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Contour Hedgerows of *Calliandra calothyrsus* Meissn. for Soil and Water Conservation in the Blue Mountains of Jamaica

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ABSTRACT

As pressure on land and forest resources increases, there is a growing need to assess and improve the sustainability of slash-and-burn agriculture in tropical uplands. On steep hillslopes (24-32º) in the forest buffer-zone of the Blue Mountains of Jamaica, following clearance of secondary forest the relative impact on surface runoff, soil erosion and soil properties of three land-use treatments: maintained weed-free without cultivation (bare); cultivated with herbaceous crops (agriculture); and cultivated with herbaceous crops and intercropped with *Calliandra calothyrsus* contour hedges (agroforestry) was assessed over a five year period and compared with an uncleared secondary forest control (forest). The forest provided good protection against surface runoff, which was consistently less than 0.2% of rainfall, and soil erosion losses, which were less than 500 kg ha^{-1} yr^{-1}. Agriculture caused a seven-fold increase in surface runoff and 21-fold increase in soil erosion. However, agroforestry was effective in conserving water, with a 45% reduction in runoff compared with agriculture, and soil, with erosion reduced by 35%. Agricultural productivity was also higher in the plots with contour hedgerows, maize grain weights were up to 45% and 63% higher per plant respectively. Despite the loss in land available for crops, yield per area was not significantly reduced by the introduction of hedgerows. The nutrient losses from the conventionally farmed plots indicated low sustainability with a significant reduction in nitrogen, phosphorus, organic matter, and base cation soil content. The results indicate that this low-input, contour-tree-hedgerow technology is effective at soil and water conservation and has the potential to enhance the sustainability of this land-use system at a plot scale.

INTRODUCTION

The Blue Mountains of Jamaica are a geologically recent tropical mountain range, characterized topographically by steep slopes (generally greater than 25°) and highly dissected terrain, with sharp ridges and deep gullies; the soils are generally poorly-developed Cambisols. The natural vegetation is montane tropical rain forest (Shreve, 1914). On slopes up to about 1600 m the forests have been subject to conversion for over 200 years; recently this has been for two major land uses: cash crop and subsistence cultivation of vegetables by small farmers and the establishment of commercial coffee plantations (Eyre, 1987). Typically, the former involves slash-and-burn clearance of the forest, and the farmers shift to a new area of land when levels of crop production fall (Barker and McGregor, 1988). The farming community in this area represents a marginalized population, suffering considerable constraints of finance and labor. After land is abandoned from agriculture, secondary forest regrows where the incidence of uncontrolled fires is sufficiently low to permit this. The importance of the remaining forests in the Blue Mountains as an ecological resource, from the point of view of their influence on water and soil conservation as well as being a unique ecosystem containing a large number of endemic species, has been acknowledged (e.g. Tanner, 1986), and this area has been incorporated into a new National Park of over 77,000 hectares. A major management objective is to reduce the rate of forest conversion and degradation by farmers, through improvement in the sustainability of the current forms of agriculture in the park's buffer zone. To this end it is important to assess the extent to which the current slash-and-burn practice in the Blue Mountains does lead to a decline in soil fertility, and the extent to which this decline can be prevented by alternative land-use practices.

The vast majority of studies into the impacts of slash-and-burn agriculture on soil properties have taken place in lowlands, and on sites that are flat, or gently sloping. However, as is the case in Jamaica, in many other countries an important agricultural frontier occurs in mountain areas where the resulting conversion and degradation of natural forest may threaten its important biodiversity and environmental protection functions. There is a lack of good evidence about the changes in soil properties caused by slash-and-burn agriculture in these very different, steep-hillslope mountain ecosystems where soils are often young, with higher inherent fertility, but potential rates of soil erosion are much higher. The impact of such land-use changes on hydrology and soil erosion is complex. Replacement of a tropical rain forest canopy with an agricultural crop has been shown to increase annual catchment water yields by 110-825 mm in the first year after clearance (Bruijnzeel, 1990). Reported increases in soil erosion are highly variable, with a range from 1- to 100-fold (UNESCO, 1978); in his review Wiersum (1984) found a median increase of 10-fold.

On steep hillslopes most attention has focused on the use of contour hedgerows (Young, 1997) and there is an

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increasing body of knowledge about their effects on soil erosion and soil properties. Young (1997) reviewed 14 studies, which showed a range of 1- to 58-fold decrease in soil erosion rate compared with agricultural controls, and the results of subsequent studies have remained within this wide range (e.g. Alegre and Rao (1996)). However, only two of these have examined slopes as steep as those encountered in the present study ($\geq 24^{o}$), and they only showed a 1-2 fold decrease in erosion rate (Young, 1997). There is a great lack of studies on the impact of contour hedgerow intercropping on soil properties on such steep slopes. On shallower slopes the recent work of Garrity (1996) and Agus *et al*. (1997, 1999) has focused on the redistribution of soil fertility from the upper to the lower sections of the cultivated land between contour hedgerows.

The principal objective of this study was to investigate the consequences of forest clearance by shifting cultivators on consequent soil fertility. The use of a potential agroforestry system - contour hedgerows - for soil conservation was also investigated as a means to provide a stable and sustainable agricultural production system for sloping lands in the tropics.

METHODS

The study area was located on the south-west slopes of the main ridge of the Blue Mountains in the catchment of the Green River, a tributary of the Yallahs River at an altitude of around 1300 m and in the vicinity of Cinchona, Westphalia, St Andrew, Jamaica, at latitude 18°N and longitude 76°W. The Yallahs is the largest river on the more populous southern slopes of the Blue Mountains and its basin as a whole has a high natural propensity for erosion: 85% of the land area of the Upper Yallahs Valley has slope angles greater than 25°, and cultivation on slopes of up to 45° has been recorded (McGregor *et al.*, 1985). The underlying geology is complex, both the 'Blue Mountain Volcanics' that include granodiorite, and 'Blue Mountain Shales', which consist of mudstones, sandstones and conglomerates, are present. Soils of the area are reported as eutric and chromic Cambisols (FAO-UNESCO, 1975), and these soils were confirmed as present in the experimental area by the authors. Mineralogical examination revealed the presence of minerals that could be derived from mafic material (epidotes, chlorites and amphiboles), as well as from shale (quartz and hydrous mica) (D.A. Jenkins, personal communication). However, the soil included a mixture of these minerals associated with unweathered sources and those from highly weathered sources (e.g. magnetite and ilmenite). Soil depth varied depending upon the proximity of bedrock or presence of accumulations of colluvium, and soils were very stony. Average content of stones (> 2 mm) in the upper 10 cm was around 70% by weight, often with a substantial quantity of boulders. Soil texture was variable, ranging from sandy loam and silt loam to clay loam, but the soil was freely drained in all situations. Profiles under forest were marked by dark, humose A horizons, but after cultivation the topsoils apparently lose organic matter (OM) and display a noticeable reddish-brown hue.

Mean annual rainfall at the nearby Cinchona meteorological station (1525 m above sea level) over a 70-year period was 2180 mm, ranging from 905 mm in 1983 to 4464 mm in 1963 (Jamaica Meteorological Service, unpublished data). The distribution of the rainfall tends to be bimodal: in most years the major wet period occurs in October and November (November mean monthly total was 405 mm) and a minor wet period in May (mean monthly total was 196 mm); March and July have the lowest mean monthly rainfalls (89 mm and 77 mm respectively). The area is subject to periodic hurricanes (most recently Hurricane Gilbert in 1988) contributing to high variability in rainfall amongst years. Over 90 years eight individual months had a recorded rainfall greater than 1000 mm (the highest being 2416 mm). Over 39 years the range in monthly mean temperatures at Cinchona was 14.6 - 17.6 °C (with an absolute minimum of 9.6 °C and maximum of 24.4 °C) (Shreve, 1914).

Experimental plots were established in: 1. Secondary forest ('forest'); 2. Forest cleared, burned and subsequently maintained weed-free ('bare'); 3. Forest cleared, burned and planted with agricultural crops ('agriculture'); and 4. Forest cleared, burned and planted with agricultural crops intercropped with *Calliandra calothyrsus* hedgerows - a ubiquitous, locally popular species ('agroforestry').

C. calothyrsus, a leguminous tree species native to Central America and Mexico with a low-branching habit, was selected for the agroforestry hedgerows because it has been found to be a suitable species for this purpose elsewhere in the tropics (e.g. National Academy of Sciences, 1980; Palmer *et al.*, 1994; Evans, 1996) and was already present in the study area. Although it was only recently introduced to the Blue Mountains of Jamaica, following its introduction in a species trial in the 1980s (D. Thompson, *pers. comm.*), the local farming community already recognizes its value for erosion control in their agricultural systems (as well as for a range of other uses) (Collins and McDonald, 1997).

Four blocks each consisting of four plots were established in areas of secondary forest, that had originally been cleared for cultivation of coffee, cinchona or other agricultural crops at various times up to the early 1970's and then abandoned by the early 1980's. The position, layout and management of each block were designed to minimize within-block variation. Each treatment was assigned randomly to one plot in each block giving a randomized complete block design. The experiment was "on-farm", and although researcher designed, each block was managed by a different individual farmer, who had control over the farming practices adopted in their agriculture and agroforestry treatment plots (e.g. the crops grown, and the timing of individual farming operations), leading to small between-block variation in farming practice.

The slope angle of the plots ranged from 24 to 32^{o} but within-block variation was only 2° on average: all the plots were in a mid-slope position between 1253 m and 1315 m altitude and none of them occupied or included obvious convex zones of higher than average net erosion, or deposition zones of net sedimentation. Each plot was 10 m (across slope) x 20 m (down slope), with an inner assessment area of 8 m x 15 m. The plots were bounded on the upper border with galvanized steel barriers, and trenched on the lateral borders to prevent erosion of sediment into the plots. This is at variance with farmers' practice, which would receive deposition from up-slope of a plot, but the plot boundaries were installed so that the collected sediment was eroded from a known land area, enabling the rate to be compared with other published studies.

In the plots of the three cleared treatments the secondary forest vegetation was cut with the tree trunks removed and other material (branches, foliage, shrubs, herbs etc.) retained *in-situ*, in accordance with local practice, in July 1992. The retained material was subsequently left to dry until August 1992 and then burned. The plots were left for up to three weeks to 'sterilize the soil' (a local practice) and crops and trees planted in September 1992. Various mixtures of escallion (*Allium ascalonicum* L.), thyme (*Thymus vulgaris* L.), carrot (*Daucus carota* L.), potato (*Solanum tuberosum* L.), beetroot (*Beta vulgaris* L. subsp. *vulgaris*), cabbage (*Brassica oleracea* L.), sweet pepper (*Capsicum annuum* L. var. *annuum*) and cucumber (*Cucumis sativus* L.) were planted in the plots of the two agricultural treatments. The farmers followed their usual practice in crop management, including weeding. In addition, farmers kept their bare treatment plot weed-free by manual clearance with a cutlass (so that there was no up-rooting and consequent soil disturbance) on a fortnightly basis.

The trees were grown from seed collected during February and March 1992 from the population of *C. calothyrsus* naturalized in and around Cinchona Botanic Garden. The seeds were sown in March 1992 in seed trays, transplanted to pots after germination, and kept in a shade house at Cinchona until outplanting when the seedlings were about 15 cm high. Three contour hedgerows were established per plot. The hedgerows were 5 m apart and each comprised a triple row of trees at 1-m intra-row spacing and 0.5-m inter-row spacing. The tree planting positions in the rows were arranged in a staggered manner down slope to maximize the barrier effect. An A-frame was used to lay out the contour lines.

The hedgerows were cut back to a height of about 30 cm on a regular basis at approximately five-monthly intervals and were never allowed to grow more than about 1 m tall, at which point they started to shade the crops. Initially, during 1993 and 1994, the prunings were laid along the upper side of the hedgerows to help build up the barrier effect, but subsequently (from 1995) they were chopped up and used as mulch on the farmed area between the hedges. The biomass and N and P concentrations of the prunings were recorded at each cut.

Three Gerlach troughs (simple metal gutters 1m long, closed at the sides, fitted with a removable lid, and with an outlet pipe running from the base of the gutter into a covered collecting vessel) were installed at the lower edge of each inner plot (following Morgan, 1986) during June – July 1992 before forest clearance. Sediment and runoff were channeled from the gutter into covered collecting buckets (three buckets per trough with overflow pipes delivering 1/6 of the volume to the second and third buckets respectively). At each sampling occasion all sediment was collected from the trough, and suspended sediment estimated by filtering a 1-l sample of runoff; runoff water quantity was measured; and water samples collected. Sampling was carried out after every rainfall event of > 25 mm, since rain events with less precipitation were observed not to cause runoff. Each entire eroded-sediment sample was separated into litter, coarse (> 2 mm) and fine (< 2 mm) mineral fractions and the dry mass of each fraction recorded. A bulked sample of the sediments collected from each plot over each year was compiled and the < 2 mm fraction analyzed for total N and P a sulphuric acid/hydrogen peroxide digestion (Allen, 1989); and for exchangeable K an ammonium acetate extraction at pH 7 (Anderson and Ingram, 1993) shaking the soil/extractant for one hour on an orbital shaker. Concentrations were then measured: for nitrate-N using a Dionex automated ion chromatograph, for ammonium-N using an automated colorimetric system with indophenol blue; for P using an automated colorimetric system with molybdenum blue; and for Na, K, Ca and Mg using atomic absorption spectrophotometry.

Three soil cores were collected from each plot, prior to clearance in June, 1992, and analyzed for bulk density, N, P and exchangeable K as above to determine the total nutrient capital stock in the 0-10 cm depth soil profile. The soil sampling and analyses were repeated annually commencing October 1993. Particle size analyses, pH, and nutrients losses in runoff water and particulate organic matter were also recorded and are reported in McDonald *et al*., 2002.

In-situ incubations (30 day) were conducted in the plots in October from 1994-1997 to assess rates of total nitrogen mineralization and nitrification.

In 1996, line planting of *Zea mays* was conducted to evaluate any effect of the hedgerows on crop productivity. The plants were established at 50cm spacing, both between plants and between rows. Lines were established at the same spacing in the agriculture plot. At harvest, measurements were taken of plant height, aboveground biomass, cob length, cob weight and percentage cob grain fill.

RESULTS AND DISCUSSION

The forest plots showed little fluctuation in their low runoff levels throughout the course of the study and these were significantly lower than in the cleared treatment plots (Figure 1). Compared with the forest treatment, runoff levels were increased by 360% in the agroforestry treatment, 460% in bare and 740% in agriculture. Total annual amounts of runoff since forest clearance remained high (10-33 mm) in the agriculture and bare treatments throughout. However, in the agroforestry treatment they declined from 21.7 mm in the second year to levels (7.4 mm down to 4.4 mm) that were closer in absolute terms to the forest than the agriculture treatment (Figure 1). Mean runoff levels were significantly lower from agroforestry than agriculture.

The difference in erosion rates amongst the treatments was broadly consistent with the observed trends in runoff. Sediment yield was significantly greater in the three cleared treatments than the forest (Figure 2). Compared with the forest treatment, the yield of total sediment was increased by 13.4-fold in the agroforestry treatment, 13.6-fold in bare and 21-fold in agriculture. Agroforestry caused significantly lower levels of erosion than agriculture. Year to year variation in annual total runoff in the forest treatment was

Table 1. Nutrient losses (kg ha^{-1}) in sediments eroded from the experimental plots expressed as a proportion of the total nutrient capital stock in 0-10 cm depth soil profile (kg ha^{-1}).

	Bare	**Forest**	**Agriculture**	**Agroforestry**
		Year 1		
Soil loss (kg ha-1)	5,476	608	19,069	13,279
Soil loss (mm)	0.7	0.1	2.5	1.6
P				
Stock	1,012	1,403	1,100	995
Loss	1.7	0.0	6.9	3.6
% of capital	1.5	0.0	8.2	3.7
N				
Stock	4,298	5,924	4,811	4,380
Loss	10.3	0.3	28.7	18.5
% of capital	1.9	0.1	8.0	3.7
K				
Stock	216	208	168	170
Loss	0.7	0.0	2.5	1.4
% of capital	3.0	0.1	18.0	7.2
		Year 2		
Soil loss (kg ha-1)	7,506	474	13,317	10,869
Soil loss (mm)	0.8	0.1	1.4	1.1
P				
Stock	1,351	970	1,155	1,072
Loss	1.9	0.0	3.6	3.3
% of capital	1.9	0.0	3.3	3.3
N				
Stock	5,037	4,905	3,693	4,223
Loss	9.3	0.1	14.4	13.3
% of capital	2.2	0.0	3.0	3.0
K				
Stock	181	249	136	151
Loss	0.5	0.0	0.7	0.8
% of capital	2.2	0.1	4.2	4.5
		Year 3		
Soil loss (kg ha-1)	11,950	576	9,531	6,249
Soil loss (mm)	1.0	0.1	0.9	0.6
P				
Stock	1,221	819	1,130	1,102
Loss	2.1	0.0	2.4	1.6
% of capital	1.5	0.0	2.1	1.5
N				
Stock	4,287	4,398	3,998	3,560
Loss	7.7	0.1	7.8	6.9
% of capital	1.5	0.0	2.1	1.6
K				
Stock	137	236	115	123
Loss	0.4	0.0	0.4	0.5
% of capital	2.3	0.0	2.6	3.0

clearly correlated with variation in annual total rainfall (Figure 1). However, measurements of erosion were much lower than previously published estimates (e.g. McGregor, 1988)). This pattern was mirrored in the rates of loss of mineral nutrients (Table 1). Even after the first year post-clearance, the nutrient capital continued to be depleted, though at a decreasing rate. The losses, as a proportion of the total capital, did decrease markedly year after year in the agriculture and agroforestry plots, but not in the bare plots. However, any consideration of changes in nutrient stocks has to be treated with caution. In the cleared treatments calculated stocks were greatly influenced by the large measured increases in bulk density as well as the changes in nutrient concentration. Furthermore, it is likely that redistribution of soil by erosion had also significantly influenced what material lay within the top 10 cm of soil at each sampling occasion. In the agroforestry plots, these losses should have been more than offset by the productivity of the hedgerows (Table 2). However, although there was an increase in the rate of nitrogen mineralization below the hedgerows (Figure 3), there was net immobilization in the farmed areas between the hedges. This was probably as a result of the prunings being scattered on the soil surface.

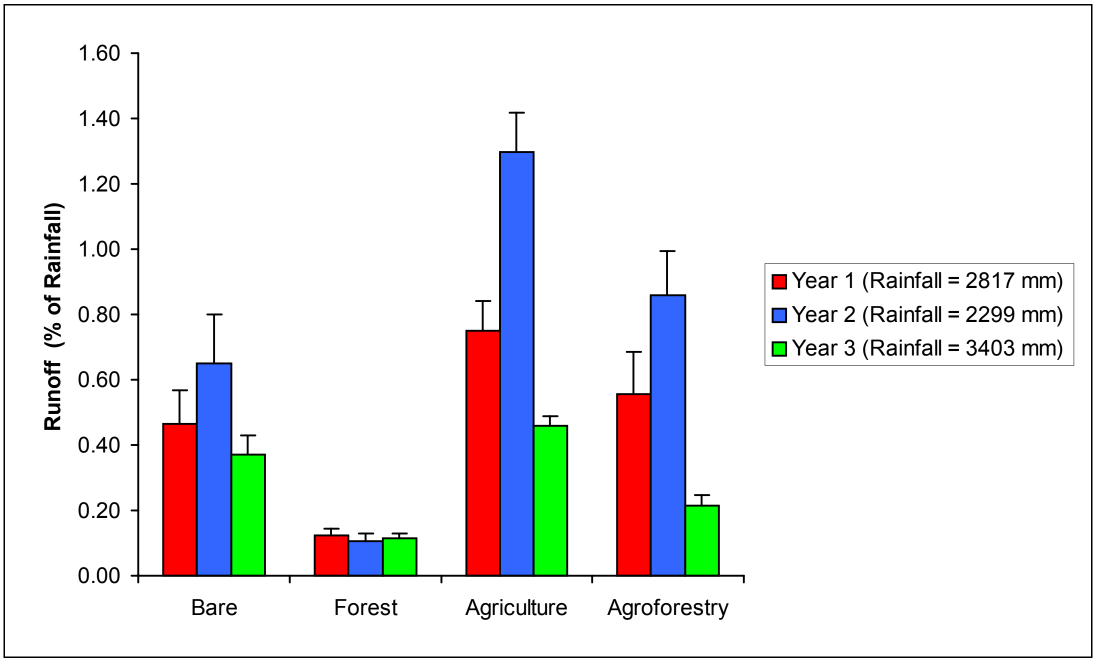

Figure 1. Runoff from the experimental plots, expressed as a proportion of annual rainfall (means and standard errors).

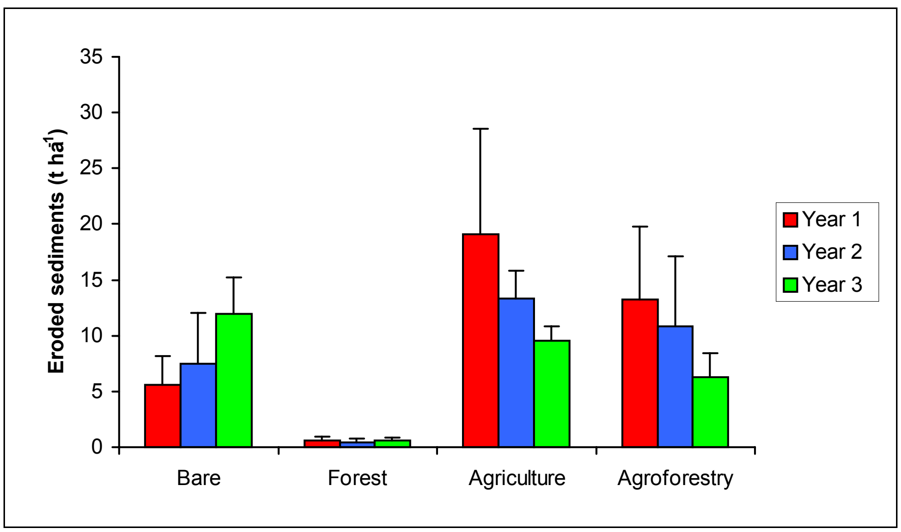

Figure 2. Sediments eroded from the experimental plots (means and standard errors).

Table 2. Productivity of *Calliandra calothyrsus* hedgerows (means and standard errors).

Total foliage biomass produced (g dry weight tree $^{-1}$)	648.09 (126.49)
Total foliage biomass produced (kg ha^{-1})	2916.40 (569.19)
Nitrogen content of foliage (%)	4.20 (0.08)
Phosphorus content of foliage (%)	0.24 (0.03)
Total foliar nitrogen production (kg ha^{-1})	122.49 (23.91)
Total foliar phosphorus production (kg ha^{-1})	7.00 (1.37)

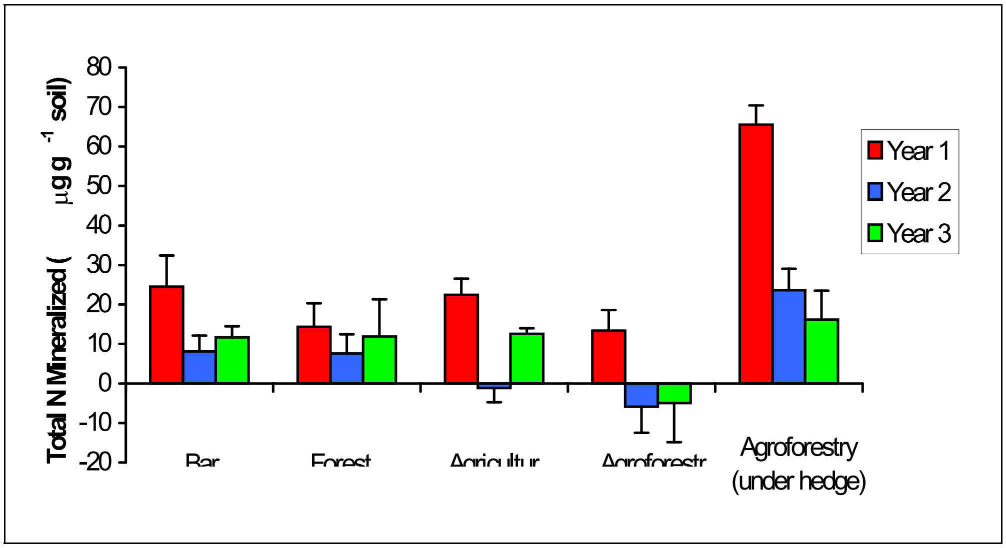

Figure 3. Total amounts of nitrogen mineralized in the experimental plots ((30 day *in-situ* incubation) (means and standard errors)).

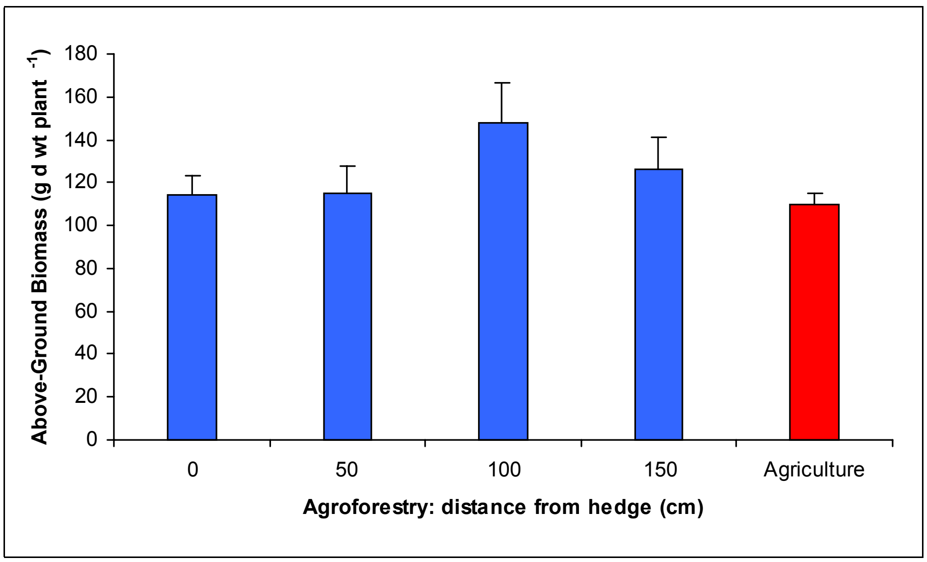

Figure 4. Aboveground biomass produced by *Zea mays* grown in the agroforestry and agriculture plots (means and standard errors).

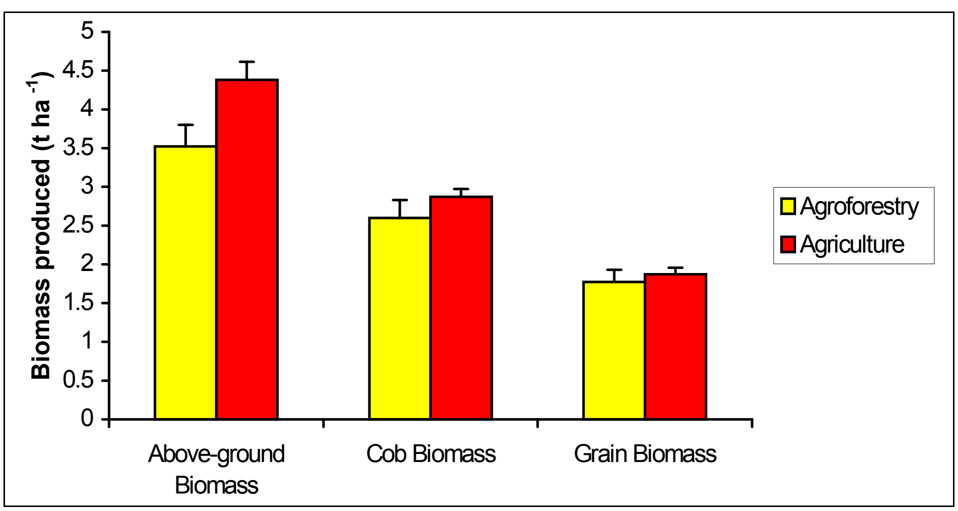

Figure 5. Productivity of Zea mays grown in the agroforestry and agriculture plots (means and standard errors).

The effect was more marked in later years as a greater proportion of the prunings were returned to the soil, rather than being stacked behind the hedgerow to maximize the barrier effect. Nevertheless, there was a slight productivity increase in the yield of *Zea mays* in the agroforestry plots compared with the agriculture plots (Figure 4). There was no difference in yield per hectare between the agriculture and agroforestry plots (Figure 5), as, obviously, there were fewer crop plants as a result of the hedgerow presence.

CONCLUSIONS

Considerable protection is offered to both the soil and water resource by secondary forest. In particular, the forest acts as a buffer against fluctuations in runoff associated with rainfall events, which may be of significance in large-scale events. Agricultural use of cleared land does result in increased erosion, but not as much as anticipated from previous estimates, and the use of contour hedgerows reduces runoff and levels of erosion to below those under conventional agriculture.

This study has demonstrated the major effects of forest conversion on soil properties and has found no clear evidence that they stabilize at a new equilibrium during the subsequent five-year period. For all the measured soil variables (except perhaps exchangeable K) there is not even any evidence that their rate of change has decreased over this period. Therefore, in general, a greater proportion of the current nutrient capital is being lost with progressive years after clearance. Following slash-and-burn the changes in the vast majority of the measured soil properties are attributable to the effects of forest removal and not to differences amongst the alternative forms of subsequent non-forest land use that were tested. The observed lack of differences between the soils of the bare and agricultural treatments indicates that nutrient losses due to a combination of erosion, surface runoff and especially leaching are a more important factor in these changes to soil properties than losses in crop offtake. The study has found no evidence that addition of prunings from agroforestry hedges as a mulch can compensate for these changes.

Numerous previous studies have examined the relative roles of leaching, runoff, erosion and crop offtake in nutrient losses in contrasting agroecosystems (e.g. Nye and Greenland, 1960, 1964; Juo and Manu, 1996; Arya *et al*., 1999). Results are variable depending on slope angle, soil permeability, and rainfall regime (Juo and Manu, 1996). In the cleared treatments annual losses of nutrients that were attributable to surface runoff and erosion were low. While slope angles were high, so was permeability, as reflected by the runoff results, indicating the potentially important role of leaching. The marked absence of any differences in cation concentrations between the bare and cultivated treatments in our study indicates that crop uptake had little role in these changes.

The results indicate that in these mountain steep hillslope sites, erosion plays a role in the decline in soil fertility. Silitoe and Sheil (1999) concluded that even where nutrient concentrations decline significantly, on less-weathered tropical highland soils they may not reach critical levels, and provided the right crops are chosen slash-and-burn farming could still be a fairly sustainable long-term land-use option.

Farmers have long recognized that within hillslopes there are major transfers of nutrients between areas of net erosion and net deposition and have adjusted their land-use practices accordingly (van Noordwijk et al., 1998). However, adoption of agroforestry practices may become more important: (a) if greater shortage of farmland and restrictions of tenure prevent farmers selecting more fertile sites for new farm establishment; (b) after a longer period of cultivation by which time soil fertility levels have fallen much further; (c) if the other products and services provided by agroforestry practices are important. The high levels of infiltration presumed in the present study indicate that use of cover crops may be a technically effective option, should locally acceptable means of incorporating them into the farming systems be identified. Experiences of farmer adoption of contour hedgerow intercropping in Indonesia demonstrate that the system is not an "off the shelf" technique, but rather one of a prototype, whose success was dependent on the farmers' ability to adapt the practice to their specific farming conditions (Wiersum, 1994). The technologies must be flexible enough for farmers to make modifications so that they meet their short-term economic needs (Cramb *et al*., 1999; McDonald and Brown, 2000).

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