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Impacts of vegetative contour hedges on soil inorganic-N cycling and erosional losses in Arable Steep-lands of the Central Highlands of Kenya

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Abstract

Moderate to steep landscapes and severe soil, water and nutrient losses characterize over 40% of arable land in the central highlands of Kenya. To study the effectiveness of biological methods in management and enhancement of productivity of these arable steep-lands, we established contour double row hedges of sole *Calliandra*, *Leucaena* and napier and combination hedges of either *Calliandra* or *Leucaena* with napier. Hedges were established on slopes exceeding 5%, pruned regularly and the resulting biomass cut into fine pieces, which were then incorporated into the plots they served. We then evaluated these plots for inorganic-N changes with depth, soil conservation and soil loss/crop growth relationships. We observed accumulation of inorganic-N in the sub-soil in the control and napier plots but a reduction of sub-soil inorganic-N and its re-accumulation in the top-soil in the leguminous hedge plots after 20 months of trial. The first season on average, registered higher soil losses ($P = 0.004$) than the second season for treatments with hedges and vice versa for the control. During the first season there were significantly lower ($P < 0.001$) soil losses in plots with hedges relative to the control on slopes exceeding 10% but with the exception of napier, no significant differences among different types of hedges. We observed higher soil loss reduction in the combination hedge relative to individual tree hedges across the two seasons ($P = 0.012$). The relationship between cumulative soil loss and any of the four crop growth parameters i.e., grain weight, plant height, stover weight and total above ground biomass was negative, linear and highly significant ($P < 0.0001$), indicating decreased crop growth with soil loss. We conclude that there are heavy productivity losses as a result of soil erosion in arable steep-lands of the central highlands of Kenya and that well spaced, managed and combined contour hedges of leguminous trees and napier can reduce soil and nutrient losses from steep arable landscapes while simultaneously enhancing soil fertility

Key words: Contour hedges, inorganic-N, soil fertility, soil erosion, slope

Introduction

Recent studies in the central highlands of Kenya have revealed leaching of up to 300 kg N $ha^{-1}yr^{-1}$ (Mugendi et al., 2003) and a soil loss of 150–200 t $ha^{-1}yr^{-1}$ (Angima, 2000). At modest soil loss level of 10 t $ha^{-1}yr^{-1}$, it is estimated that soils lose on average 28 kg N, 10 kg P and 33 kg K $ha^{-1}yr^{-1}$(Mantel and Van Engelen, 1999). Construction of physical soil conservation structures is expensive, laborious and time-consuming, and farmers do not have adequate resources to invest in construction due to scarcity and multiple competing enterprises that characterize the households. This leads to low adoption of physical soil conservation technologies and hence heavy soil and nutrient losses. In addition to causing serious monetary losses to farmers, soil loss pollutes rivers and other water bodies potentially causing eutrophication, bottom water hypoxia and health hazards to both humans and animals (Cast, 1985; Duijvenbooden and Matthijsen; 1987; Justic et al., 1995). The usefulness of contour hedges as alternatives to physical soil conservation

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structures has been demonstrated in Kenya (Raintree and Torres, 1986; Angima; 2000), Nigeria (Lal, 1989) and Java Indonesia (Pacardo and Montecillo, 1983). Basically, contour hedgerows control soil erosion by two mechanisms: (1) the hedgerows act as permeable barriers for slowing the flow of runoff and (2) The pruned biomass which is deposited as green manure between the hedges provides a protective cover from raindrop impact (Young, 1997).

Incorporating leguminous pruning residues from contour hedges improves soil fertility as these materials decompose and release nutrients, which translates into better crop production (Yemoah et al., 1986; Mugendi et al., 1999). Apart from improving the soil nutrient status, the pruned residues may also increase the soil organic matter content (Yemoah et al., 1986). This in turn improves the soil physical properties, creating favorable conditions for plant growth. In alley cropping trials of nine leguminous trees with maize in Hawaii, Rosecrane et al. (1992) reported an increase in maize yields with addition of tree pruning mulches. For every kilogram of nitrogen applied in form of mulch, approximately 12 kg of additional maize grain yield was produced. Most of these studies however, have been done on-station and therefore do not adequately simulate farm situations, where many uncontrolled factors account for poor performance of technologies that are successful on-station. Studies combining soil conservation aspects of agroforestry with nutrient enhancement/management and crop production which is the ultimate farmers' goal are also few.

To address these problems, we established an on farm trial with thirty-three farms in the central highlands of Kenya to determine the extent of top-soil loss through water erosion and the effectiveness of leguminous (*Calliandra calothyrsus* Meissner and *Leucaena trichandra* (Zucc.) Urban) and non leguminous (napier grass) vegetative contour hedges in soil conservation and nutrient enhancement.

Materials and methods

Description of the study area

This study was conducted in Chuka Division, Meru South District, which is a predominantly maize growing zone in the central highlands of Kenya. The area is on the eastern slopes of Mt Kenya at an altitude of approximately 1500 m above the sea level. Mean annual rainfall is 1200 mm, distributed in two distinct seasons; the long rains (mid March to June) with an average precipitation of 650 mm and the short rains (mid October to December) with an average of 550 mm of rainfall. The average monthly maximum temperature is 25°C and the minimum is 14°C. The long-term monthly average temperature is 19.5°C. The soils of this area are mainly humic Nitisols (FAO, 1990) equivalent to Paleustalf in the USDA soil taxonomy system (Soil Survey Staff, 1990) with an average soil reformation rate of 2.2–4.5 Mg ha^{-1} per year for the top 0–25 cm soil depth and 4.5–10 Mg ha^{-1} per year for the 25–50 cm soil depth (McCormack and Young, 1981; Kilewe, 1987). They are deep, well weathered with friable clay texture with moderate to high inherent fertility.

Experimental design and methodology

Slopes and contours of 33 trial farms were determined by use of a clinometer and surveyors level, respectively. We evaluated mono-specific hedges of: *Calliandra*, *Leucaena*, napier and combination hedges of *Calliandra* + napier and *Leucaena* + napier. Plots with no hedges served as controls in each farm. Each hedge was made up of 2 rows of the above species arranged in interlocking/zig-zag manner with inter-row spacing of 0.25 m and intra-row spacing of 0.5 m. The plots were 10 m long with variable inter-hedge spacing calculated according to Young (1997) as follows:

$$W = 200/S\% \quad (1)$$

where W = inter-hedge spacing in metres and S% is the per cent slope. Where there was a napier + either *Calliandra* or *Leucaena*, the tree row preceded the napier grass row upslope. Each farm represented a block. The aim of blocking was to minimize the effects of site variation so that the treatment effects could be more accurately quantified using statistical tests. Care was taken to ensure that none of the plots fell on obvious convex zones of higher than average net erosion, or deposition zones of net sedimentation. We also trenched the plots on the upper lateral borders to prevent eroded sediments from up-slope areas from entering into the test plots.

After planting, the hedges were left for one year to become well established after which they were regularly pruned every 2 months to a height of 50 cm for trees and 10 cm for napier. This was meant to ensure that they did not overgrow the crop and pose significant aboveground competition. The resulting biomass from any one hedge was cut into fine pieces and incorporated into the plot it served.

Soil sampling and analysis

Initial sampling for soil characterization was done on each farm before commencing the trials. The second set of soil samples was collected 20 months after establishment of the trials. For each collection date, at least six samples from each plot were collected. The six samples were mixed thoroughly and sub-sampled to form one composite sample. Field moist sub-samples were refrigerated at 4°C immediately after collection. Twenty grams of this field moist soil was extracted using 5 mL of 2N KCl within 3 days of collection (ICRAF, 1995) by shaking for 1 hour at 150 revolutions min^{-1}. The solution was filtered using a pre-washed Whatman No.5 filter paper. Soil water content was determined gravimetrically from stored field moist soil at the time of extraction and used for expression of inorganic-N on dry weight basis. Nitrate plus NO_2^- were determined by Cd reduction (Dorich and Nelson, 1984) with subsequent colorimetric determination of NO_2^- (Hilsheimer and Harwig, 1976). NH_4^+ was determined by the salicylate hypochlorite colorimetric method (Anderson and Ingram, 1993). Soil bulk density was determined by the undisturbed core method (Anderson and Ingram, 1993) and used for conversion of NO_3^- and NH_4^+ values from milligrams per kilogram to kilograms per hectare. Results are presented as inorganic-N (NO_3^- and NH_4^+).

Soil loss assessment

Soil loss was assessed by use of plastic erosion pins (FAO, 1993) fixed at a spacing of 2 × 2 m on each plot. The measurements were taken to the nearest millimeter, to allow any seasonal change in soil level to be clearly recognized. The resulting soil loss measurements were converted to t ha^{-1} by first calculating the volume of top-soil washed per plot by use of an equation:

$$Vplot = (Average\ depth\ of\ washed\ soil) \times (Plot\ length) \times (Alley\ width) \quad (2)$$

The resulting volume was then multiplied by the bulk density to get the mass of soil lost, which was then converted to tons per hectare.

Maize yield assessment

Yield assessment was done on sub-plots of 5 × 5 m. Maize (*Zea mays* L.) was harvested by cutting at the root collar. It was weighed immediately to determine the total fresh weight (stover + unshelled cobs). The unshelled cobs were then separated from the stover. The total fresh weight of the stover was then determined and a sub-sample taken for dry weight determination. To obtain grain yields, grains were separated from the core by hand shelling, weighed, and a sub-sample taken for dry weight determination. Similarly, empty cobs (without grains) were weighed and a sub-sample taken for dry weight determination. To determine dry weight, the above sub-samples (cobs, stover and grain) were oven dried at 60°C for three days to a constant weight.

To determine the relationship between top-soil loss and maize crop growth, the control plots on fifteen of the farms where slope was between 10 and 20% were sampled. Control plots were used because it is on these plots where there was no treatment interference, while 10–20% slope was used because it was the most common slope in the study area and the soils on it were similar. These farms were sampled on the basis of farmer's adherence to proper and uniform agronomic aspects such as planting time, weeding, plant spacing/population 25 cm within row and 75 cm between rows) and planting the same seed variety (i.e., H513). H513 is one of the recommended and most widely used maize variety in the central highlands of Kenya. In addition to the yield parameters cited above, crop height was measured at maize tassling stage.

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Statistical analysis

We analyzed data by use of GenStat for windows software (version 6.1, Rothamsted Experimental Station) (GenStat, 2002). We used analysis of variance (ANOVA) to test the hypothesis that leguminous contour hedges enhance soil inorganic-N, reduce soil losses and enhance crop yields. Protected least significant difference (LSD) at $P = 0.05$ (Fisher, 1935) was used to separate the means. The hypothesis that soil erosion is directly linked to losses in maize production was tested by regressing soil loss against various maize crop growth parameters. The best fit models were fitted into the data based on the one that had the highest R^2 to describe the nature of relationships between soil loss and maize crop growth parameters.

Results

Rainfall characteristics

We recorded a total annual rainfall of 1032 mm split into 467 mm during the long rains and 565 during the short rains. This annual rainfall was 14% lower than the long-term average for this area (i.e., 1200 mm). Rainfall peaks coincided with the months of April and November while the lowest precipitation was recorded in the months of February, June and September (Figure 1). This monthly rainfall distribution is in agreement with the expected rainfall pattern for this area.

Soil inorganic-Nitrogen

Soil inorganic-N trend at the start of experiment was similar in all the treatments (Figure 2). There was a significantly higher concentration of inorganic-N at 30–90 and 90–150 cm depth relative to 0–30 cm depth during this sampling campaign ($P < 0.0001$).

During the second sampling, inorganic-N at the 0–30 cm depth was significantly higher in the Leucaena plots than the control and napier plots ($P < 0.05$) (Figure 3). During this sampling campaign, we observed significant reduction of inorganic-N accumulation at 30–90 and 90–150 cm depth in leguminous hedge plots relative to the control and napier ($P < 0.05$). Soil inorganic-N was also higher in the 0–30 cm depth in the sole *Leucaena* and *Calliandra* plots in comparison to the control and napier plots ($P < 0.05$).

Effects of hedges on soil erosion

Table 1 shows soil loss from plots with the different types of hedge during the first and second season, broken down by slope categories: 5–10, 10–20, 20–30 and >30%. The first season of soil loss estimation was done 12 months (short rains) after establishment of hedges while the second season was done 17 months (long rains) after hedge establishment. The first season on average, registered higher soil losses ($P = 0.004$) than the second season for treatments with hedges and vice versa for the control. Soil losses from plots on 5–10% slope had a narrow range (10–17 t ha yr^{-1}) for different treatments and seasons in comparison to other slopes and there were no significant differences between treatments ($P < 0.05$). During the first season there were significantly lower ($P < 0.001$) soil losses in plots with hedges relative to the control on slopes exceeding 10% but with the exception of napier, no significant differences among different types of hedges.

Consistent significant differences between hedges were observed during the second season on slopes exceeding 10% ($P < 0.05$). Napier hedges were the most effective at reducing erosion losses in both seasons (Table 1). We observed higher soil loss reduction in the combination hedge relative to individual tree hedges across the two seasons ($P = 0.012$). Soil loss on 10–20% slope category was higher than soil loss

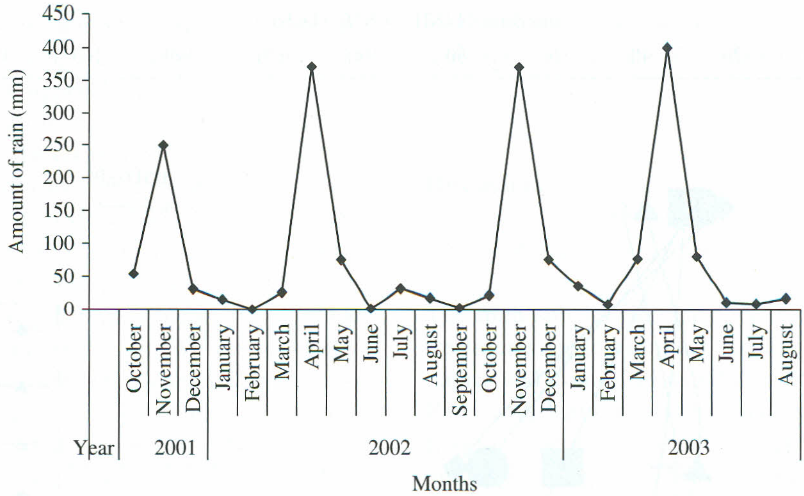


Figure 1. Rainfall pattern in Kirege Location during the study period.

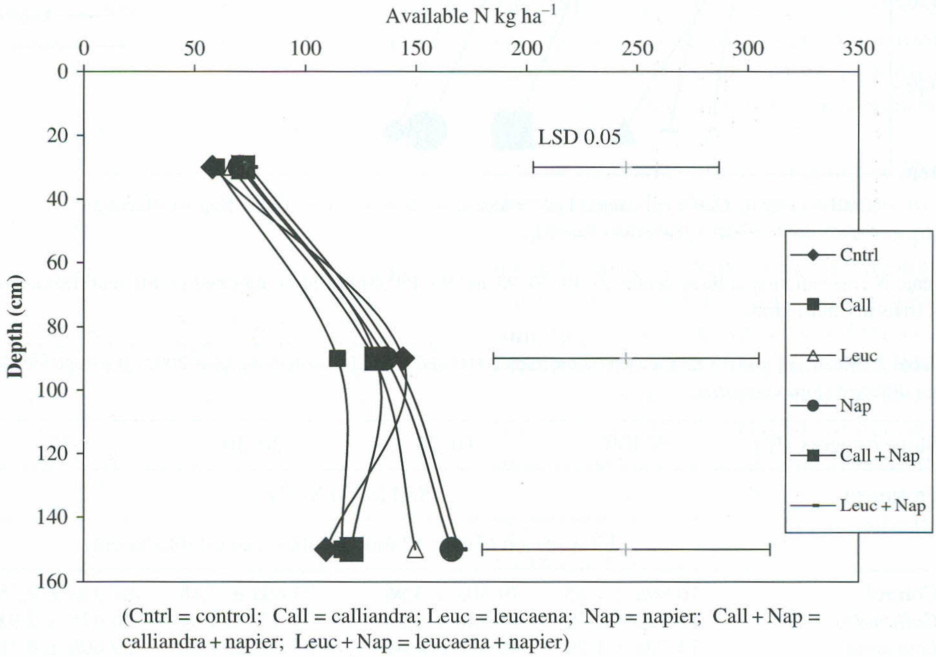
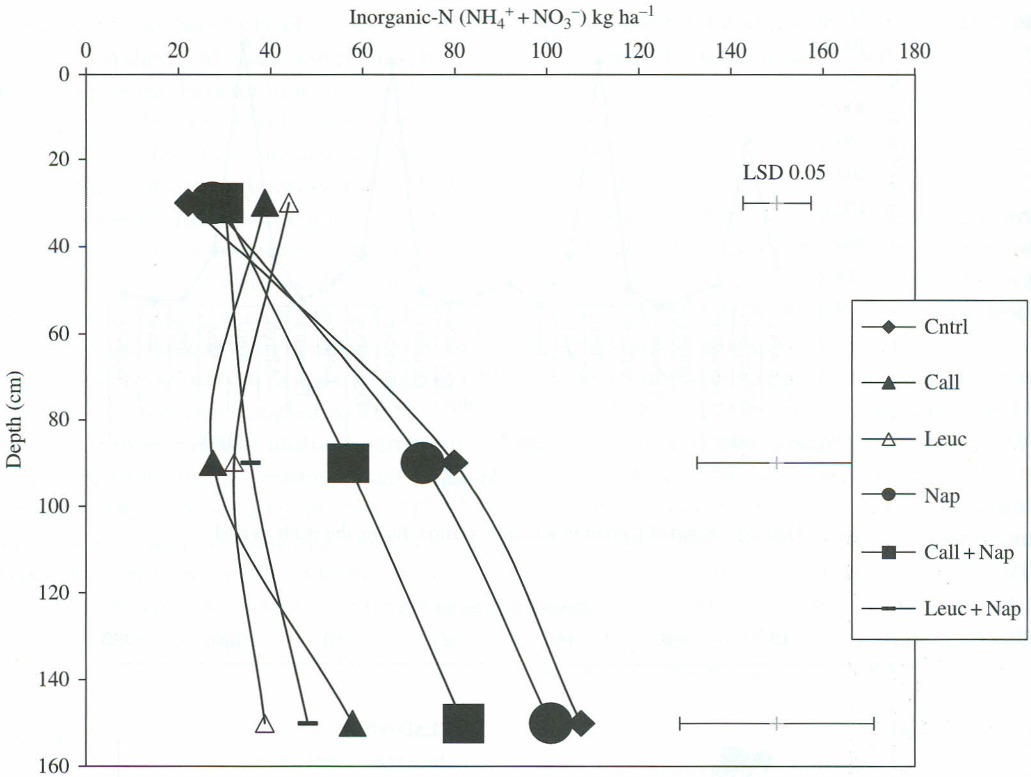


Figure 2. Inorganic-N concentration at three depths (0–30, 30–90 and 90–150 cm) of plots allocated to different treatments at the beginning of trials in September 2001 in Chuka farms.

on any other slope category (P = 0.043) although ordinarily we would have expected soil loss to increase with slope. In efforts to explain this unexpected phenomenon we analyzed the soil texture results on a per slope basis. We found significantly lower (P < 0.001) clay particles on the 10–20% slope relative to 20–30 and > 30% slope (Table 2).

Maize growth and yield

The presence of hedges had very little impact on maize crop yields during the first season (Table 3). Sole napier hedges suppressed yields during this season, but not during the second. The effects of the hedges were more apparent during the second season. A number



(Cntrl = control; Call = calliandra; Leuc = leucaena; Nap = napier; Call + Nap = calliandra + napier; Leuc + Nap = leucaena + napier)

Figure 3. Inorganic-N concentration at three depths (0–30, 30–90 and 90–150 cm) of plots allocated to different treatments 20 months after establishment of trials in Chuka farms.

Table 1. Mean soil loss for first season (short rains 2001) and second season (long rains 2002) at Kirege location for different slope categories

Slope category (%)	5–10%	10–20	20–30	>30
Treatment	Soil loss (t ha^{-1})			
	First season (Time: 12 months after trial establishment)			
Control	16.80a ± 1.85	79.50a ± 3.96	77.40a ± 7.46	67.53a ± 7.25
Calliandra	15.52a ± 2.51	37.53b ± 1.54	34.87b ± 1.91	26.47b ± 2.91
Leucaena	14.70a ± 1.90	46.63b ± 4.40	37.50b ± 1.49	29.60b ± 8.38
Napier	12.64a ± 1.84	20.87c ± 2.69	22.90c ± 1.89	20.62b ±2.76
Calliandra + Napier	13.57a ± 1.93	30.57b ± 2.49	26.50bc ± 2.10	26.58b ± 2.98
Leucaena + Napier	14.17a ± 0.94	35.18b ± 4.76	33.73b ± 1.79	21.78b ± 1.87
	Second season (Time: 17 months after trial establishment)			
Control	16.48a ± 1.67	79.61a ± 8.41	79.25a ± 7.63	78.90a ± 5.85
Calliandra	11.00a ± 1.52	26.14b ± 3.82	28.92b ± 3.15	22.18b ± 2.68
Leucaena	12.31a± 1.64	29.68b ± 6.22	28.62b ± 3.58	23.50b ± 4.56
Napier	10.10a ± 2.13	10.21c ± 0.25	11.90c ± 0.44	9.67c ± 0.62
Calliandra +Napier	12.83a ± 1.98	17.70bc ± 1.85	14.15c ± 1.40	11.55c ± 0.931
Leucaena + Napier	10.66a ± 1.31	17.67bc ± 1.46	13.38c ± 0.34	12.98c ± 0.44

For each slope category and season, means within a column followed by different letters indicate significant difference based on Fisher's protected LSD test (P = 0.05). Values are means ± SE.

of treatments resulted in significant increases in yields, particularly when N-fixing trees were part of the system. Maize yield was higher during the second season than first season for all the treatments with vegetative hedges, but lower on the control.

The influence of soil loss on crop growth for each season was not consistent ($P < 0.05$). Cumulative soil losses on the 10–20% slope were 4 to >20 fold higher than the established tolerable soil loss limit of 10 t $ha^{-1}yr^{-1}$, implying that this was a highly fragile slope category in this region (Table 4). We observed significantly lower grain yield when cumulative soil loss exceeded 150 t $ha^{-1}yr^{-1}$ ($P = 0.01$) and significantly lower plant height and stover weight when cumulative soil loss exceeded 150 t $ha^{-1}yr^{-1}$ ($P<0.0001$) (Table 4). Total aboveground biomass was significantly affected by any soil loss above 100 t $ha^{-1}yr^{-1}$ ($P<0.0001$).

The relationship between cumulative soil loss and maize grain weight, stover weight, plant height, and total above ground biomass was negative, linear and highly significant ($P < 0.0001$) (Figure 4).

Table 2. Characteristics of soil texture at different slope categories in Kirege

Slope category (%)	Particle size (g kg^{-1})		
	Sand	Silt	Clay
5–10	318.6a ± 8.8	284.9ab ± 9.2	396.5a ± 1.5
10–20	304.3a ± 5.3	310.1a ± 7.8	385.6a ± 8.1
20–30	299.6a ± 9.5	279.8b ± 9.7	420.5b ± 3.7
>30	299.5a ± 7.3	300.5ab ± 11.3	411.0b ± 5.2

For each column, means followed by different letters indicate significant difference based on Fisher's protected LSD test (P = 0.05). Values are means ± SE.

Table 3. Maize yield at Kirege farms in plots served by various vegetative hedges during first and second season of the trial (2002 and 2003 respectively)

	First season	Second season	Treatment mean
Treatment	Maize grain (t ha^{-1})		
Control	2.2a ± 0.5	2.0b ± 0.3	2.1b
Calliandra	1.9a ± 0.4	2.9a ± 0.4	2.4ab
Leucaena	2.1a ± 0.6	3.1a ± 0.5	2.6ab
Napier	0.9b ± 0.1	2.1b± 0.4	1.6b
Calliandra + Napier	2.2a ± 0.7	3.4a ± 0.8	2.8a
Leucaena + Napier	2.3a ± 0.8	3.6a ± 0.6	2.9a

For each column, means followed by different letters indicate significant difference based on Fisher's protected LSD test (P = 0.05). Values are mean yield ± SE.

Discussions

Effects of treatments on soil inorganic-N

The high sub-soil inorganic-N in napier and control treatments suggest a higher leaching of mineral-N from napier and control plots relative to other treatments. Plots with leguminous trees had a higher concentration of mineral-N at 0–30 cm depth than the control and napier probably as a result of interaction between their N fixing ability and deep nutrient capture (Van Noordwijk, 1989; Van Noordwijk et al., 1996). *Calliandra* and *Leucaena* roots deeper than napier (NAS, 1983; Mugendi et al., 2003) and therefore capture nutrients far beyond the reach of napier roots which are then transferred to the surface in form of leaf litter and prunings from their leaves and branches (Scroth G. 1994).

Low inorganic-N concentration at 20 months relative to initial levels can be attributed to weather and sampling time differences. The first sampling was done towards the end of September after a long dry spell and during land preparation for planting, while the second sampling (time 20 months) was done in July after the March to May rains (long rains) and July drizzles and at maize tussling stage. So probably alot of nitrate had been immobilized, leached, denitrified or even taken up by the growing crop at the time of sampling. Maize has the highest demand for N at the tussling stage (Karlen et al., 1988), so nitrogen would be locked in maize plant tissues at this time.

Effects of hedges on soil conservation and maize crop performance

Lower soil losses during the second season on the contour hedge plots in comparison to the first season can be attributed to hedge species differences in stage of growth over the two seasons, and natural terrace formation. During the second season, hedges were more mature and therefore formed a more intact barrier to sufficiently obstruct runoff and enhance deposition of the sediment load carried down slope by the runoff. Natural terraces form along contour hedges, advance

Table 4. Relationship between various soil erosion classes with selected maize growth parameters in Kirege location

Soil loss ($t\ ha^{-1}yr^{-1}$	Grain weight ($t\ ha^{-1}$)	Plant height (cm)	Stover weight ($t\ ha^{-1}$)	*TAGB ($t\ ha^{-1}$)
40–100	1.9a ± 0.2	247.3a ± 5.0	7.0a ± 0.2	10.2a ± 0.5
100–150	1.5a ± 0.2	259.0a ± 8.5	7.3a ± 0.2	4.1b ± 0.3
150–200	1.5a ± 0.2	226.2b ± 8.6	5.6b ± 0.5	3.2bc ± 0.1
>200	0.9b ± 0.3	190.1c ± 2.8	3.3c ± 0.2	1.6c ± 0.1

For each column, means followed by different letters indicate significant difference based on Fisher's protected LSD test (P = 0.05). *TAGB – total above ground biomass. Values are means ± SE.

and become more effective in obstruction of soil movement with time due to entrapment of washed off soil on the up-slope side of the hedge (Lal, 1989).

Napier hedge was overall the best vegetative hedge in soil conservation possibly due to its rhizomatous rooting characteristics. These rhizomatous roots spread out superficially over a large area reinforcing soil around them and bringing about an increase in cohesion and hence in shear strength (Dissemeyer and Foster, 1985). It also sprouts many tillers within a short time, forming an intact hedge. Lower soil loss values on combination hedge plots as compared to single tree species hedge could partially be attributed to presence of napier component and the positive interaction between napier and leguminous tree species which recycle and fix N (Young, 1997). This corroborates with the findings by National Research Council (1983) and Goudreddy (1995) that *Calliandra* and *Leucaena* improve soil fertility and hence enhance growth of associated crops, which in this case was napier.

The lower soil loss in the 20–30 and > 30% slope categories relative to 10–20% slope was most likely a result of higher clay concentration in the 20–30%, and >30% slope in comparison to the 10–20% slope. High clay content in the soil leads to surface sealing resulting in low soil particle detachment (Morgan and Rickson, 1995). High percentage of silt and fine sand decreases the raindrop energy required to break down soil clods increasing the susceptibility of soil particles to detachment and hence erosion (Morgan, 1986). This means that on steeper slopes, the ability of soil to resist detachment by runoff flow energy was probably higher than on the 10–20% slope category. Our estimate of lower soil loss on steeper slopes of up to 40% in the Central highlands of Kenya is consistent with observations by Angima (1996) and Angima et al. (2001) who reported higher soil loss on 20% slope in comparison to 40% slope.

The negative regression relationships between soil loss and maize crop growth can be attributed to loss of top-soil, which is the most favorable soil for crop growth. The loss of top-soil inevitably reduces soil productivity, which in turn deters crop growth because the top-soil is usually the most fertile, containing natural plant nutrients, humus and any fertilizers that farmers have applied (Lal, 1989). The fact that soil loss negatively affects crop growth parameters and contour hedges reduce soil loss implies that contour hedges can enhance crop production on sloping landscapes. This is consistent with observations of yields and other crop growth parameters decline as a function of soil erosion by (Gachene et al., 1998; Pesant and Vigneux, 1992; Andraski and Lowry, 1992).

Conclusion

This study showed that generally majority of farms in central highlands of Kenya lose more than the established tolerable amount of soil (10 $t\ ha^{-1}yr^{-1}$). We demonstrated a substantial reduction in crop yield as a function of soil loss and ability of leguminous contour hedges to simultaneously control soil erosion, enhance soil inorganic-N and improve crop yields. Although soil loss was negatively correlated to crop growth, the high efficiency of napier in soil conservation did not translate into high crop yields. We can therefore conclude that the higher maize yield observed in leguminous tree hedge plots was a result of interaction between soil fertility improvement by incorporated leguminous biomass and management of both

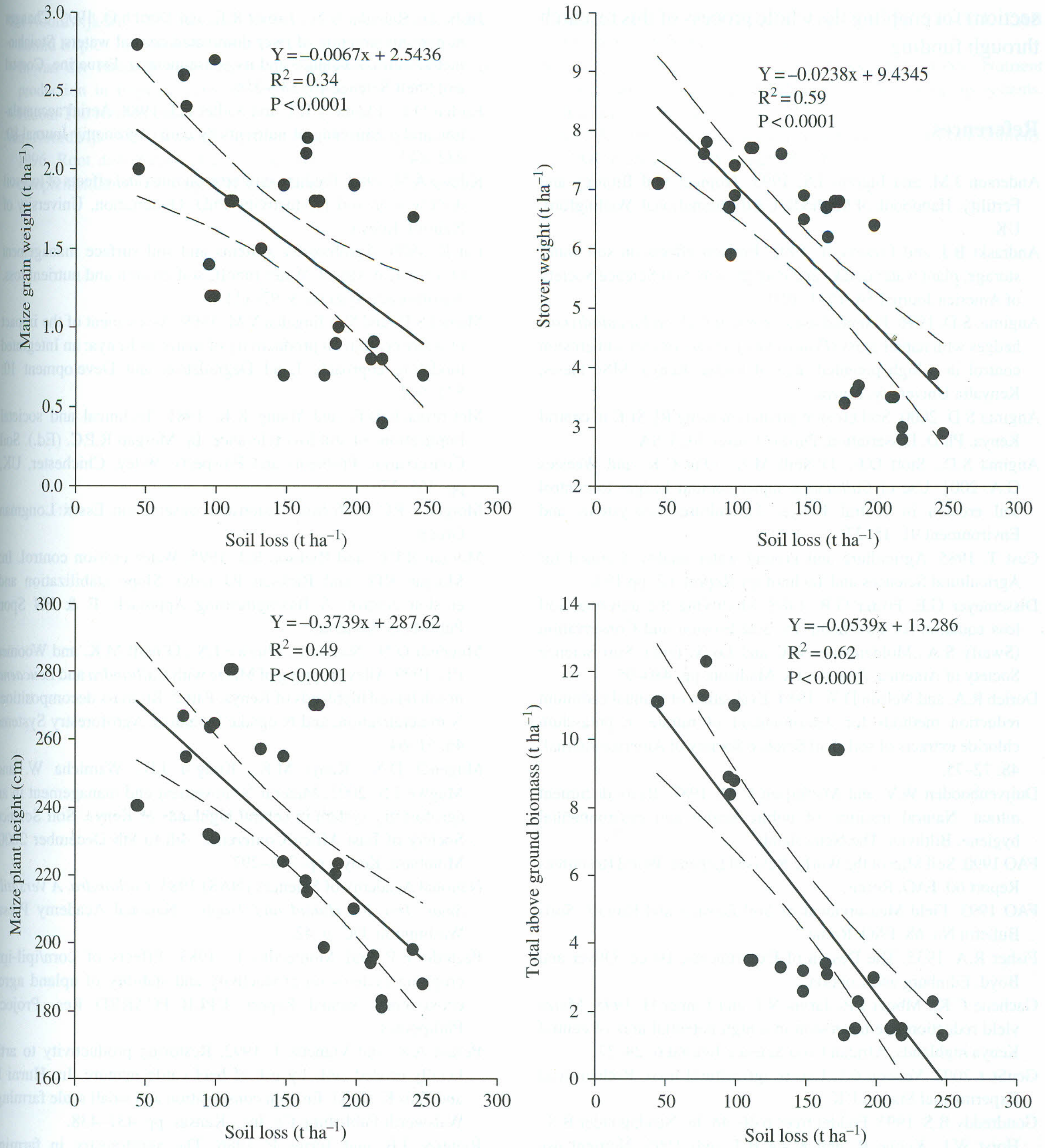


Figure 4. Relationship between cumulative soil loss and various maize crop growth parameters. Dotted lines represent the 95% confidence interval for regression.

added and existing soil nutrients through soil conservation by these hedges. Adoption of these technologies by small scale resource poor steep-land farmers would therefore save them the cost of purchasing expensive inorganic fertilizers and improve crop yields while maintaining land quality and checking pollution of water bodies by eroded sediments and nutrients.

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