Soil fertility class and tillage practices had significant interactive effects on crop yield (Table 4). Fields in the good and medium classes had greater yields with regular tillage than under minimum tillage but tillage practice did not affect yield in the poor fields.

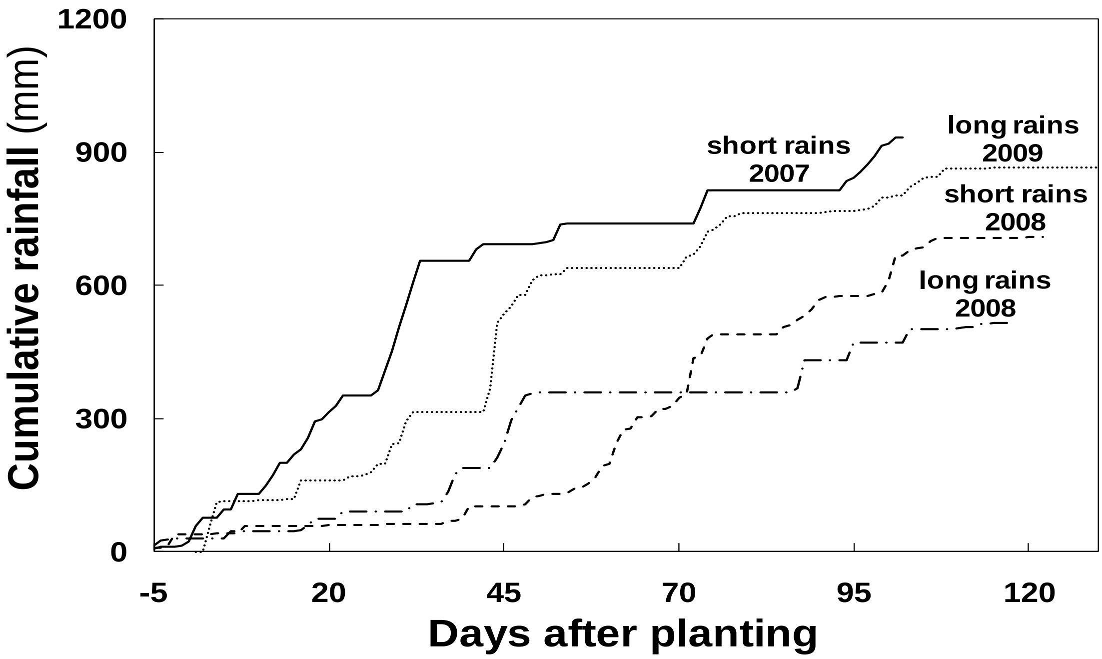

Figure 1. Cumulative rainfall for the four consecutive seasons (short rains 2007 – long rains 2009) in the experimental area.

The crop suffered mid-season moisture stress for 5 weeks during the long rain 2008 season which was the driest season (Figure 1). Mean maize yield was 1.7 Mg ha^{-1} across soil fertility classes, tillage and crop residue practices. The harvest index ranged widely between 36 to 48% across the experimental treatments (data not shown). There were significant (P<0.01) soil fertility class and tillage interactive effects on crop yields (Table 4). Fields in the good class had significantly greater yields under minimum tillage than with tillage and vice-versa for those in the poor soil fertility class. The grain yields for the fields in the medium class were similar across tillage and crop residue practices.

There was inadequate rainfall after maize planting in the short rain 2008 season (Figure 1) but the crop recovered from this early setback to attain a mean grain yield of 2.7 Mg ha^{-1} with an average harvest index of 36% (data not shown) across soil fertility classes, tillage and crop residue practices. There were no significant differences in average grain yield between the good and medium fields across tillage and residue practices (Table 4). Soil fertility class had significant interactive effects with either tillage or crop residue practice (Table 4).

Table 4. Seasonal grain yields as affected by soil fertility classes (n=6), tillage and crop residue practices (n=24) for four seasons (short rains 2007-long rains 2009)

Fertility class	Tillage	Residue	Grain yield (Mg ha^{-1})			
			Short rains 2007	Long rains 2008	Short rains 2008	Long rains 2009
Good	With	Removed	4.51	2.33	2.99	6.55
		Retained	-	2.12	3.20	6.25
		Mean	4.51	2.23	3.10	6.40
	Minimum	Removed	3.78	2.57	3.27	6.15
		Retained	-	2.94	3.84	4.97
		Mean	3.78	2.76	3.56	5.56
	Mean		4.15	2.49	3.33	5.98
Medium	With	Removed	2.70	1.28	2.76	5.26
		Retained	-	1.63	2.67	5.48
		Mean	2.70	1.46	2.72	5.37
	Minimum	Removed	2.27	1.14	2.93	5.20
		Retained	-	1.22	3.43	5.79
		Mean	2.27	1.18	3.18	5.50
	Mean		2.49	1.32	2.95	5.43
Poor	With	Removed	1.09	1.42	2.09	4.28
		Retained	-	1.38	2.11	3.89
		Mean	1.09	1.40	2.10	4.09
	Minimum	Removed	1.14	0.96	1.24	3.03
		Retained	-	1.01	1.38	3.07
		Mean	1.14	0.99	1.31	3.05
	Mean		1.12	1.19	1.71	3.57
SED						
Fertility class	**(F)**		**0.17*** **	**0.18*** **	**0.26*** **	**0.56** **
F x Tillage	**(T)**		**0.22***	**0.20** **	**0.14*** **	**0.20*** **
T x Residue	**(R)**		**-**	**0.5**	**0.12***	**0.98**
F x T x R			**-**	**1.09**	**1.50**	**0.28***
Cumulative rainfall (mm)			933	514	670	866
Rainfall distribution			Even	5 weeks of mid-season drought	2 weeks of early season drought	Even

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

There were greater grain yields in the good and medium fields with minimum tillage and retention of crop residue whereas in the poor class, minimum tillage gave strongly reduced yields.

Rainfall during the long rains 2009 season was evenly distributed without intra-seasonal drought and an average grain yield of 4.3 Mg ha^{-1} was attained across soil fertility classes, tillage and residue practices. The crop stand in the good fields under minimum tillage and residue retention had slower early season growth with symptoms of nitrogen deficiency (yellow leaves with a score of 3-4 on an ordinal scale of 0-10), which translated into a substantial yield reduction.

The three-way interaction between soil fertility class, tillage and crop residue practice was significant (Table 4). In the good fields, maize under minimum tillage gave 1.2 Mg ha^{-1} less grain yield with crop residue retention as opposed to removal, while the same treatment combination in the medium fields increased grain yield by 0.6 Mg ha^{-1}. As in the previous season (short rains 2008), there were no significant differences in average yield between fields in the good and medium classes across tillage and crop residue practices (Table 4).

The cumulative grain yields across the four seasons were significantly affected by the three-way interaction of soil fertility class, tillage and crop residue practice (Figure 2). The overall responses for all the treatment combinations in the good fields were similar whereas the best crop performance in the medium fields was with crop residue retention, and regular tillage in the poor fields enhanced crop performance.

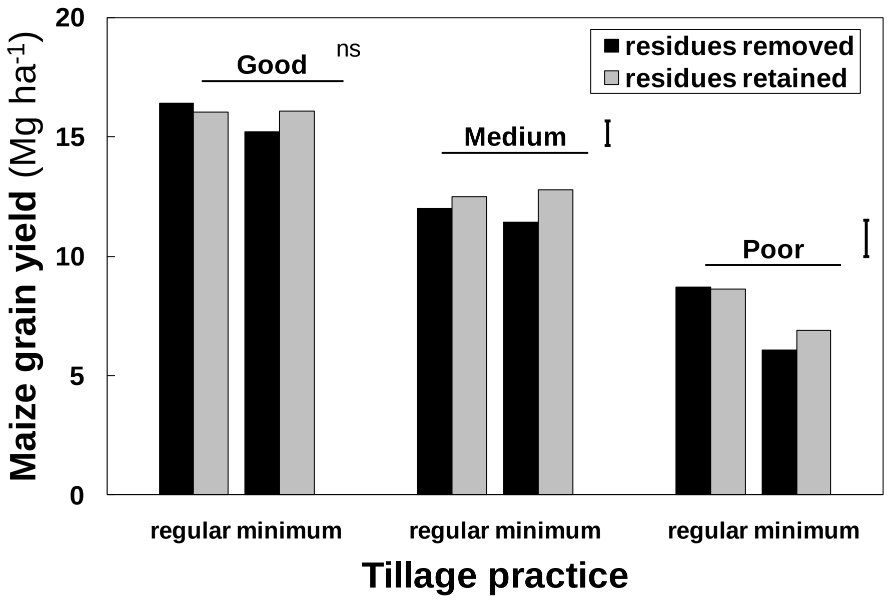

Figure 2. Cumulative maize grain yields for four seasons (short rains 2007-long rains 2009) as affected by soil fertility class, tillage and crop residue management practice. Error bars represent SEDs for effects of residue management and tillage in the “medium” and “poor” class, respectively at $P<0.05$.

5.3.2 Residue cover

The initial residue cover increased linearly with increase in stover yields (Figure 3) and the relationship was strong and significant (R^2 = 0.95**) across soil fertility classes and tillage practices. The amount of residue cover declined at a faster rate early in the season (2.03 – 3.72% week^{-1}) than towards the end of the season (0.063 – 0.097% week^{-1}) in all of the soil fertility classes (Figure 4).

In the medium and good soil fertility classes, there was a carry-over of 6-24% residue cover in short rains 2008 and 12-44% in long rains 2009, with greater residue quantities under minimum tillage than with tillage. There was no residue cover in the poor fields by the 10th week after planting in short rains 2008 and the 12th week after planting for the long rains 2009 with tillage. At the end of both seasons, less soil cover (1-4%) remained in the poor fields under minimum tillage (Figure 4).

5.3.3 Soil chemical and physical attributes

The soil organic carbon in the last season in the surface 6 cm increased from the poor to the good fields across the tillage and crop residue practices (Table 5). Across crop residue practices, soil organic carbon stocks were larger under minimum tillage in the good soil fertility class but independent of tillage in the medium soil fertility class while it was smaller with minimum tillage in the poor soil fertility class. Across tillage practices, retaining crop residue increased soil organic carbon by about 1.5 Mg ha^{-1} in the good and medium soil fertility classes over the four seasons whereas in the poor fields, residue retention had a marginal effect on soil organic carbon.

The soil bulk density increased significantly from the good to the poor soil fertility classes (Table 5) across tillage and crop residue practices while infiltration rate increased in the opposite direction. The bulk density was significantly greater under minimum tillage than with tillage while the infiltration rate was greater with tillage than under minimum tillage independent of the soil fertility classes.

There was no significant relationship between penetration resistance and soil moisture content and penetration resistance ranged between 1.2 and 2.4 kg cm^{-2} across soil fertility classes, tillage and crop residue practice. The penetration resistance increased from the good to the poor fields (Figure 5) but was greater with minimum tillage for the fields in the poor class. Residue retention reduced the penetration resistance for fields in the medium class, but penetration resistance for the fields in the good class was independent of either tillage or crop residue practice.

Table 5. Top-soil (0-6 cm) means of soil organic carbon, bulk density, infiltration and pore space as affected by soil fertility classes (n=4), tillage and crop residue practices (n=16) at the end of the long rains 2009 season

Fertility class	Tillage	Infiltration (mm h^{-1})	Pore space	Bulk density (g cm^{-3})	Soil organic C (Mg ha^{-1})		
					Residue removed	Residue retained	Mean
Good	With	126	0.51	1.12	16.1	17.4	16.7
	Minimum	107	0.52	1.14	17.8	19.5	18.7
	Mean	117	0.52	1.13	17.0	18.4	17.7
Medium	With	76	0.50	1.24	15.3	17.1	16.2
	Minimum	71	0.50	1.25	15.8	17.3	16.5
	Mean	73	0.50	1.25	15.6	17.2	16.4
Poor	With	64	0.49	1.30	9.95	12.0	11.0
	Minimum	37	0.49	1.33	12.3	12.7	12.5
	Mean	50	0.49	1.32	11.1	12.3	11.7
SED							
Fertility class	**(F)**	**9*** **	**0.006*** **	**0.011*** **	**0.43** **		
Tillage	**(T)**	**8***	**0.005^{ns}**	**0.009** **	**0.32** **		
Residue	**(R)**	**9^{ns}**	**0.005^{ns}**	**0.009^{ns}**	**0.32***		
F x T		**14^{ns}**	**0.009^{ns}**	**0.015^{ns}**	**0.58***		
F x R		**14^{ns}**	**0.009^{ns}**	**0.015^{ns}**	**0.58***		
F x T x R		**20^{ns}**	**0.0012^{ns}**	**0.022^{ns}**	**0.80***		

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

5.3.4 Total variable costs, gross benefits and benefit-to-cost ratios

Across field classes and tillage practice, the removal of crop residues required US$ 1335 ha^{-1} labour costs while US$ 1278 ha^{-1} was spent on labour if crop residues were retained (Table 6). Across field classes and crop residue practices, labour costs were US$ 1195 and 1418 ha^{-1} for minimum and regular tillage, respectively. The total variable costs across field classes and crop residue practice were US$ 2050 for minimum and 2193 ha^{-1} for regular tillage. Further, between crop residue practices but across field classes and tillage practice, the total variable costs were US$ 2141 and 2103 ha^{-1} for crop residue retention and removal practices, respectively.

Across tillage and crop residue practices, the gross benefits reduced gradually from the good to the poor fields. The benefit-to-cost ratio differed significantly between soil fertility classes, tillage and crop residue practices (Table 6).

Table 6. Cumulative costs and benefits as affected by soil fertility classes (n=6), tillage and crop residue practices (n=24) for four seasons (short rains 2007 to long rains 2009)

Fertility class	Tillage	Residue	Labour (hours ha^{-1})	Labour costs (US$ ha^{-1})	Non-labour costs (US$ ha^{-1})	Total costs (US$ ha^{-1})	Gross benefits (US$ ha^{-1})	Benefit-to-cost ratio
Good	With	Removed	4950	1435	772	2207	5963	2.7
		Retained	4843	1404	773	2177	5336	2.5
	Minimum	Removed	4194	1216	843	2059	5528	2.7
		Retained	3917	1136	860	1996	5521	2.8
	Mean		4476	1298	812	2110	5587	2.7
Medium	With	Removed	4969	1441	769	2210	3985	1.8
		Retained	4761	1381	799	2180	3671	1.7
	Minimum	Removed	4219	1223	837	2060	3942	1.9
		Retained	4106	1191	884	2075	4090	2.0
	Mean		4514	1309	822	2131	3922	1.8
Poor	With	Removed	5050	1465	769	2234	3332	1.5
		Retained	4761	1381	772	2153	2808	1.3
	Minimum	Removed	4231	1227	848	2075	2690	1.3
		Retained	4055	1176	862	2038	2451	1.2
	Mean		4525	1312	813	2125	2820	1.3
Means								
	With		4889	1418	776	2193	4183	1.9
	Minimum		4120	1195	856	2050	4037	2.0
		Removed	4602	1335	806	2141	4240	2.0
		Retained	4407	1278	825	2103	3980	1.9
SED								
Fertility class		**F**	50^{ns}	15^{ns}	5^{ns}	11^{ns}	133^{**}	0.006^{***}
Tillage		**T**	41^{**}	12^{***}	4^{***}	9^{***}	109^{ns}	0.048^{ns}
Residue		**R**	41^{***}	12^{**}	4^{*}	9^{**}	109^{ns}	0.048^{ns}
		F x T x R	100^{ns}	29^{ns}	5^{ns}	21^{ns}	266^{ns}	0.117^{**}

SED: ns - not significant; *, **, *** significant at P ≤ 0.05, 0.01 and 0.001, respectively

Benefit-to-cost ratios were above 2 in the good fields for all tillage and crop residue practices while in the medium fields, only minimum tillage with crop residue retention had its ratio above 2. In the poor fields, all the tillage and crop residue practices had benefit-to-cost ratios below 2.

5.4 DISCUSSION

5.4.1 Effects of tillage and crop residue practices on grain yields

There were positive effects of minimum tillage on grain yield in good fields during the long rains 2008, while in the short rains 2008 there were positive interactive effects between minimum tillage and crop residue retention in both good and medium fields. The maize crop experienced mid-season drought in the long and short rain seasons of 2008 (Figure 1) and since fertilizer application rates were constant across the soil fertility classes, it is likely that improved water availability caused the positive minimum tillage and crop residue retention effects. Minimal soil disturbance coupled with the increased soil cover resulting from retention of crop residues may have decreased direct evaporation of water from the soil surface, as shown elsewhere (Thierfelder and Wall, 2009). Rockstrom et al. (2009) reported yield improvements under minimum tillage with decrease in rainfall across East and Southern Africa.

Maize yields in the poor fields were greater with regular tillage (Table 4). This is in line with results from other studies (e.g. Rieger et al., 2008; Verch et al., 2009), although these authors attributed poor crop performance with zero tillage to reduced plant density, which was not the case in our experiments. Franzluebbers (2004) suggested that not tilling the soil can result in compaction immediately below the surface during initial seasons. In the poor fields, penetration resistance was much stronger with minimum tillage (Figure 5), the soils were poor in organic matter (Table 2) and there was low residue cover (Figure 3) – much less than the minimum 30% recommended (Hobbs et al., 2008) that can lead to tremendous soil degradation and yield reduction (Govaerts et al., 2009). Under these conditions, maize yielded much better with regular tillage, presumably due to the loosening of the soil, which increases soil water infiltration, stimulates mineralization of N from the soil organic matter and creates a more favourable environment for root growth.

In the long rains 2009, minimum tillage and residue retention gave the smallest yields in the good fields but the greatest yields in the medium fields. Among the three soil fertility classes, the largest quantity of residue carry-over from the previous season occurred in the good fields (Figure 3). The large amounts of cereal crop residues with a high C-to-N ratio may have induced N immobilization in the good fields leading to less available N for the maize crop (Palm et al., 2001). Minimal soil disturbance (with minimum tillage) coupled with the good rains may have led to excess soil moisture that can accelerate loss of nutrients by leaching or denitrification. In medium fields, residue quantities were lower and both residue retention and minimum tillage had positive effects on yields. The benefits could have been due to reduced run-off losses, resulting in increased plant-available water that improved fertilizer use efficiency.

Across tillage and crop residue practices but within each of the soil fertility classes, grain yield increased across the four seasons (Table 4). There were no significant yield differences between the good and medium fields in the third and fourth seasons. The poor fields had consistently smaller yields compared with the medium and good fields. The most probable cause for reduced performance in the poor fields was the poor soil organic matter status and low soil cover that affects soil structure, soil moisture evaporation and nutrient availability.

The cumulative grain yields varied significantly between soil fertility classes and cropping seasons, but were either independent of tillage and crop residue practice in the good fields or marginally influenced by tillage and crop residue practice in the medium and poor soil fertility classes (Figure 2). Cropping season differences and inherent soil fertility status had a strong influence on the effects of tillage and crop residue practices on maize performance. Franzluebbers (2004) and Monneveux et al. (2006) have reported lack of consistent tillage practice effects on crop performance. Our results indicate that the inherent soil fertility status of the fields has a strong influence on the effects of tillage and crop residue practice on crop yield and this provides insight into the inconsistent effects reported in the literature.

5.4.2 Tillage and crop residue practice effects on soil properties

The soil organic carbon in the surface layer (0-6 cm depth) was greater with minimum tillage across the soil fertility classes (Table 5). Minimum tillage can increase soil organic matter in the soil surface by better conservation of organic residues within the field, greater physical protection of residues due to lack of erosion and reduced soil mixing. The rates of soil organic matter storage under minimum tillage in this study maybe overstated because the entire plough depth was not considered. In a review, Govaerts et al. (2009) report increased soil organic matter for some soils under minimum tillage in the upper soil layers rather than the entire soil profile.

The positive effects of crop residues on crop growth appear not to have been necessarily linked to N supply but rather to positive effects on soil structure by increased soil porosity and water infiltration (Table 5), ease of root penetration (Figure 5) and reduced soil surface evaporation (Scwartz et al., 2010). These observations tally with those made by de Ridder and van Keulen (1990). The lack of overall positive effects of minimum tillage in good fields maybe due to the inherently high initial soil organic carbon such that the soils are not likely to obtain additional benefits with adoption of minimum tillage because inherent soil characteristics were already good.

5.4.3 Soil fertility class and tillage practice effects on crop residue cover

Across the soil fertility classes and seasons (short rains 2008 and long rains 2009), initial residue cover increased linearly with increased stover yields (Figure 3). Other studies have reported an asymptotic positive relationship (e.g. Steiner et al., 2000). The difference would be because of a delay between crop harvesting and the time of initial residue cover measurement (1-3 months; longer for the long rain seasons) during which some of the residue decomposes as livestock are not allowed to graze in cropping fields in the study area. Bationo et al. (1999) reported that 21-39% of the stover production at harvest time is available as mulch at the onset of subsequent season in the Sahel region of West Africa, where livestock graze freely, a much larger reduction in soil cover than that we observed in central Kenya. Besides, Kihara et al. (2008) report faster rates of crop residue depletion due to termite activity in the semi-arid Western Kenya, which was rare in our experiments.

Residue cover was greater under minimum tillage than with tillage across the soil fertility classes (Figure 4). Tillage involves soil movement that incorporates crop residues, though the degree of incorporation was limited in this study because of the implements used (a forked hand-hoe and machete). In poor fields with low crop residue yields, soil disturbance was sufficient to incorporate a greater fraction of the crop residues and maintaining adequate soil cover was difficult. Inadequate soil cover in the poor fields would increase water loss and create unfavourable conditions for crop growth and development.

The soil organic carbon in the soil surface was greater with residues retained compared with removal (Table 5) in the good and medium soil fertility classes. Removal of the crop residues has implications for soil organic matter dynamics as it represents a loss of carbon input to the soil resulting in a decline in soil organic matter compared with crop residue retention (Kapkiyai et al., 1999). In the poor soil fertility class, there was a modest change in surface soil organic carbon (Table 5) regardless of the crop residue practice due to the small amounts of crop residues generated.

5.4.4 Economic performance of tillage and crop residue practices

Across field classes and tillage practices, crop residue removal required 4% more labour compared with retention (Table 6). Removal of crop residues required more manual labour for cutting and collecting crop residues as opposed to chopping the residues when retained (Table 3). Across field classes and crop residue practices, minimum tillage had 28% less labour requirement over regular tillage while non-labour costs were 7% higher for minimum tillage over regular tillage. Regular tillage required more labour for manual land preparation and hand weeding (Table 3) while greater non-labour costs were incurred with minimum tillage for the purchase of herbicides. In an assessment of improved tillage and crop residue practices in Zambia and Zimbabwe, households attributed similar decreased costs to less weed density due to accumulation in crop residue and acquisition of experience in the technology (Mazvimavi and Twomlow, 2009). By contrast, Rockstrom et al. (2009) found a 30% increase in weeding costs with minimum tillage due to weed management problems even though herbicides were used.

Across tillage and crop residue practices, gross benefits were greatest in the good fields, least in the poor fields but intermediate for medium fields (Table 6). All the tillage and crop residue practices were profitable in the good fields since the benefit-to-cost ratios were above two (Table 6). In the medium fields, only minimum tillage with crop residue retention was profitable. For the poor fields, none of the tillage and crop residue practices were profitable. The benefit-to-cost ratio was more sensitive to changes in the price of labour and maize grain but less sensitive to herbicide and crop residue prices (Figure 6). The economic benefits in this study are comparable to those previously obtained in the region by Mucheru-Muna et al. (2010).

5.4.5 Socio-ecological niches for tillage and crop residue practices

Socio-ecological niches can be identified because none of the tillage and crop residue practices was consistently efficient for the different cropping seasons across soil fertility classes. Maize grain is a staple food in the study area and the farm gate prices varied widely (Table 3). Across tillage and crop residue practices, maize grain from the good fields will be profitable if the price is above US$ 0.26 kg^{-1} whereas in the medium fields, the price should be above US$ 0.37 kg^{-1} (Figure 6). For the poor fields, maize production was not profitable even with the highest projected farm gate prices in the study area. Minimum tillage and crop residue retention cannot be therefore implemented in the poor fields prior to investments in rehabilitation of soil attributes for better crop performance. Options to do this could be crop residue transfer from the good to the poor fields (taking into consideration competing on-farm uses: Giller et al., 2006; Tittonell et al., 2009) or use of legume cover crops (Baijukya et al., 2005) that involve substantial investment of scarce labour without immediate returns.

In the good fields, the choice between crop residue retention and removal will depend on the amount of N fertilizer the farmers can afford to apply. This is because enhancement of crop performance by crop residue retention was smaller in seasons with unfavourable rainfall compared with yield reduction due to N immobilization when rainfall was adequate. Farmers should therefore retain crop residues in the good fields on the condition that they apply sufficient N fertilizer. In addition, the choice will depend on the profitability from sale of crop residues influenced by the prevailing prices.

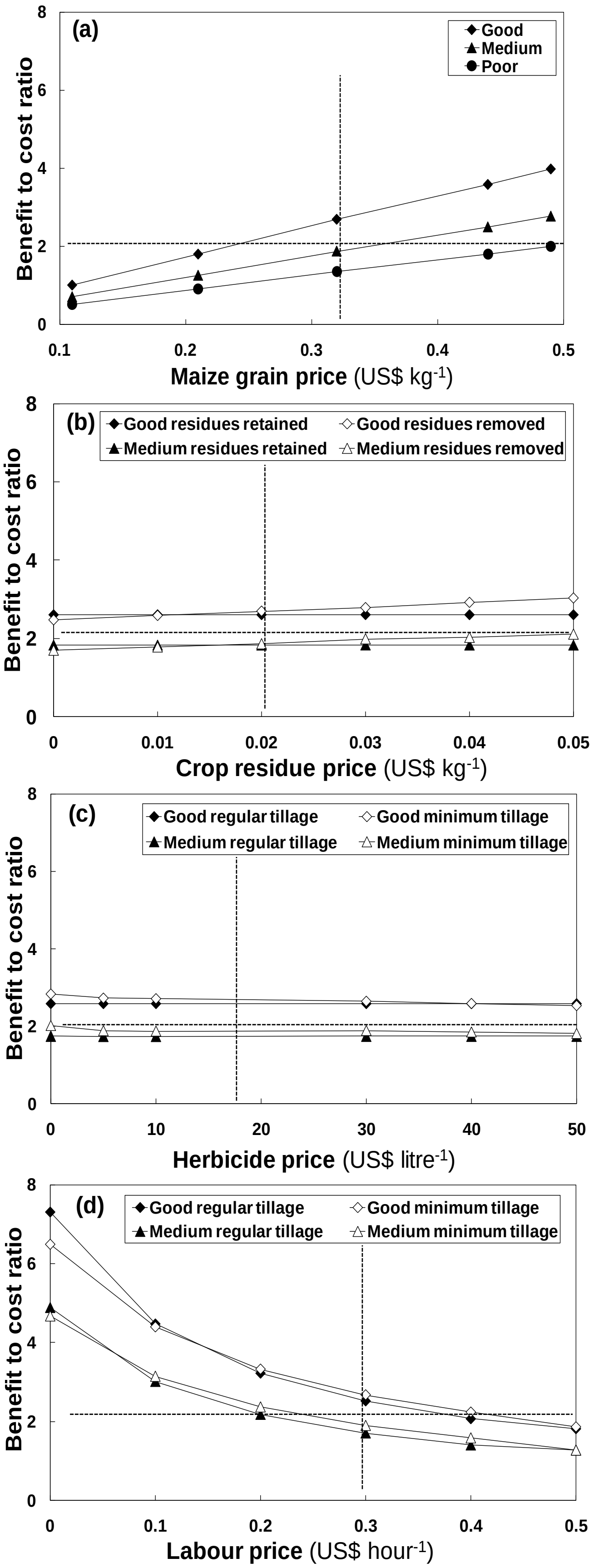

Figure 6. Sensitivity of benefit-to-cost ratios to the price of (a) maize grain, (b) crop residues, (c) herbicide and (d) labour. The dotted vertical lines indicate the prevailing prices for the items while the dotted horizontal lines represent the lowest profitable benefit-to-cost ratio.

Crop residues can be retained if the prevailing local price is below US$ 0.012 kg^{-1} (Figure 6). The choice between regular and minimum tillage will depend on the price of labour (Figure 6). Minimum tillage can be adopted if prevailing labour price is above US$ 0.14 $hour^{-1}$ (Figure 6). Since the prevailing local prices for labour and crop residues are above the identified margins (Table 3), retaining crop residues and minimum tillage may not be economically attractive under the present conditions in the good soil fertility class.

In the medium soil fertility class, crop residue retention gave significantly greater yields across the different tillage practices (Figure 3). Considering income from selling crop residues, residues can be retained if their price is below US$ 0.016 kg^{-1} (Figure 6). The decision as to whether to combine it with minimum or regular tillage will depend on the price of labour. Minimum tillage may be economically attractive in the medium fields provided labour price is above US$ 0.06 $hour^{-1}$ (Fig. 6). Crop performance and, the prevailing prices of crop residues and labour (Table 3) make retention of crop residues and minimum tillage feasible in the medium soil fertility class.

5.5 CONCLUSIONS

The effects of tillage and crop residue practices on maize performance varied strongly across soil fertility classes and cropping seasons. We can therefore formulate differentiated recommendations for tillage and crop residue practices across socio-ecological niches found on smallholder farms. Minimum tillage will be an unsuitable tillage practice for the good and poor soil fertility classes because regular tillage has comparatively greater economic benefits. In addition, the prevailing prices of crop residues make retention of crop residues in the good and poor soil fertility classes less economically beneficial. Also, in the poor soil fertility class, none of the tillage and crop residue practices was profitable and the emphasis should be on the rehabilitation of their soil physical and chemical attributes. Retention of crop residues will give improved maize performance in the medium fields, and the prevailing crop residue, herbicide and labour prices make crop residue retention and minimum tillage beneficial.

Our research contributes to a better understanding of where modified tillage practices and mulching, two key components of conservation agriculture, may play a role in raising agricultural productivity under the conditions of smallholder farming in sub-Saharan Africa.

Chapter 6

General discussion & conclusion: General discussion and conclusions: Chakula bila kulima?[§] Tradeoffs concerning soil and water conservation in heterogeneous smallholder farms of Central Kenya

[§] Chakula bila kulima? Translated from Swahili this means “Food without tillage?”

6.1 INTRODUCTION

The question in the title of this chapter was posed by a smallholder farmer in Central Kenya and reflects his hesitation to cultivate food crops without tilling the soil although he was aware of enhanced soil loss with intensive tillage. This captures the situation across Central Kenya region in which soil erosion is widespread and acknowledged by farmers (Gachene et al., 1997; Angima et al., 2003; Okoba and Sterk, 2006) but uptake of improved soil management practices by local farmers remains limited (Ovuka 2000; Okoba and de Graaff, 2005). Most of these practices were formulated as technical interventions with emphasis on their performance at field level. Besides, improved soil management practices such as minimum tillage demand a radical shift in field management demanding a fundamental change in the regular field operations (seedbed preparation and weed management). To attract farmer interest and encourage investment, there is need to focus on farmer concerns to ensure that such practices address opportunities and constraints in local smallholder farming systems (Knowler and Bradshaw, 2007; Giller et al., 2009).

Smallholder farming systems are complex with various crops and livestock (Ncube et al., 2009; Ebanyat et al., 2010), off-farm income sources (Clay et al., 1998; Tittonell et al., 2010) and differences in agro-climatic conditions and production orientation (Giller et al., 2010). The complexity leads to a wide range of competing farming objectives that necessitate some trade-offs when farmers make decisions on implementing soil and water conservation conservation practices (Tenge et al., 2005; de Graaff et al., 2008). Farming system studies have improved the understanding of the complexity in smallholder farms by identifying main drivers of household diversity. The drivers allow formulation of farm typologies that can be used to categorise smallholder farms and establish recommendation domains for better targeting of improved soil management practices.

The overall aim of this thesis was to identify viable soil conservation options and provide insights on better targeting into local farming systems. The Nutrient Use in Animal and Cropping systems – Efficiencies and Scales (NUANCES) approach provides guidelines for such targeting (Giller et al., 2010) through ex ante analysis at farm level.

In previous chapters, attributes of the local farming systems were explored and four farm types identified with varying resource endowment (Chapter 2). Farmer preference for practices with multiple benefits such as vegetation barriers that required less labour for establishment was established. Newly introduced practices such as minimum tillage and crop residue retention needed to be tailored to local farming systems. In Chapter 3 and 4, feasibility of tillage and vegetative barriers was tested. Leucaena barriers would be combined with minimum or regular tillage practices due to complementary resource use patterns with associated crops. Napier barriers however would only be combined with regular tillage to avoid intense competition for resources. In Chapter 5, the feasibility of tillage and crop residue management practices was tested in fields varying in soil fertility status. Minimum tillage and crop residue retention options were feasible in good and medium fields. For poor fields, the two improved soil and crop residue management practices were not feasible due to poor crop performance and unprofitable benefit-to-cost ratios.

In this chapter, we introduce the soil and water practices previously tested and confirmed to be viable at field level to “virtual farms” specifically constructed to represent different farm types in Meru South. The overall aim is to explore and discuss the possibility that these conservation options would be feasible for diverse farmers who face different site-specific socio-economic and bio-physical conditions, i.e. the third objective posed in the introduction for a current situation and an alternative production scenario. There were three virtual farms constructed to represent farms with high (Farm type 2) medium (Farm type 4) and low (Farm type 5) resource endowment (Table 1). The farm and household characteristics used to distinguished the three farm types, included farm size, family size and number of dairy cattle.

Table 1. Resource endowment for the virtual farms that represent the heterogeneity in smallholder farming system of Meru South District

Farm type	Family size	Farm size	Dairy cows	Field type (%)		
	(nr)	(ha)	(nr)	Good	Medium	Poor
Wealthy	5	3.0	5	100	0	0
Medium	4	1.5	2	20	60	20
Poor	4	0.2	0	0	0	100

6.2 CROP PRODUCTION IN THE VIRTUAL FARMS

6.2.1 Farming area and cropping systems

The farm area was divided into cropping fields varying in relative soil fertility status. Three soil fertility classes were identified by farmers: good (high fertility), medium (moderate fertility) and poor (low fertility) fields (Chapter 5). The area occupied by these fields varied but for the purpose of this discussion, production of main food crops in the wealthier farm was assumed to be on high fertility fields, the poor farm on low fertility fields while in the medium farm, crops were planted in moderately fertile fields (Figure 1 and 2).

The current crop production situation involved rotation of maize and beans in all farms. Arable fields did not have vegetation barriers to control soil erosion. The cropping fields were under regular tillage and crop residues were removed from cropping fields either to feed livestock or sold to generate farm income. In the alternative scenario, soybean was introduced to the cropping fields instead of beans. Vegetative barriers were also introduced to cropping fields and spaced according to the formula proposed by Thomas (1997) assuming fields to have 12% uniform slope. Minimum tillage and crop residue retention was practiced in the fields based on crop performance and benefit-to-cost ratios from previous field experiments (Chapter 5).

6.2.2 Crop yields and soil loss

Estimates of crop production for different fields were based on results from field experiments (Chapter 3 and 5) and data gaps were filled using values from literature. Maize crop yields in fields with Napier barriers were reduced by 11% and legume (beans and soybean) yields by 8% to take into account competition and the area occupied by the barriers (Chapter 4). For leucaena barriers, better crop yields fully compensated for the yield losses due to competition and reduction in cropping area. A harvest index of 60% was used to determine maize stover yields. Soil loss was estimated from the cropping fields based on results from field experiments (Chapter 3). Soil loss from fields with tea, coffee and Napier grass was assumed to be minimal and run-on effects between cropping fields was not considered.

Crop yields from different fields were aggregated to obtain farm grain yields and farm self-sufficiency in food production evaluated. An adult required 170 kg of grains yr^{-1}

(Shepherd and Soule, 1998) and maize was assumed to contribute 60% and legumes 40% of the adult annual grain requirement.

6.2.3 Farm labour demand

Data on labour use for crop production from field experiments (Chapter 3 and 5) and informal surveys were itemised into labour requirements for land preparation, fertilization, planting, weeding and harvesting for minimum and regular tillage. Monthly labour requirements for different field activities in every month for the tillage practices were aggregated to obtain monthly farm labour demand. Some assumptions were made on the availability of farm labour to simplify the assessment.

In the wealthier farm, family labour was not available for farm work and one permanent worker was employed to carry out farm activities but casual labour was hired in case of shortage. In one year (365 days), the permanent worker had 290 days available for farm work after excluding all Sundays that is a normal rest day in the area (52 days), formal holidays (7days) and days for festivities or other non-farm activities (13 days). The average monthly farm labour available in the wealthier farm was therefore about 24 person days. In the medium farm, two family members worked in the farm: one fulltime and the other half time. Average available monthly labour in the medium farm was therefore 36 person days.

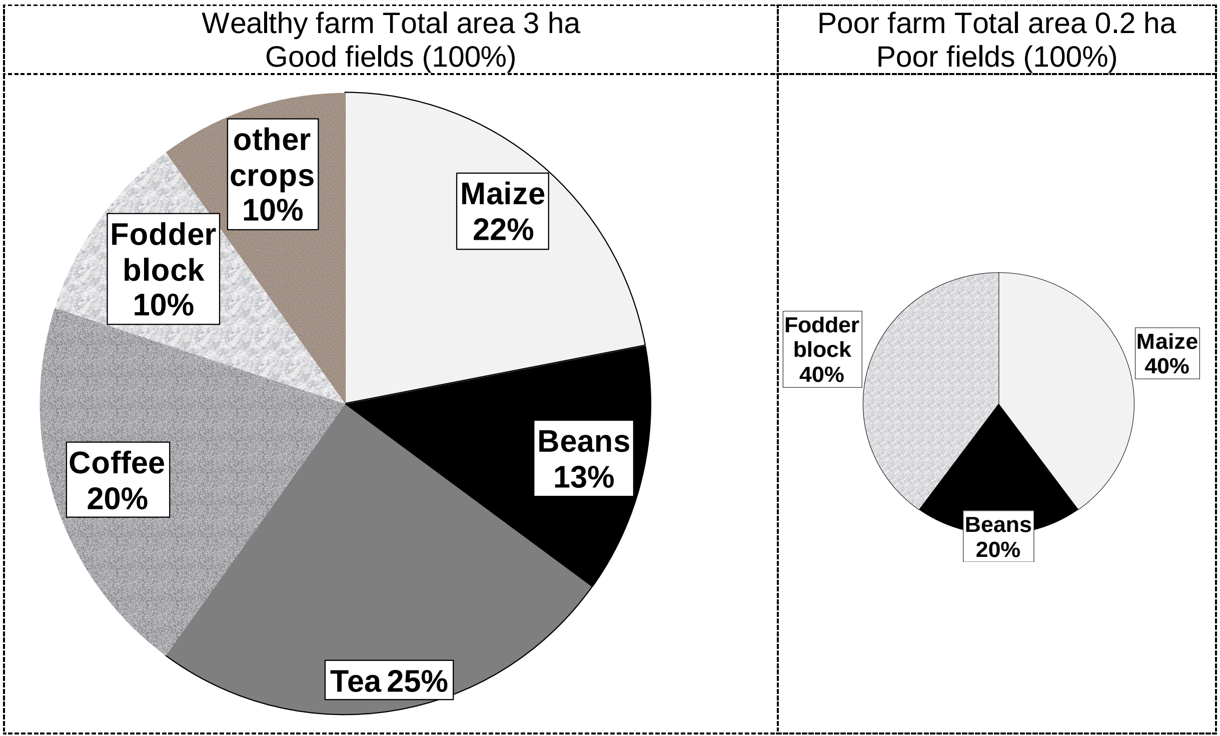

Figure 1. Allocation of crop enterprises to the farming area in the wealthy and poor farms.

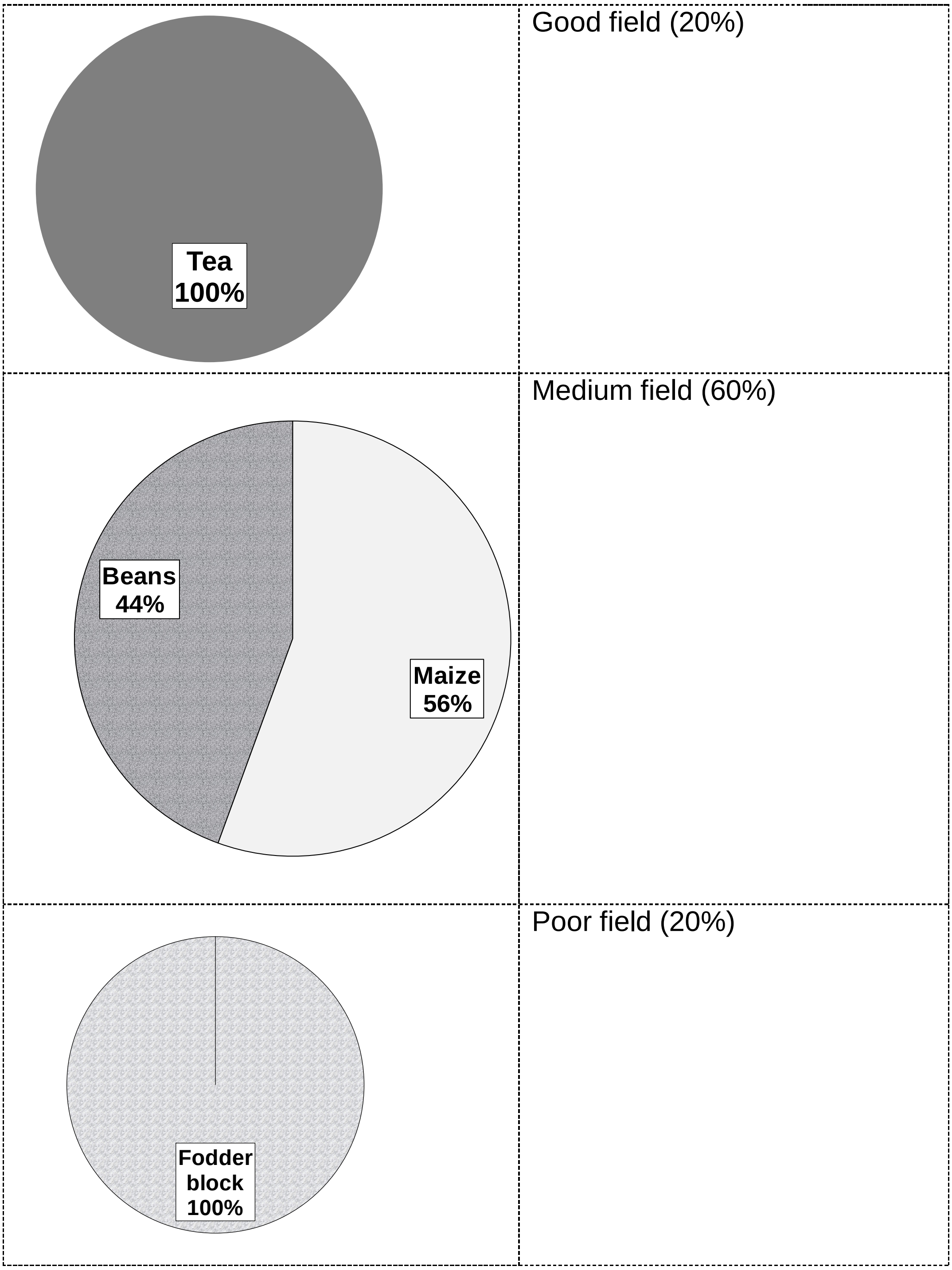

Figure 2. Allocation of crop enterprises to the farming area in the medium farm

In the poor farm, only one family member provided farm labour but also took part in off-farm activities to generate farm income, especially during periods of peak labour demand. Two periods of peak labour demand were identified; in March for the long rain season and October for the short rain season (Figure 3).

6.3 FODDER AND LIVESTOCK PRODUCTION

6.3.1 Fodder production and livestock feeding

Napier fodder was used to feed dairy cows during the wet period (October to December and April to June). During dry periods (January to March and July to September) when Napier fodder was scarce, maize crop residues were used to complement Napier fodder. In the current situation, Napier grass was grown in fodder blocks while in the alternate scenario, additional fodder was obtained from vegetative barriers. Fodder production estimates were based on observations in trial farms and field experiments (Chapter 3). In the poor and medium fields where fertilizer and manure were not applied, Napier fodder biomass yields were 8 Mg ha^{-1} $season^{-1}$ in the short rains. Better management in good fields increased fodder yields to 10 Mg ha^{-1} $season^{-1}$. Napier fodder yields in long rain season were 30% lower. Influence of soil fertility status and seasonal variations on leucaena biomass yields was minimal and biomass yields were 3 Mg ha^{-1} $season^{-1}$ independent of field type and cropping season.

In the current situation, the wealthier farmer used energy concentrates (dairy meal) to supplement the basal diet at the recommended rate of 2 kg cow^{-1} day^{-1} over the lactation period (Franzel et al., 2003). In the medium farm, concentrates were not used to supplement the basal feeding diet. For livestock production in the alternative scenario, dairy meal supplementation in the wealthier farm was varied to obtain an optimal feeding regime for maintenance and production needs of lactating dairy cows. Increasing the proportion of concentrates in feed rations for dairy cows during early lactation has been recommended and shown to increase milk yield (Rufino et al., 2009).

6.3.2 Livestock production assessment

Maximum daily DM intake by dairy cows was 3% of their live body weight. For feeding with supplementation, precaution was taken to ensure that supplements contributed not more than 40-70% daily DM feed intake. Pearson square method (Chamberlain, 1989) was used to balance feed ingredients (Table 2) to obtain feed rations to supply adequate nutrients for maintenance and lactation of dairy cows (Table 3). Manure production from dairy cows was calculated as: DM feed intake x

(1- DM digestibility) and adjustments made for feed selection (Table 2). Milk production by dairy cows was based on total crude protein after making adjustments for maintenance requirements (Table 4).

Table 2. Quality of feeds used in feed formulation Meru South

Feed type	Voluntary dry matter intake (%)	Digestibility (%)	Crude protein (%)
[a]Napier	80	60	8.5
[b]Maize stover	30	50	6
[b]Dairy meal	90	80	18
[c]Leucaena	80	65	18

[a]Chamberlain (1989); [b]Rufino et al. (2009); [c]Franzel et al. (2003)

Table 3. Feed rations for dairy cows at different phases of lactation based on voluntary dry matter intake

Feed ration and ingredients	Early lactation (Oct – Dec)	Mid lactation (Jan – Mar)	Late lactation (Apr - Jun)	End of lactation (Jul)	Dry period (Aug – Sept.)
Napier+Stover (6 kg milk day^{-1})					
Napier requirement (DM Mg day^{-1})	1.4	0.8	1.0	0.2	0.4
Stover requirement (DM Mg day^{-1})	0	1.0	0	0.3	0.9
Napier+Stover+2 kg dairy meal (8 kg milk day^{-1})					
Napier requirement (DM Mg day^{-1})	1.2	0.8	0.7	0.07	0.4
Stover requirement (DM Mg day^{-1})	0	0.2	0.3	0.2	0.9
Dairy meal (DM Mg day^{-1})	0.2	0.2	0.2	0.06	0
Optimal feeding (13 kg milk day^{-1})					
Napier requirement (DM Mg day^{-1})	1.0	0.6	1.1	0.2	0.6
Stover requirement (DM Mg day^{-1})	0	0.7	0	0.1	0.2
Dairy meal (DM Mg day^{-1})	0.4	0.3	0.2	0.13	0

Note:
Ration 'a' is current feed ration in medium farm (without supplementation)
Ration 'b' is current feed ration in wealthy farm (blanket supplementation)
Ration 'c' is optimal feed ration with targeted supplementation for lactating animals

6.3 PRODUCTION AT FARM LEVEL

6.3.1 Crop production, food sufficiency and soil loss

Table 4. Parameters used in feed formulation and livestock production assessment

Parameter	Parameter units	Parameter value
Dairy cattle live weight	Kg	450
Maximum dry matter intake	kg cow^{-1}	13.5
Milk butter fat content	g kg^{-1}	35
Milk crude protein requirement	g kg^{-1}	82
Maintenance requirements		
Mature lactating cows		
Crude protein	g cow^{-1}	403
Metabolizable energy	Mj cow^{-1}	55.6
Mature dry cows		
Crude protein	g cow^{-1}	763
Metabolizable energy	Mj cow^{-1}	71
Dry period	Days	60
Lactation period	Days	300
Maximum milk production	kg lactation $period^{-1}$	4000
Minimum milk production	kg lactation $period^{-1}$	2400

Annual household maize grain requirement across virtual farms was 0.3-0.5 Mg yr^{-1} while the legume grain requirement was 0.2-0.4 Mg yr^{-1}. The wealthier farmer attained household food self sufficiency of 1000 and 600% for maize and bean respectively. The medium farmer produced less maize and bean but still attained household food self-sufficiency. In the poor farm, the crop production was 0.1 Mg yr^{-1} for both maize and beans (Table 5a) and food household self-sufficiency was 25% for maize grain and 33% for beans.

Introduction of Napier barriers across the farms reduced maize and soybean crop production due to inter-specific competition for resources and reduction in crop area. The reduced crop production did not compromise household food security status for the wealthier farm whereas the food security status in the poor farm deteriorated further (Table 5b). When leucaena barriers were established in all the cropping fields instead of Napier, current maize production levels were not affected but legume grain production increased.

Table 5a. Crop and livestock production and soil loss in the current situation for the wealthy, medium and rich farms

	Wealthier farm	Medium Farm	Poor farm
Farm characteristics			
Family size	5	4	4
Maize requirement (Mg yr^{-1} $farm^{-1}$)	0.5	0.4	0.4
Legume requirement (Mg yr^{-1} $farm^{-1}$)	0.4	0.3	0.3
Number of dairy cattle	5	2	0
Food production			
Maize produced (Mg yr^{-1} $farm^{-1}$)	5.0	2.1	0.1
Beans produced (Mg yr^{-1} $farm^{-1}$)	2.4	1.8	0.1
Extra maize production	4.5	1.7	-0.3
Extra beans production	2.0	1.5	-0.2
Maize sufficiency	1000	525	25
Beans sufficiency	600	600	33
Livestock production			
Napier requirement (DM Mg yr^{-1} $farm^{-1}$)	17	8	0
Crop residue requirement (DM Mg yr^{-1} $farm^{-1}$)	6	4	0
[1]Dairy meal requirement (DM Mg yr^{-1} $farm^{-1}$)	3.0	0	0
Napier produced (DM Mg yr^{-1} $farm^{-1}$)	5	4	2
Crop residue produced (DM Mg yr^{-1} $farm^{-1}$)	8	4	2
Napier fodder sufficiency	29	50	-
Crop residue sufficiency	133	100	-
Milk and manure production			
Milk production (Mg yr^{-1} $farm^{-1}$)	12	2	0
Manure production(Mg yr^{-1} $farm^{-1}$)	26	6	0
Soil loss (Mg ha^{-1})	43	28	3

Table 5b. Soil loss, crop and livestock production in the alternative scenario with Napier and leucaena barriers for the wealthy, medium and poor farms

	Wealthier farm	Medium farm	Poor farm
Livestock production			
Napier requirement (DM Mg yr^{-1} $farm^{-1}$)	12		
Crop residue requirement (DM Mg yr^{-1} $farm^{-1}$)	5		
[2]Dairy meal requirement (DM Mg yr^{-1} $farm^{-1}$)	5		
Milk production (Mg yr^{-1} $farm^{-1}$)	20		
Manure production(Mg yr^{-1} $farm^{-1}$)	19		
Napier on strips			
Maize produced (Mg yr^{-1} $farm^{-1}$)	4.5	1.8	0.09
Soybeans produced (Mg yr^{-1} $farm^{-1}$)	1.72	0.27	0.03
Napier produced from strips (DM Mg yr^{-1} $farm^{-1}$)	2.0	1.2	0.1
Crop residue produced (DM Mg yr^{-1} $farm^{-1}$)	7	3	1.6
Total Napier (blocks & strips) (DM Mg yr^{-1} $farm^{-1}$)	7	5	2.1
Napier fodder sufficiency (%)	58	65	0
Crop residue sufficiency (%)	140	75	0
Soil loss (Mg ha^{-1})	21	13	2
Leucaena on strips			
Maize produced (Mg yr^{-1} $farm^{-1}$)	5.0	2.1	0.1
Soybeans produced (Mg yr^{-1} $farm^{-1}$)	2.7	1.2	0.1
Napier sufficiency (%)	42		
Crop residue sufficiency (%)	160		
Leucaena from strips (DM Mg yr^{-1} $farm^{-1}$)	0.75	0.45	0.12
[3]Leucaena from boundaries (DM Mg yr^{-1} $farm^{-1}$)	1.44	0.72	0.10
Total leucaena fodder (DM Mg yr^{-1} $farm^{-1}$)	2.19	1.2	0.22
Substituted dairy meal (%)	44		
Soil loss with minimum tillage (Mg ha^{-1})	27	17	3
Soil loss with regular tillage (Mg ha^{-1})	32	20	4

[1]Farm type 1 and 2 use 2 kg dairy meal per day as supplement during lactation
[2]Dairy meal supplementation varied to meet varying nutrient requirements during lactation
[3] A 1.5 ha farm can have 500 leucaena trees on farm boundaries producing 2 kg dry matter day^{-1} (Franzel et al., 2003)

In the current situation where barriers were not established in the cropping fields, massive soil losses occurred in the fields across the farms (Table 5a). With Napier barriers, soil loss reduced considerably (Table 5b). Leucaena barriers also controlled soil loss but less efficiently compared with Napier.

6.3.2 Livestock production and feed sufficiency

Napier fodder production across the farms was inadequate and supplied between 30-50% of the Napier fodder required for feeding. Fodder purchase from the market was necessary for the wealthier and medium farms. Establishment of Napier barriers in the alternative scenario increased Napier fodder supply and enhanced fodder self sufficiency across the farms but self sufficiency was still not attained (Table 5b). Improved feeding regime in the alternate scenario reduced the crop residues required for feeding across the farms. In the poor farm, 2 Mg DM yr^{-1} of Napier and 2 Mg DM yr^{-1} of crop residues were produced and at the current price of US$ 0.12 kg^{-1} DM of Napier and 0.02 kg^{-1} DM of crop residues (Chapter 3), the poor farmer would obtain US$ 240 from the sale of Napier fodder and US$ 80 from crop residues. With leucaena on the barriers, leucaena fodder from barriers was 0.12-0.75 DM yr^{-1} across the farms (Table 6b). Additional fodder was obtained from leucaena grown on farm boundaries. In the wealthier farm, leucaena fodder substituted the required dairy meal and the farmer did not have to buy supplements for improved feeding. In the poor farm, 0.22 Mg DM of leucaena fodder was produced that would generate US$ 64 as farm income if sold.

In the current situation, milk production was 12 Mg milk $farm^{-1}$ yr^{-1} for the rich farm and 2 Mg $farm^{-1}$ yr^{-1} for the medium farm. Manure production was 26 and 6 Mg DM $farm^{-1}$ yr^{-1} for the rich and medium farm respectively. In the alternative scenario, improved feed rationing increased milk production by 67% in the rich farm over that in the current situation but reduced manure production by 27%.

6.3.3 Monthly farm labour requirements

During the period of peak labour demand in October for the wealthier farmer, 72 person days were required to carry out crop farm production activities with regular tillage compared with only 44 person days if minimum tillage was practiced. With regular tillage, the wealthier farmer needed to hire in an equivalent of 48 person days of labour to fill the gap in labour shortage as opposed to only 20 person days with minimum tillage. When minimum tillage was practiced in medium farm, there were no labour shortfalls. In the poor farm, there was serious labour shortage during peak periods due to hiring out of farm labour that would potentially be addressed by practicing minimum tillage.

6.4 FEASIBILITY OF SOIL AND WATER CONSERVATION PRACTICES INTO HETEROGENEOUS SMALLHOLDER FARMS

6.4.1 Tillage and vegetative barrier practices

Napier and leucaena barriers reduced soil loss at farm level making these barriers suitable conservation-farming options for erosion control and restoration of soil productivity. The area occupied by Napier barriers was compensated by increased Napier fodder supply coupled with milk and manure production. Leucaena barriers were attractive due to provision of high quality fodder that substituted concentrates required for feeding in the rich farm or for supplementing the feed ration in the medium farm. Leucaena barriers also did not affect the farm crop production status but were however less efficient in soil conservation and maybe suitable for farmers willing to trade-off soil conservation efficiency in favour of high quality fodder. Napier barriers were efficient in soil conservation and fodder production but reduced farm crop production and maybe suitable for a farmer willing to trade-off crop production in favour of feed production. A combination of Napier and leucaena barriers at farm level would however present a win-win scenario for farmers due to efficient soil conservation, provision of Napier fodder for feeding and high quality leucaena fodder for supplementing the basic feed ration.

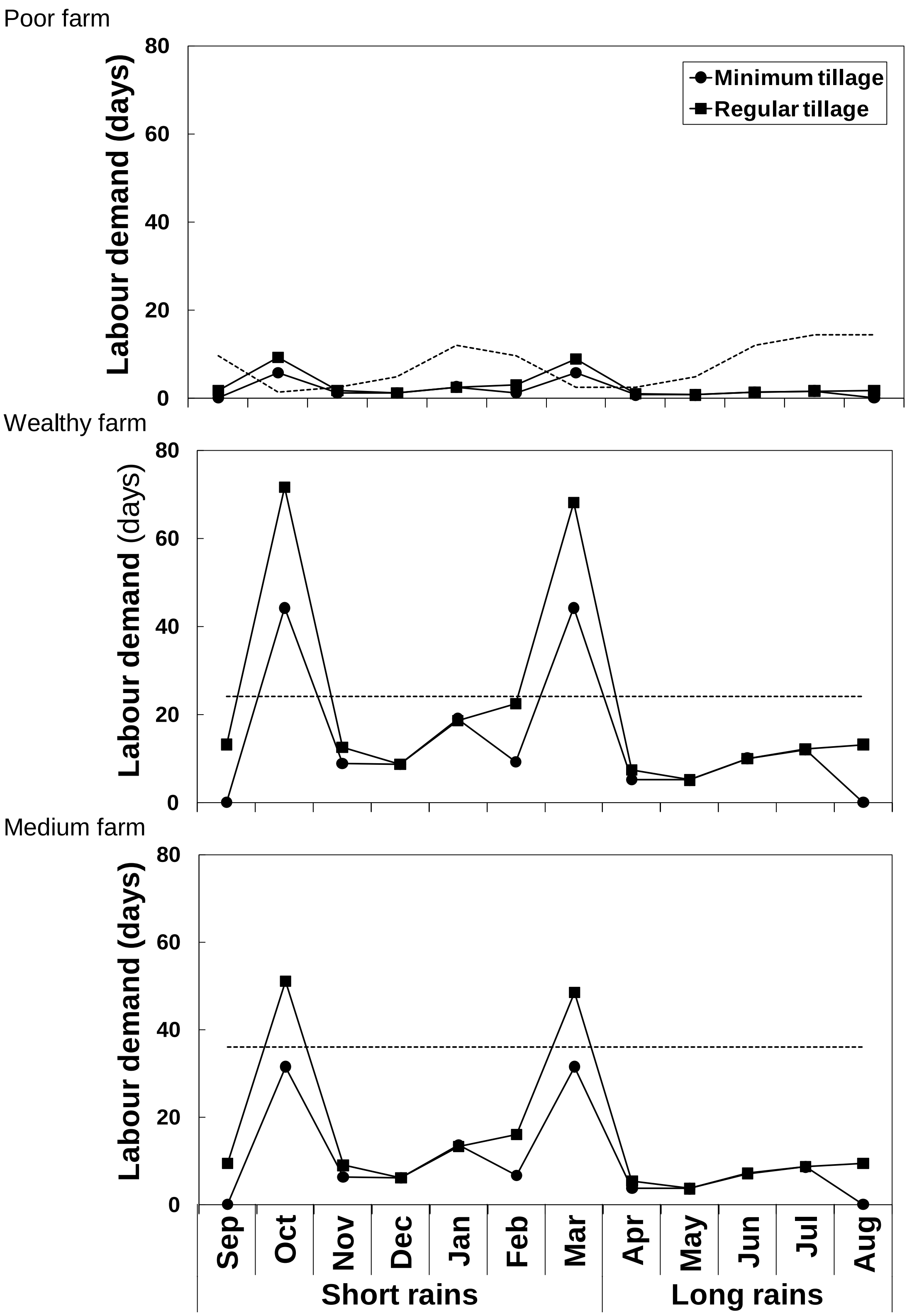

Figure 3. Farm labour demand for minimum and regular tillage for the virtual farms in short and long rain seasons for crop production based on farm experiments and observations in trial farms. The dotted line represents available farm labour.

6.4.2 Chakula bila kulima: an answer to all farmers?

As pointed in the introduction, farmers doubt if you can produce food without some degree of soil inversion. We conducted an impact assessment for farmers involved in the field experiments and held focused group discussions to explore farmer perceptions on minimum tillage. Farmers agreed that it's possible to produce food without regular tillage hence saving the labour required for land preparation and for timely planting and weeding. The interest to save labour varied across household types. The wealthier farmers who had most of their children in boarding schools and relied on hired labour were interested in labour saving with minimum tillage. Medium resource farmers who relied on family labour complemented with children in day schools had a difficult choice to make. One such a farmer wondered if he should use scarce farm resources to buy herbicides for the control of weeds and have the children who would otherwise cultivate the fields sit at home.

In the discussions with farmers, some instances of past failures in the promotion of minimum tillage to smallholder farmers in the area were partially attributed to minimum tillage being a new technology. Most of the farmers were not sure about its performance and to minimize risks on food security, they mainly tried it in poor fields. In the farmer's opinion, efforts on promotion of minimum tillage and other new technologies should aim at working closely with farmers in early stages on small portions of different fields so as not to compromise food security concerns and establish where the technology works best before large scale promotion.

Herbicides are used for timely and effective weed control in minimum tillage. Proper herbicide use requires knowledge on the efficacy of herbicides and application requirements. Few farmers felt that they had adequate knowledge for proper herbicide use and some training was necessary. Farmers however pointed out that the results of herbicide application were not immediate. In case of an error in herbicide application (for example the use of sub-optimal application rates or missed spots), there is no time to make corrections. This can have serious consequences where the rainfall is erratic and delay in weed control has a huge yield penalty. Farmers practicing minimum tillage would lose out heavily and put their food security at risk.

The urgent equipment required for minimum tillage would be a spray pump for application of herbicides. Well-endowed farmers had ready access to sprayers through buying or hiring. Medium resource farmers had limited access to sprayers because in the past when coffee was doing well as a cash crop, they would own and maintain a sprayer. Most of the sprayers in medium farms were currently in poor condition and would not be used for effective application of herbicides. The wealthier and medium farmers who did not have sprayers were also well integrated to the local social network and would easily borrow and use sprayers from neighbours. Poor households lacked both the capital and strong communal social networks for accessing sprayers.

For retention of crop residues in cropping fields, generation of adequate crop-residues in smallholder farms to satisfy competing farm demands was difficult, particularly for livestock feeding. In the impact assessment and focused group discussions, none of the farmers was willing to try out or continue to retain crop residues in their fields. This concurred with the farm assessment for different farms in the virtual farms where there was inadequate crop residues for feeding. As pointed out elsewhere, although the minimum tillage is more effective, or only effective if there is sufficient mulch (Rockstrom et al., 2009; Erenstein, 2003), use of crop residues as mulch is not an acceptable practice for many smallholders in mixed crop-livestock farming systems.

6.5 Conclusions and recommendations for future research

Napier fodder supply was inadequate in farms with dairy cows and introduction of Napier barriers in the alternative scenario controlled farm soil losses and increased fodder supply enhancing farm feed sufficiency but reduced household food production. High quality fodder from leucaena barriers substituted energy concentrates in rich farms while improving feed rationing for medium farmers without affecting household food production. A win-win scenario at farm level would involve combination of leucaena and Napier barriers. Farmers no longer doubted “chakula bila kulima” (producing food without tillage). Complexity in smallholder farming systems leads to a wide range of competing farm production objectives. Smallholder farmers’ have multiple production objectives and are faced with trade-offs when changing their farm management. Recommendations on soil and water conservation practices for eventual adoption by farmers therefore need to be tailored to suit local opportunities and constraints to attract farmer interest and guarantee investment. There is need for long-term multi-locational studies on the soil and water conservation practices to address the diversity in smallholder farms. As well, farm scale dynamic models such as NUANCES-FARMSIM (van Wijk et al., 2009) would in addition be used for better fitting of soil and water conservation practices into heterogeneous smallholder farming system.

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Degradation of soil and water resources in East Africa remains widespread while uptake of recommended conservation practices by smallholder farmers is limited. This in part because underlying the immediate causes of soil erosion that recomended practices address are site specific socio-economic and bio-physical conditions. These conditions determine the priority that smallholder farmers attach to soil conservation as well as the kinds of conservation practices they are likely to invest in. Smallholder farms were hived from large settler farms evolving into a complex farming system with various types of crops and livestock and off-farm income sources across different sites and soils. Complexity in smallholder farming systems leads to a wide range of competing farming objectives necessitating trading-off when farmers decide whether to implement or reject recommended conservation practices. Recomended conservation approaches therefore need to be tailored to suit local farming system opportunities and problems of Meru South and Mbeere Districts of Central Kenya.

Farm scale studies in Meru South and Mbeere Districts identified four farm types: small farms reliant on substantial off-farm income (farm type 1), large wealthy farms less dependent on off-farm income (farm type 2), households with medium resource endowment (farm type 4) and small poor households dependent on irregular off-farm income (farm type 5). Farmers' were aware of the occurrence of soil erosion in their farms and showed appreciable knowledge of the water erosion processes. In Meru South, two or more conservation practices were observed in 67% of the farms compared with 33% in Mbeere. Trash lines were common in the low potential Mbeere area except for farmers with high resource endowment who instead preferred [1]fanya juu and vegetation barriers. Stone lines were found in farms of medium and poor resource endowment. In Meru South, contour farming was popular across farm types but farmers preferred conservation measures such as vegetative barriers with multiple benefits. Vegetation barriers were preferred by farmers who had small land holdings or labour constraints. Fanya juu terraces were however favoured by rich

[1] *Fanya juu is an anti-erosion barrier established on the contour by digging up a trench and throwing soil upslope*

than poor farmers. Three field types on a relative scale of soil fertility were identified by the farmers: good, medium and poor. Farm type 1 and 2 had good fields only, farm type 3 had good, medium and poor fields while farm type 5 had only poor fields. Physical and vegetative measures were larger and well maintained in good fields but smallest and poorly maintained poor fields.

For soil conservation, Napier barriers with regular tillage conserved most soil (72%) followed by Napier with minimum tillage (53%) while minimum tillage without anti-erosion barriers conserved least soil (1%) with leucaena barriers having intermediate conservation efficiency. Across tillage practices, negative economic returns were realized in the first cropping season with vegetative barriers whereas without barriers, economic returns were also negative with minimum tillage but slightly positive with regular tillage. Considering economic returns and the soil conserved, minimum tillage without anti-erosion barriers or adequate soil cover was inefficient in soil conservation and had poor economic returns making it an unsuitable option for the local farming system. Leucaena barriers had attractive economic returns across tillage practices but conserved less soil. But for leucaena barriers with minimum tillage, labour price should be below US$ 0.36 $hour^{-1}$ and herbicide price below US$ 20 $litre^{-1}$ to guarantee attractive economic returns to the farmers. Napier barriers with regular tillage presented a win-win scenario for farmers and environmental impacts because of simultaneous attractive economic returns and efficient soil conservation. However, the price of labour should be below US$ 0.30 $hour^{-1}$ for acceptable economic returns.

Anti-erosion barriers influenced soil water content during wet and dry periods. For wet periods, more run-off was conserved with than without vegetative barriers. Across tillage practice, more water accumulated in plots with barriers especially near the barriers with Napier than leucaena. In the dry period, reduction of conserved water commenced early and at a faster rate near than away from the barriers. The rate of water reduction near barriers was higher with Napier than leucaena, particularly if minimum tillage was practiced. With Napier barriers, row crop yields were significantly reduced by 28-78% up to 3 m away from the barriers if minimum tillage was practiced, and up to 1.5 m with regular tillage. Such yield reductions were less pronounced with deep-rooted leucaena barriers. Napier barriers therefore competed for water and nutrients with companion crops while leucaena had complementary resource use pattern. Farming without installation of anti-erosion barriers leads to soil degradation and establishment of vegetative barriers can curb soil erosion and reverse the trend. Napier grass barriers are efficient in conserving soil and water but compete with crops for available water especially with minimum tillage even when intensely pruned. Leucaena barriers have complementary water use pattern with crops across tillage practices and but are less efficient for soil and water conservation.

Maize grain yields in the good fields were above 2.5 Mg ha^{-1} across cropping seasons and cumulated yields were not influenced by tillage and crop residue practices. The grain yields in the medium fields ranged between 1.3 and 5.4 Mg ha^{-1} and were greater with crop residue retention. In the poor fields, grain yield was less than 3.6 Mg ha^{-1} and minimum tillage resulted in yield decrease while crop residue practices did not affect yields. Regular tillage and crop residue removal resulted in largest gross benefits in the good fields (US$ 5376 ha^{-1}) while in the medium fields, minimum tillage with residue retention was most profitable (US$ 3214 ha^{-1}). Retention of crop residues will give improved maize performance in the medium fields and the prevailing prices favour minimum tillage and crop residue retention. In the poor fields, the emphasis should be on the rehabilitation of soil physical and chemical attributes because none of the tillage and crop residue practices was profitable.

The potential of improved soil and water conservation practices is site specific. The retention of crop residues was not viable due to intense competition for alternative on-farm uses of crop residues, particularly livestock feed. Minimum tillage was of interest to well endowed farmers who had labour constraints and had access to herbicides and sprayer pumps. Poor famers would not afford herbicides and had no access to pumps. There is need to simulate the production situation using farm scale models for comprehensive understanding of the options available to facilitate better fitting of soil and water conservation options into the heterogeneous smallholder farming system.

Degradatie van bodem en water komt wijd verspreid voor in Oost Afrika maar kleine boeren maken nog maar weinig gebruik van voorgestelde maatregelen die deze degradatie tegengaan. Dit komt gedeeltelijk omdat deze maatregelen betere sociale, economische en biofysische condities vragen dan in de huidige situatie, dezelfde die nu ook aan de bodem erosie ten grondslag liggen. Deze condities sturen welke prioriteit kleine boeren geven aan bodembescherming en in welk type beschermingsmaatregelen zij wensen te investeren. Bevolkingsgroei, steeds kleiner wordende bedrijven en intensievere teelt heeft geleid tot een complex boerenbedrijf systeem dat varieert tussen verschillende locaties en bodems in type gewassen, veeteeltsystemen en mate van afhankelijkheid van inkomen verkregen buiten het bedrijf. Deze complexiteit leidt tot een veelheid van met elkaar conflicterende doelstellingen in een bedrijf. Boeren hebben te maken met meerdere productiedoelen en met uitruil tussen die doelen wanneer zij hun bedrijf en management willen veranderen. Voorstellen tot bodembeschermingsmaatregelen moeten dan ook op maat gemaakt zijn zodanig dat zij geschikt zijn om de lokale uitdagingen en beperkingen te kunnen aangaan en dat boeren interesse krijgen en bereid zijn te investeren.

De bedrijven zijn gekarakteriseerd in twee districten in Kenya met contrasterende agro-ecologische condities: Meru South en Mbeere. In Meru South is het landschap heuvelachtig en is het potentieel van de landbouw redelijk bij een gemiddelde regenval van 1500 mm $jaar^{-1}$. In Mbeere is het terrein vlakker en de regenval lager (750 mm $jaar^{-1}$). Via studies op bedrijfsniveau zijn vier bedrijfstypen geïdentificeerd: kleine bedrijven afhankelijk van een substantieel inkomen buiten het boerenbedrijf, grote welvarende bedrijven en minder afhankelijk van inkomen buiten het bedrijf, bedrijven met gemiddelde middelen van bestaan en kleine bedrijven afhankelijk van een onregelmatig inkomen buiten het bedrijf. In Meru South kwamen op 67 % van de bedrijven twee of meer bodembeschermende maatregelen voor in vergelijking tot 33 % in Mbeere. Gewasresten in contourlijnen gelegd kwamen algemeen voor in

Samenvatting

Mbeere behalve bij boeren met veel middelen die liever [1]fanya juu en barrières van vegetatie gebruikten. Stenenrijen kwamen vooral voor in bedrijven met weinig of geen middelen van bestaan. In Meru South was gebruik van contouren in alle typen bedrijven populair, maar boeren prefereerden barrières van vegetatie die voor meerdere doelen kunnen worden gebruikt. Fanya juu terrassen hadden een grotere voorkeur bij rijke dan bij arme boeren. In Meru South werden door boeren op basis van bodemvruchtbaarheid drie typen velden onderscheiden: velden met goede, gemiddelde en arme gronden. Vegetatie in barrières was op goede gronden weelderiger en beter onderhouden dan op arme gronden.

Barrières van Napier gras met toepassing van de lokaal gebruikelijke grondbewerking beschermt de bodem het beste (72%) gevolgd door Napier gras met minimale grondbewerking (53%) terwijl minimale grondbewerking zonder anti-erosie barrières de bodem het minste beschermde (1%). Vegetatie barrières van leucaena zijn minder efficiënt in bodembescherming dan Napier gras. Alle onderzochte grondbewerkingsmaatregelen overziend leverde negatieve economische opbrengst op in het eerste seizoen zowel in combinatie met Napier als met leucaena barrières. Zonder barrières met lichte grondbewerking leidden ook tot negatieve economische opbrengsten en slechts licht positieve resultaten in combinatie met de gebruikelijke grondbewerking. Economische opbrengsten en verlies aan grond door erosie in ogenschouw nemend, zijn de minimale grondbewerking zonder anti-erosie barrières of die met adequate grondbedekking inefficiënt in bodembescherming en zijn de economische opbrengsten gering waardoor het geen geschikte opties zijn voor de lokale bedrijven. Barrières van leucaena zijn attractief in economisch opzicht bij elk systeem van bodembewerking maar bescherming van de bodem is dan gering. Bij minimale bodembewerking gecombineerd met leucaena barrières moet de prijs van arbeid lager dan 0.36 US$ uur^{-1} zijn en de prijs van herbiciden lager dan 20 US$ l^{-1} om attractieve economische opbrengsten te garanderen. Barrières van Napier gras gecombineerd met gebruikelijke grondbewerking lijkt zowel in economische opbrengst als in bodembescherming een goede oplossing. Echter, de prijs van arbeid moet dan onder de 0.30 US$ uur^{-1} blijven wil deze optie rendabel blijven.

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[1] Fanya juu is een gegraven geul op een contourlijn waarbij de uitgegraven grond als een barrière helling opwaarts wordt gedeponeerd

De waterbeschikbaarheid in de bodem gedurende natte en droge perioden werd beïnvloed door barrières met vegetatie. In natte periodes werd er meer run-off vastgehouden dan zonder barrières met vegetatie. De onderzochte grondbewerking beziend, werd er meer water vastgehouden in de plots met barrières vooral dicht bij de barrières van vegetatie en dan beter bij Napier gras dan leucaena. In droge perioden, begon de afname van vocht in de bodem eerder en sneller dichtbij de barrières dan verder daar vandaan. De afname in bodemvocht bij de barrières was sneller bij Napier gras dan bij leucaena, zeker als ook minimale bodembewerking werd toegepast. Bij barrières van Napier gras met minimale grondbewerking waren gewasopbrengsten per rij significant 28-78% lager voor de rijen tot 3 meter van de barrières en tot 1.5 meter van de barrière bij gebruikelijke grondbewerking. De terugval in opbrengst was minder geprononceerd bij barrières van leucaena die diep wortelen. Door oppervlakkiger wortelen is Napier gras in concurrentie met het gewas voor water en nutriënten terwijl leucaena een complementair water- en nutriëntengebruik heeft. Landbouw bedrijven zonder gebruik van anti-erosie barrières leidt tot bodemdegradatie en aanbrengen van barrières met vegetatie kan dit tegenhouden en de trend omkeren. Napier gras is efficiënt in bodembescherming en watergebruik, maar concurreert met de gewassen om het beschikbare water zeker als minimale grondbewerking wordt toegepast zelfs als de vegetatie sterk wordt teruggesnoeid. Barrières met leucaena leiden tot een complementair watergebruik maar zijn minder efficiënt in bodembescherming.

Graanopbrengsten van maïs waren op rijke gronden meer dan 2.5 Mg ha^{-1} in alle gevolgde seizoenen en de over de seizoenen geaccumuleerde opbrengsten werden niet beïnvloed door grondbewerking of door het al dan niet gebruiken van gewasresten. De opbrengsten op de gematigde, armere gronden varieerden tussen 1.3 en 5.4 Mg ha^{-1} en waren hoger wanneer gewasresten werden gebruikt. Op arme gronden waren de opbrengsten minder dan 3.6 Mg ha^{-1} en beperkte grondbewerking leidde tot lagere graan opbrengst terwijl gebruik van gewasresten dan geen effect had. De lokaal gebruikelijke grondbewerking in combinatie met het weghalen van gewasresten leidde tot het hoogste bruto voordeel (5376 US$ ha^{-1}) op goede gronden terwijl op de gematigde gronden beperkte grondbewerking met het laten liggen van de gewasresten het meest voordeling was (3214 US$ ha^{-1}). Het laten liggen van gewasresten zal verbeterde maïs groei op de gematigde gronden brengen en bij de huidige prijzen is de combinatie minimale grondbewerking en laten liggen van gewasresten de beste. Op arme gronden zou het herstel van de bodem fysische en chemische eigenschappen van de bodem de hoogste prioriteit moeten hebben omdat geen van de grondbewerkingen nog gebruik van gewasresten rendabel was.

In de huidige productiesituatie van boerenbedrijven werd alleen in de rijke en gemiddelde bedrijfstypen voldaan aan productie voor zelfvoorziening in voedsel, maar dan alleen met een massaal verlies aan bodem. Het aanbod aan Napier gras als veevoer voor melkkoeien was niet voldoende. Introductie van barrières met vegetatie in het alternatieve scenario kan de erosie controleren. Barrières met Napier gras kan dan bijdragen aan het oplossen van het tekort aan veevoer, maar dan vermindert de voedselproductie voor het huishouden. Voer van leucaena, van een hoge kwaliteit, kan in het rijke bedrijf de plaats innemen van de energie anders gegeven via duur krachtvoer. In gemiddelde bedrijven kan dit een verbeterd rantsoen van veevoer opleveren zonder dat dit ten koste gaat van de voedselproductie voor het huishouden. Een win-win scenario op bedrijfsniveau zou een combinatie van velden met Napier gras en velden met leucaena zijn. Boeren twijfelden niet langer aan “chakula bila kulima” (voedselproductie zonder grondbewerking). De voordelen van “chakula bila kulima” waren voor hen het beperken van arbeid en het garanderen van een juiste periode van planten en wieden. Rijke boeren die ook arbeid inhuren zullen beperking van gebruik van arbeid attractief vinden in tegenstelling tot de gemiddeld bedeelde boeren die afhankelijk zijn van arbeid geleverd door de familie. Arme boeren kunnen voordeel hebben bij het tijdig planten en wieden van hun gewassen als gevolg van deelname aan activiteiten buiten het bedrijf maar toegang tot gebruik van herbiciden kan dan een struikelblok zijn. De complexiteit van de kleine boeren bedrijfssystemen betekent dat introductie van enig nieuw systeem van bodembewerking en watergebruik niet eenduidig verbetering brengt. Nieuwe systemen moeten op maat worden gesneden van de lokale sociale, economische en biofysische condities willen boeren deze attractief vinden.

I thank the Government of Kenya through the Ministry of Agriculture and the Directorate of Personnel Management who granted me study leave to pursue this course. Special thanks to Charity Mariane and Ruth Mwangi from Ministerial staff training sub-division and Jane Aseka from the human resource development branch for administrative and logistical support.

It was a unique experience to work with my promotor Ken Giller. We met for the first time in Nairobi during a Nitrogen fixation workshop and discussed how and when to start my PhD study. His critical analysis contributed to my critical thinking and coherent writing. Besides our interaction reminded me on the need to be open minded and ready to look at other possibilities. I cannot forget Nico, my daily supervisor at Wageningen for the fruitful formal and informal discussions, especially when scaling up the experimental results from plot/field to farm level. Ken and Nico also allowed me full access to the NUANCES project work that gave me head start in my work. I cannot also forget to mention the several dinners organized by Ken and Nico that made me feel at home away from home. I also appreciate the PPS secretariat (Ria and Charlotte), CSA group secretariat (Sjane) and finance (Berkhout and later Alex) who assisted with administrative and logistical issues throughout the study.

I had the privilege of working with two supervisors in Kenya, Bernard Vanlauwe and Pieter Pypers. Bernard was the first person I discussed with the PhD proposal while in its rudimentary form and it was important that he believed in my dreams and urged me to proceed. Pieter Pypers made immense contributions to my field work. Thank you Pieter for all the long hours we spent together on statistical analysis and data presentation! It was a pleasure working together.

I received support from staff of TSBF-CIAT. I am grateful to Peter Okoth whose comments during formal and informal meetings assisted in focusing the study. I also thank Alice Kareri, Josephine Meyo, Caleb Mulagoli for the administrative and logistical support. Additionally, I also appreciate the TSBF-CIAT laboratory staff,

Acknowledgements

Wilson Ngului and his colleagues, who prepared and analysed my soil and plant samples.

I am indebted to Richard Onwong'a and the staff in the soil physics laboratory of Nairobi University who assisted in carrying out soil physical analysis. The farmers on whose plots data was collected and those who participated in surveys and focus group discussions deserve appreciation. I also thank Bernard Gitonga and Alex Mutembei who alongside others assisted in field data collection.

For my fellow African PhD students Aisha Abdulkadir (mama Nigeria), Naomi (mama Africa) and Chris Murungweni, it was a pleasure to share several dinners including the "no mood" jokes and all the other laughter that ensured that I remained sane and sober despite the pressure and stress associated with PhD in Wageningen. The office mates at the Radix with whom I shared coffee and cakes cannot be forgotten: Juliana, Maria, Maurice, Mink, Moreno, 'Marabou', Argyris, Wairegi, Moritz, Idzert and Florin. Aisha, Tumwine (strong guy) and Alba whom we shared life at the containers in Haarweg cannot be equally forgotten.

I thank my parents (mother, father, father/mother-in-law), brothers and sisters (including in-laws), who encouraged and prayed for me without ceasing. Special mention for my Dad who was critically sick towards the end of the study but still found the strength for inspiration and encouragement. It was a delight to have Denno as my informal ICT consultant who always came to my rescue when the computer misbehaved.

Lastly, I want to thank the most important and special person in my life, my dear wife, Pendo Sumai. Besides putting up with my long absence away from home, she encouraged me and always prayed with me several times over the phone whenever I felt low and exhausted. I look forward to returning the favour as she in turn winds up her studies.

Samuel Nyachio Guto was born on 5th December 1969 at Nyasike village, Kisii District, Kenya as a fourth child to Yunes Kerubo and Joseph Guto. He started schooling at the age of six but dropped out after a short while because he found pre-school rhymes and songs boring. He resumed schooling one year later on assurance that he would proceed to standard one. He sat for his Certificate of Primary Examinations (CPE) in 1983 at Getacho primary school and was the best student in the school that year. He then proceeded to Nyanchwa Adventist Secondary School where he sat for his Kenya Ordinary Certificate of Education Examination (KCE) in 1987 and was again the best student in the year. Against the advice of close friends and some family members, he took a science combination for which the school had a poor track record instead of an arts combination for his Kenya Advanced Certificate of Education (KACE) in Sameta High School. He almost paid for the choice as the subsequent examination score was only just above the cut-off for university admission after sitting for his A-level examinations 1989. He taught in Nyanturago Secondary School as an untrained teacher for one year (1990) and proceeded to Egerton University for a Bachelor's degree in Agriculture Education and Extension. He graduated in 1994 and went back to teach in his old school (Nyachwa Secondary) for one year after which he re-joined Egerton University to pursue a Masters degree in Soil Science on a World Bank sponsored capacity development program. The MSc course culminated in the writing of a thesis on integration of legume crops into wheat based cropping systems for soil fertility improvement. On completion of his MSc in 1997, he joined the Ministry of Agriculture where he served in different capacities that included co-ordination of agricultural extension activities to backstopping on soil and water conservation. While working with the Ministry of Agriculture, he got involved in a project on dissemination of zero tillage jointly with private seed and chemical companies, Kenya Agricultural Research Institute and farmers who had to donate a piece of land to set up demonstration plots. There was considerable success in the promotion of zero tillage with farmers, except for one incident where the promotion team was taken into task by a farmer who wanted to know why the technology did not do well on his plot even though he had followed all the guidelines given. The promotion team was cornered and it was the farmer's young child who literally saved the situation by pointing out that crops never performed well in that part of the farm anyway!!! The farmer thereafter admitted to have donated that piece of poor quality land with the intention of seeing if zero tillage had the magic to address whatever hindered better crop performance. The incident formed the basis of his PhD study that commenced in 2006 formulated around better targeting of improved soil and water conservation practices into smallholder farming systems by identifying where, when and for whom such practices can have the greatest impact.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational 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)

- Soil and water management in sub-Saharan Africa

Writing of project proposal (4.5 ECTS)

- Soil and water conservation in the smallholder farms of central Kenya: integration and exploration of options for productive and sustainable farming systems

1.1 Post-graduate courses (4 ECTS)

- Getting to the bottom of Mount Kenya; PE&RC (2009)

Laboratory training and working visits (2.4 ECTS)

- Rapid assessment of leaf chlorophyll content in maize; Jomo Kenyatta University (2008)
- Analysis of soil physical properties; Nairobi University soil physics laboratory (2009)

Deficiency, refresh, brush-up courses (6 ECTS)

- Qualitative analysis of land use systems (2006)

Competence strengthening / skills courses (4.8 ECTS)

- Basic statistics; PE&RC (2006)
- Information literacy for PhD students; PE&RC (2010)
- Multivariate statistics; PE&RC (2010)
- Techniques for writing and presenting scientific papers; WGS (2010)

1.2 PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Weekend (2006)
- PE&RC Day (2010)

1.3 Discussion groups / local seminars / other scientific meetings (7.5ECTS)

- Annual Africa NUANCES workshops; Wageningen/Arusha (2006/2007)
- Nairobi University-TSBF-CIAT monthly PhD discussion group (2006-2009)

1.4 International symposia, workshops and conferences (10.5 ECTS)

- Blended learning event on research methods-thinking scientifically; 13th-28th August (online learning), 1st-5th October (face to face); World Agroforestry Centre (ICRAF), Nairobi, Kenya (2007)
- International meeting of the Africa Soil Fertility Network (Afnet): innovation as key to the green revolution in Africa: exploring the scientific facts; Arusha, Tanzania (2007)
- International meeting of the Soil Society of East Africa (SSEA): improving livelihoods through applied soil science and land management; Embu, Kenya (2007)
- Farming systems and tradeoffs analysis using models; Butare, Rwanda (2009)

The research described in this thesis was financially supported by a PhD scholarship by NUFFIC