

Land Use Effects on Soil Erosion in the Lowland Humid Tropics of Papua New Guinea

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Abstract

A comparative study of the effect of 3 main types of land use (systems) on soil erosion levels was carried out in a traditionally farmed lowland forested region of Morobe Province, Papua New Guinea. Nine erosion plots were built at 3 sites at almost the same altitudinal level, area corrections were done to eliminate the effect of varying slopes. Volumes of runoff, sediments concentration, and soil main nutrients collected within the plots were measured on a weekly basis. The parameters measured were closely depended on rainfall amounts along the time. Significant differences were found among them, explained mainly by land cover types and their soil particularities such as infiltration rates, bulk density, and texture. Even though forest and grassland systems proved to be more effective in controlling soil losses, their areas were rapidly been converted into croplands, raising concerns for the sustainability and improvement of land use planning in the region.

Keywords: land use changes, agricultural systems, soil erosion, soil degradation, tropical soils

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Introduction

Papua New Guinea (PNG) faces multifaceted environmental problems as its population increases rapidly in rural areas. More than 70% of the 6 million country's population lives in rural areas and it is estimated that population growth is of about 5% annually (Ningal *et al.* 2008). Population increase places unprecedented pressure on land resources in most developing countries including PNG. For example in Morobe province of PNG, the population grew by 99% and consequent increase in the cropped land area is by 58% between 1975 and 2000 which expanded cultivated land area by 58% (Ningal *et al.* 2008). More than 70% of the land area in PNG is covered with forests; disorderly encroached by traditional farming in which one of the major concerns is lack of sound management of soil fertility. The practice of shifting cultivation involves slashing the land cover and burning the vegetation to clear the lands for subsistence agriculture. After a sequence of crop cycles the garden is either abandoned or fallowed for regenerating soil fertility. In coastal regions of PNG, long bush fallows and burning are common agricultural practices. In the highlands planted fallows, legume rotations, composting, mounding, drainage, soil retention barriers, and tillage are widespread (Bourke 2001). Without an improvement of fertility management, of farming systems, and of crop production in general, the current trend of agricultural land expansion will continue (Ningal *et al.* 2008).

Laminar erosion is defined as a decrease in depth of the topsoil layer due to almost uniform removal of soil by runoff water or by wind, which leads to temporary or permanent decrease of the productive capacity of the land. In the world 75 billion tons of soils are lost each year from agricultural lands (Alt *et al.* 2008), 78% of total degrading land is in

humid regions (Bai *et al.* 2008). This removal of top soil decreases soil fertility and subsequently crop yields (Bel-lows 2000). As much as 44.4% of the total area in PNG is susceptible to erosion, especially in Southern Highlands, Milne Bay Islands, New Britain, and New Ireland Provinces (Bourke 2001). Climate, soil characteristics, topography, and patterns of land use determine runoff and erosion potential, being difficult to isolate a single factor (Lal 1983). Natural soil erosion could be accelerated even when manual tillage is employed (Turkelboom *et al.* 1997). Tillage causes a net down slope movement of soil material redistributing soil on the landscape (Thapa *et al.* 2001). Deforestation studies revealed considerable changes in soil physical and chemical properties (Hartemink 2005). Recent conversion to short fallows in traditional farming systems also intensifies soil degradation (Goeltenboth 1990). Studies in the highlands of PNG found that soil erosion ranges from 10 ton ha⁻¹ year⁻¹ in slopes of less than 10° with crop covers up to 70%, to 50 ton ha⁻¹ year⁻¹ from soils without vegetation cover, with slopes up to 30° (Humphreys & Wayi 1990).

Basic soil differences may cause long-time average soil losses to vary more than 30-fold. Aggregate breakdown and subsequent particle detachment from bare soil by a given rainfall (or overland flow) depends on aggregate stability and their size distribution characteristics (Lal 1983). When soil infiltration is low the erosion risks increase (Schroeder 1987). Sediments production is inversely related to organic-matter content of the soils (Diaz-Zorita & Grosso 2000).

We hypothesize that in the lowlands of PNG rapid changes like logging and subsistence agriculture can cause significant loss of surface soil and major nutrients. There is scant information available on the effects of land cover change

on sheet erosion and nutrient loss associated with the soil and water loss in the country. Hence this study aims to investigate the relationship between land use practices and soil erosion, and to propose suitable methods of land use that maintains soil fertility. The findings of this study will support and direct future programs of land rehabilitation in the province, as preventing erosion is more effective than its control.

Methods

The experimental site was located in Oomsis Village, 10 km from Lae City, Morobe Province. The mean annual rainfall is of 2,900 mm, with an average temperature of 24–30 °C (Breget *et al.* 2008). Soils at Oomsis area are inceptisols. The erosion plots were set up in 3 different land use systems. The area underwent a succession of land use changes driven by human pressure and the market. Originally the area was a lowland rainforest, currently numerous species are of secondary growth. The understory is dominated by residuals and the forest floor is covered with saplings and grippers. In some patches the forest covers have been cleared for crop cultivation and small scale logging. Near the village settlements cultivated gardens were also selected for the study. Common crops in the gardens were sweet potato (*Ipomoea batata*), chinese taro (*Colocasia esculenta*), cassava (*Manihot esculenta*), yam (*Dioscorea alata*), winged beans (*Psophocarpus tetragonolobus*), pumpkins (*Cucurbita moschata*), sugar cane (*Saccharum officinarum*), pit pit (*Saccharum* sp.), corn (*Zea mays*), peanut (*Arachis hypogaea*), pineapples (*Ananas sativus*), bananas (*Musa paradisiaca*), and papaya (*Carica papaya*). Common native trees are kapiak (*Artocarpus altilis*), tulip (*Gnetum gnemon*), gorgor (*Riteria* sp.), tanget (*Lilia cotylon*), taun (*Pometia pinnata*), amberoi (*Pterocymbium becarii*), rosewood (*Pterocarpus indicus*), basswood (*Endospermum medullosum*), croton (*Croton choristadenius*), and kwila (*Intsia bijuga*).

As much as 9 pentagon-shaped erosion plots (3 in each land use type) were constructed at 50 m distance between them at approximately the same altitude above sea level. Plot borders were constructed with PVC planks of 0.1 m thickness buried down to 0.03 cm with minimal disturbance of the site. The sides were sealed with cement and PVC pipes were placed at the outflow to channel runoffs into containers. The plot sizes varied (4.36–4.8 m²). Corrections on plot size were done in cases of significant slope variation (as in the case of the grassland site). Drained water plus sediments from the plots were channeled and collected on plastic containers with lid to prevent evaporation for its weekly monitoring (total volume and concentration of sediments). Rainfall was daily recorded in a rain gauge. The experiment was monitored during 4th April–15th August 2010 for surface runoff volume, soil loss and loss of nitrogen, and phosphorous in runoff.

Runoff water collected in containers were measured on a weekly basis using a measuring jar. Paired sub samples (about

500 ml) were collected from the containers after thorough mixing of their contents. Samples were filtered through a Whatman No. 42 filter paper to remove sediments. Sediment mass determined gravimetrically after oven-drying tared filters at 105 °C. An aliquot of unfiltered runoff sample was taken in a 250 ml glass beaker, evaporated to dryness and total nitrogen content of the residue was estimated by Kjeldahl method. Another aliquot was dried, and total phosphate (P) content of the residue was estimated colorimetrically after digesting the material in di-acid mixture.

Soil infiltration test was conducted insitu with a double-ring infiltrometer of 30 and 80 cm diameters for the inner and outer rings respectively, and a height of 30 cm installed besides the runoff plot boundaries. After both cylinders were filled with water to a height of 15 cm, cumulative infiltration (cm) was recorded up to 15 min. Soil core samples were obtained close to erosion plots by driving metal cylinders of known dimensions (100 cm³) to estimate soil bulk density by the soil core method. Cores were dried to constant weight (105 °C). Bulk density values were calculated by dividing the oven dry weight of the soil core with the volume of the soil core (cm³). Soil cores were later gently crushed, sieved in 2 mm mesh, and its texture determined by Hydrometer method.

Weekly runoff volume, soil loss, and nutrient loss from 3 different land use systems were analyzed with ANOVA by linear model procedure. Data were analyzed by factorial experimental design in Statistix 8 software (Snedecor & Cochran 1989). Data on soils physical properties under different land uses were analyzed by completely randomized design at probability level of $p = 0.05$. Whenever the F -test was significant, means were compared by Tukey's method.

Results and Discussion

Soils under grasslands had lower soil bulk density (0.83 g cm⁻³) than those under agriculture (1.21 g cm⁻³) and forests (1.10 g cm⁻³) (Table 1). This difference was statistically significant ($p > 0.05$). Higher bulk density of agricultural soils indicates the slight compaction effects of tillage. In PNG most of the soil tillage is done by human labor with digging sticks and spades, with absence of farm animal traffic and machineries. Grassland soils had the highest water infiltration rates of 1.5 cm hr⁻¹ among the 3 land use systems. Main reason is the relatively higher content of the coarser size fraction i.e. sand, compared to agricultural and forest soils, although this difference was not substantial. Soils with coarser size fraction are known to have higher water infiltration rates due to higher macro-porosity. Generally, conversion of forest and grasslands into farms decreases water infiltration through the soils mainly due to compaction and soil structural degradation in the near surface horizons (Jimenez & Rossi. 2001). This degradation results in losses in macro-pore space and a discontinuity in pore space between the cultivated surface and the subsurface soil.

Effect of land use systems on soil and water loss The experi-

Table 1 Details of erosion plots and physical properties of the soils in different land use systems

Land use type	Corrected plot size (m ²)	Plot slope (%)	Bulk density (g cm ⁻³)	Infiltration rate (cm min ⁻¹)	Soil texture (%)		
					Sand	Silt	Clay
Forest	4.52–4.53	16–27	1.10± 0.04	1.0	20.4	40.4	39.2
Agriculture	4.34–4.47	17–30	1.21± 0.09	1.0	29.6	27.2	43.2
Grassland	4.36–4.78	30–50	0.83± 0.07	1.5	29.9	34.0	36.1

mental site received a cumulative rainfall of 1011 mm at a weekly average of 48.2 mm during the study period, which was 43% of the total precipitation in 2010 (Figure 1). Maximum precipitation of 155.2 mm was noticed on the standard meteorological week 25 of the 2010. There was a wide variation in the volume of runoff water generated and soil loss across the experimental period during April–August 2010. Agricultural systems generated significantly ($p < 0.05$) greater volumes of surface runoff compared to the forest and grass-

land ones (Figure 2). Mean runoff volume from agricultural system was around 50 and 37% higher than from forest and grassland systems, respectively. The main reason for this trend could be the lower cumulative water intake during the rainfall events in soils of agricultural plots (Table 1). Soil compaction due to manual tillage operation in agricultural gardens can increase surface runoff (Broersma *et al.* 1995). Furthermore, rooting cavities, earthworms activity, and surface litter, are generally known to increase infiltration rates of water from rainfall

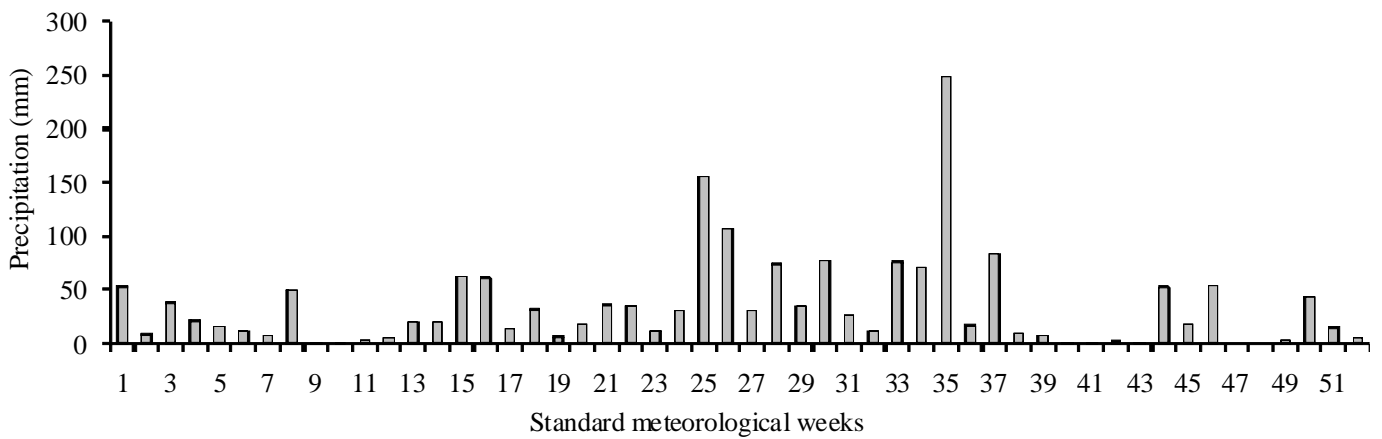
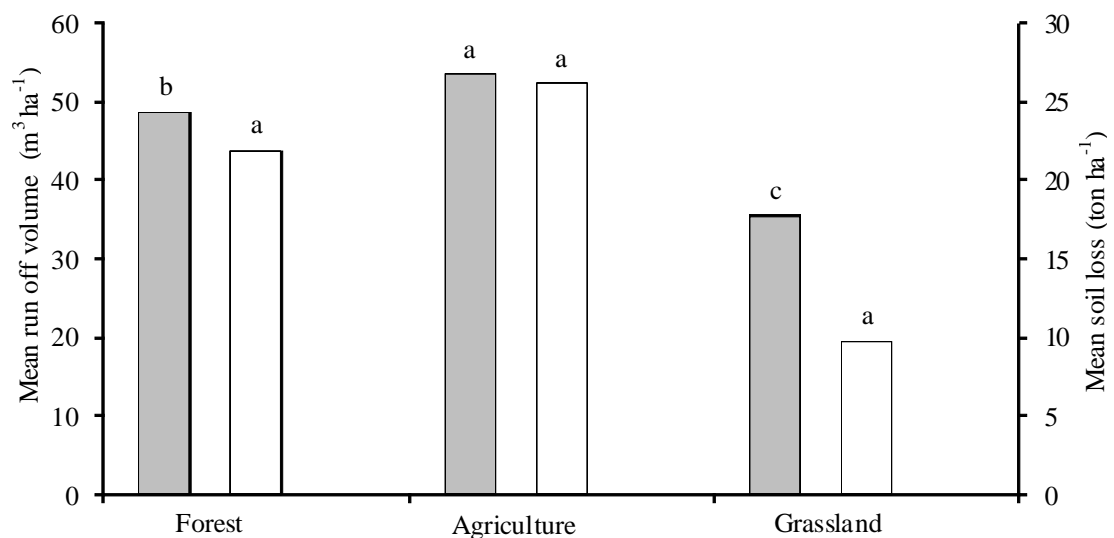


Figure 1 Weekly distribution of precipitation in 2010.



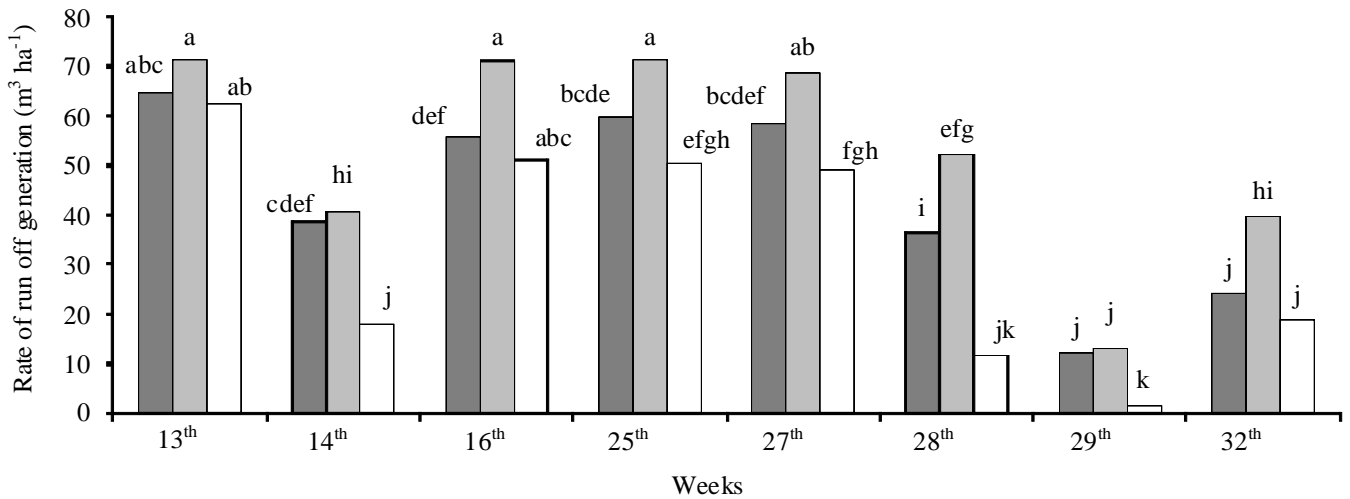
Columns with the same letter indicate that means are not significantly different from each other.

Figure 2 Effect of land use systems on runoff volume and soil loss. Mean run off volume (■) and mean soil loss (□).

thus reducing the surface runoff. In a study conducted at Philippines, Magcale-Macandog *et al.* (2006) suggested that the *Imperata cylindrica* grasslands or continuous maize cultivation produce greater runoff than the Eucalyptus-maize hedge grow land use systems. The dominant grass species *Imperata cylindrica* forms a network of fibrous root system, and the root channels of dead roots may facilitate rapid water infiltration.

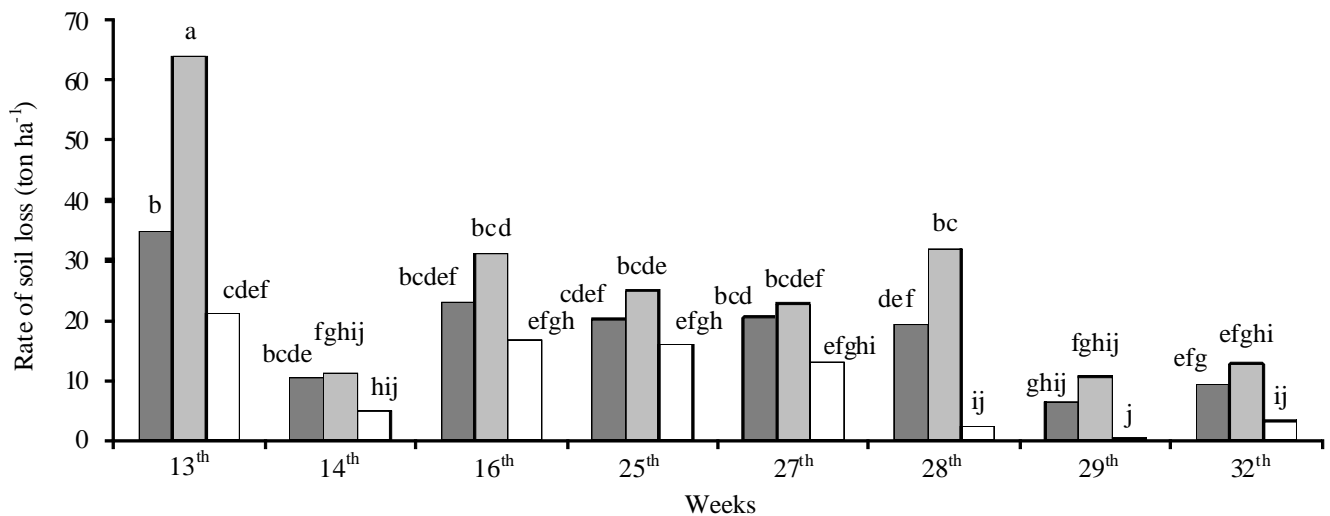
Surface runoff was greatest on the 13th standard meteorological week which corresponds to a peak weekly precipitation of 155.2 mm (Figure 3). Amount of runoff generated on the soil surface depend on soil conditions (soil erodibility and land cover characters), amount of rainfall and intensity of rainfall (rainfall erosivity). Regarding soil loss, grassland plots were efficient in checking soil erosion, while, forest and agricultural

systems were on par with each other. In the same week maximum soil loss was also recorded (Figure 4). In general runoff volume and soil loss decreased in the following order: agricultural systems > forest systems > grasslands. Grasslands and cultivation of perennial grasses are known to promote macro aggregation of soil particles. Macro-aggregates thus formed can help to reduce soil erodibility (Handayani *et al.* 2008). The interaction effect of land use systems X weeks for runoff volume and soil loss was significant for the *F*-test ($p = 0.000$ and $p = 0.001$, respectively). This indicates that weekly soil loss and runoff values varied mainly due to variation in the quantity and intensity of precipitation received. Soils subjected to agricultural practices become compact, reducing water infiltration and therefore with the highest rates of surface runoff and sediments production.



Columns with the same letter indicate that means are not significantly different from each other.

Figure 3 Temporal changes in runoff generation by different land use systems. Forest (■), agriculture (▒), and grassland (□).



Columns with the same letter indicate that means are not significantly different from each other.

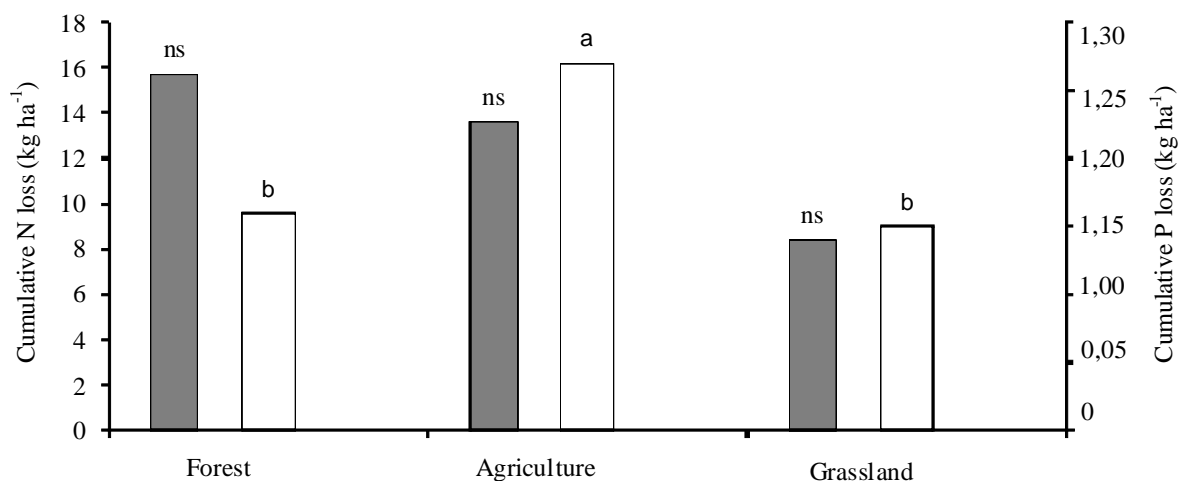
Figure 4 Temporal changes in soil loss pattern by different land use systems. Forest (■), agriculture (▒), and grassland (□).

Effect of land use systems on runoff of nutrients There was no significant difference ($p > 0.05$) in surface runoff loss of N among the 3 land use systems studied (Figure 5). Greatest cumulative loss of $15.7 \text{ kg N ha}^{-1}$ was observed in forest plots, followed by $13.6 \text{ kg N ha}^{-1}$ in agriculture and 8.4 kg N ha^{-1} in grasslands. Agricultural system produced maximum runoff loss of water and sediments than the other 2 systems and therefore it was expected that the loss of N in them should be greatest. Loss of N or any nutrient as a matter of fact is a function of concentration of nutrient in the discharge and the volume of discharge. Runoff discharge from agriculture plots had lower N concentration than the other 2 systems and hence despite of lower discharge volume, net loss of N from the system is greatest. Loss of nitrogen is also reported to be associated with the runoff water portion and not with the sediment material. Water soluble forms of organic and inorganic N from the leaf and litters of the forest floor can be laden in rain water and transported offsite. Pristine tropical landscapes may have relatively high N runoff rates which result from high rates of N fixation and the general lack of N limitation in tropical forest systems (Vitousek & Sanford 1986). Besides, N mineralization rates of tropical and sub-tropical forests have been found to be significantly higher ($3 \text{ mg kg}^{-1} \text{ day}^{-1}$) compared to pastures (less than $1 \text{ mg kg}^{-1} \text{ day}^{-1}$) (Motavalli *et al.* 1998). The increase in the build up of microbial biomass following fire in the dry season, canopy growth, and N-mineralization rates in the wet season, are nutrient conserving mechanisms that prevent nutrient loss (Singh 1994).

In contrast to these findings, runoff loss of phosphorous varied significantly ($p < 0.05$) with the land use systems (Figure 5). P runoff loss was greatest in agricultural systems which was almost 5-time greater than that of forest systems. P loss from grassland systems and forests were statistically on par with each other. Compared to N, loss of nutrient P was very small and it was about $0.27 \text{ kg P ha}^{-1}$ for the entire period of

monitoring in agriculture system. These values are comparable on the low side but still within the range for 24 US soils where the estimated average ranged $0.09\text{--}8.3$ (fallow), $0.06\text{--}7.5$ (cropland), and $0.01\text{--}6.0 \text{ kg P ha}^{-1} \text{ year}^{-1}$ for grassland (Elrashidi *et al.* 2003). Troitino *et al.* (2008) studying the effect of the main types of land uses in Galicia (forest, grassland, and arable) on some soil properties related to the risk of loss of soil phosphorus found that agricultural use has the greatest effect, since it decreases both the organic matter and the oxide content. Decreases in both soil components affect the structural stability and may therefore affect erodibility of the soil and the possible passage of nutrients to watercourses via processes of erosion, and, in the case of the oxides, the P fixing capacity of the soils. There is a close relationship between biogeochemical cycling and landscape processes. According to Vitousek and Sanford (1986) lowland rain forests cycle little phosphorous (limiting nutrient) in their litterfall, while montane rain forests cycle little nitrogen (limiting nutrient). Total phosphorous content can be exhausted within few hours if not replenished by weathering (Briggs & Smithson 1992).

Shifting cultivation and selective removal of trees for timber do not cause serious permanent depletion of nutrients, but the system can usually support only $10\text{--}20$ persons km^{-2} (Whitmore 1998), 6–10 years fallows are enough to replenish macronutrients (Manlay *et al.* 2002). It is necessary to maintain at least about 30% surface contact cover at times when runoff-inducing rainfall can occur (Rose 2001). The conversion of forest to perennial crops usually results in lower levels of soil fertility decline because these systems mimic the forest cover to some extent (Hartemink 2005). These farming practices do not merely extract soil nutrients, but evolve in response to changing conditions over many years (Hiemstra *et al.* 1992) through informal experimentation and experience.



Columns with the same letter indicate that means are not significantly different from each other.

Figure 5 Influence of land use systems on the cumulative surface runoff. Nitrogen (■) and phosphorous (□).

Conclusions

Soil resources are dynamic element, responding to the demands placed on them by human beings and governing expectations of food security. Sustainable utilization depends on working within the limits of ecosystem nutrient cycles. Results from the present study revealed that there are significant differences on soil laminar erosion between the 3 main types of land uses in the low land humid tropical region of PNG. Land converted for agricultural purposes are prone to higher laminar erosion and runoff loss of nutrient *P*, meaning that appropriate techniques are needed in those areas like mulch spreading on the surface, minimum tillage, level contouring and tree/shrubs planting in the gardens. Combinations of structures such as terraces and intercropping are the best response, however mechanical structures require human and financial resources, especially labor and money, and are out of the reckoning of most subsistence farmers. The area of gardens is expanding horizontally and vertically due to human pressure as there are not many methods to intensify production and improve the soil fertility. Forested areas and grasslands produced less sediments than agricultural plots in general, indicating that both of them are more effective land covers in relation to soil conservation, although the economic value per unit area of natural grasslands is the lowest and primary forests are losing value due to selective logging. Government assistance in the form of awareness and credits with low interest are necessary to promote the enrichment of degraded forests and grasslands, and to diversify the traditional agroforestry systems, as no general intensive method of mechanical agriculture has been found in the tropics to supplant the traditional style requiring only a digging stick and fire.

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