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Land Use Conversion and Soil Properties in a Lowland Tropical Landscape of Papua New Guinea

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Abstract

Land use conversion affects natural soil processes and can potentially decrease soils productivity. A representative area was selected to study the effects of land use conversion in Unitech Campus, Southeastern lowlands of Papua New Guinea (PNG). Area selected for the study was once covered by tropical rainforest and has been subjected to various land use types over time. Representative soil samples were collected under 4 main land use types (secondary forest, plantation forest, grassland, and agricultural garden) at 2 depths (0–0.15 m and 0.15–0.30 m) with 3 replicates per land use. Soil bulk density, water infiltration rate, and cumulative water infiltration values were significantly greater ($p < 0.05$) under grasslands than under secondary and plantation forests. Among soil chemical properties, extractable potassium content and pH showed significant differences ($p < 0.05$) among the land uses, pH values increased upon conversion of forested lands to grassland or agricultural gardens. Conversion of secondary forests into grasslands or agricultural gardens leads to depletion of Bray's phosphorus and extractable potassium. Tree-based land uses were optimum due to better nutrient cycling conditions and lower bulk density compared to grassland and agricultural garden despite the low pH conditions and lower water infiltration.

Keywords: effects of land use, soil physical and chemical properties, soil fertility loss, land productivity decline

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Introduction

In the last decades extensive land use changes occurred in tropical countries through conversion of natural forest lands into subsistence farming, cash cropping, mining, and logging to meet growing needs for the increasing population (Hartemink *et al.* 2008). They accelerate land degradation and decrease land productivity (FAO 1999), making vital the establishment of sustainable patterns of land use (Houghton 1994).

Papua New Guinea (PNG) has a land area of 46.3 million ha of which 65% are forests; their area decreased from 38 to 33 million ha between 1972–2002 at a rate of 362,000 ha year^{-1} (Hanson *et al.* 2001; Shearman *et al.* 2009). Customary land ownership dominates on 97% of the land, only 3% of it is under state ownership. In the last few decades an increase of rural population by more than 40% boosted an increase in cropped areas by 10% (McAlpine *et al*. 2001). Major factors of deforestation in PNG are commercial logging (48% of net forest cover change) and land clearing (46%) for subsistence agriculture (Shearman *et al*. 2008). Deforestation studies shows considerable changes in soil physical and chemical properties some of which can influence the productivity potential of forest soils. During land conversion extent and type of vegetation cover changes, and such changes can influence soil erosion process. Studies in the highlands of PNG found that soil erosion could range from 10 t ha^{-1} year^{-1} in slopes of less than 10° with vegetation cover up to 70% to 50 t ha^{-1} year^{-1} from soils without vegetation cover with slopes up to 30° (Humphreys & Wayi 1990). Land cover changes disrupt soil nutrient cycles. Previous studies in PNG have shown that under agricultural land use up to 5-times greater amounts of phosphorous nutrient is lost due to higher runoff and soil loss compared to forests or grasslands (Lopez & Rao 2011). Cropping destabilizes soil structure and increases soil bulk density (BD), the concomitant decrease on soil pore spaces affect water infiltration rate (IR) and accelerates runoff and erosion.

Conversion of forest lands to cropping areas in oxisols of Brazil resulted in 28% of organic matter loss after 5 years of conventional cropping in the top soil layer (Neufeldt *et al*. 2002). A similar soil type in Peru lost 30.23 and 25 kg ha^{-1} of nitrogen (N), phosphorus (P), and potassium (K) through leaching and volatilization resulting in productivity decline of 1.5 t ha^{-1} in 3 years (Jordan 1985). Conversion of *Imperata spp.* grassland to farms (legume fields, agroforestry, and cassava fields) in mollisols of Indonesia, increased the soil porosity by 7%, soil organic carbon (SOC) by 6%, and total nitrogen by 18% (Handayani *et al*. 2012).

The balance between input and output of soil nutrients determines their availability. Major sources of input are soil mineral weathering, atmospheric deposition, and biological fixation and litter decomposition; of output are lost through leaching, erosion, denitrification, and plant uptake (Binkley 1986). Changes in land use pattern can affect the inputs and output of nutrients in soil system thus can influence available nutrients and soil physical quality. Soil quality in turn determines the ability of the soil to sustainable support plant growth. This study aims to investigate the relationship between land use practices and their effects on soil properties. The findings of this study will support and direct future programs of land rehabilitation, soil conservation, agricultural intensification, and reforestation by providing scientific evidence of the effects of land uses on soil fertility. It is hypothesized that specific land use conversions have significant effects on soil fertility in a lowland tropical landscape of PNG.

Methods

Study site and land use types The study site was located at Taraka Campus, 5 kilometers from Lae city in Morobe Province, PNG. Soil at the study site was classified as entisols with different vegetation covers, at an average altitude of 63 m asl, and with average rainfall of 2,900 mm. The climate in the lowland is hot and humid with temperature ranges between 24 to 30 °C and average of 27 °C (Breget 2008). The study site was originally a lowland tropical rainforest, in the last decades gradually converted to plantation forest (*Pinus caribaea*), secondary forest (*Terminalia complanata*, *Pterocarpus indicus, Homalium foetitium*, *Antiaris toxicaria*), patches of grasslands *(Imperata cylindrica),* and agricultural gardens (*Arachis hypogaea, Musa* sp., *Saccharum officinarum, Colocasia esculenta,* and *Ipomoea batatas)*.

Sampling and data collection Soil samples were collected from the 3 subplots of 1.0 m^2 selected to represent each land use system in the June, 2012. Within each subplot 12–15 soil cores were collected at random and bulked. Thus, 3 replicates for each land use were collected for both 0–0.15 m and 0.15–0.30 m depths, totaling 24 soil samples for laboratory analysis. Water infiltration field tests were conducted by double ring infiltrometer method in the subplots chosen for sample collection, which consists of 2 galvanized rings of 0.30 and 0.80 m diameter with 0.30 m height. Infiltration rate was recorded every 5 minutes (ASTM 2003). In each subplot infiltration measurement was taken for 30 minutes. Soil bulk density (BD) was estimated by core method after oven-drying the soil cores collected with a core cutter of 0.05 m height (Gradwell & Birrell 1979).

Soil analysis Soil samples were air-dried, ground and sieved with a 2 mm sieve prior to chemical analysis. Samples were analyzed at the soils laboratory of National Agricultural Research Institute (NARI) in Port Moresby. Total nitrogen content was determined by Kjeldahl digestion method (Blakemore *et al*. 1987), extractable phosphorus by Bray-1 method (Bray & Kurtz 1945), exchangeable potassium by neutral normal ammonium acetate extraction method (Blakemore *et al*. 1987), soil organic carbon by Walkley-Black method (Ogle *et al.* 2003), and soil pH were recorded by dipping a glass electrode in a 1:2.5 (w/v) soil-water suspension (Blakemore *et al*. 1987). Soil texture was determined by the hydrometer method, in which soil particles were first treated with 30% hydrogen peroxide to destroy organic matter. Later, the sample was dispersed with sodium metaphosphate, agitated with a mechanical stirrer and density of soil particles in the dispersed fluid was measured with a hydrometer (Gee & Bauder 1986).

Statistical analysis Soil test results for bulk density, textural analysis, pH, organic carbon content, Bray's phosphorous content, and extractable potassium contents were analyzed by Factorial ANOVA model with Statistix 8.0 at 95% confidence level. Land use types and soil depths were considered as 2 factors and linear model procedure was used to determine the *F*-test significance. Whenever, F test was significant then means were separated by Least Significant Differences (LSD) test. Data on water infiltration test was subjected to simple one-way ANOVA in Completely Randomized Design. Pearson's multivariate correlation analysis was also carried out to ascertain relationship between and among different soil variants.

Results and Discussion

There were highly significant differences ($p < 0.001$) in BD among different land use types and varied significantly ($p < 0.05$) with soil depth (Table 1). Lower BD values were recorded under secondary forest (0.56 mg m^{-3}), closely followed by agricultural gardens (0.61 mg cm^{-3}), plantation forest (1.09 mg m^{-3}), and highest value under grassland (1.31 mg m^{-3}). Similar trend was noticed in subsurface soil (0.15–0.30 m). BD values were greater in subsurface soil (0.15–0.30 m) than surface soils (0–0.15 m) irrespective of the land use types. Our results were comparable to those reported by several researchers (Batjes & Dijkshoon 1999; Yao *et al.* 2010). Loss of organic matter by the conversion of natural forests into pasture/grasslands and cultivated land generally causes higher BD values (Kizilkaya & Dengiz 2010). Besides, anthropogenic activities such as tillage and traffic can also result in loss of biogenic soil structure and therefore increase the BD values. Larger BD values were an indication of slight compaction under grasslands. Studies have shown that forest land conversion to pasture/grasslands could result in soil compaction (Deuchars *et al*. 1999).

Soil particle size distribution did not show any significant ($p > 0.05$) differences between the land use types particularly regarding sand and clay content (Table 1). However, significant ($p < 0.05$) differences were found between different land uses regarding silt content. Lowest silt content (14%) was recorded in agricultural gardens, while, greatest value (29.7%) was noticed under grasslands. Generally, lands subjected to agricultural activities are prone for soil loss due to surface soil erosion during runoff events. Over the years of agricultural use of the soils under repeated tillage activity, soil particles could detach from soil aggregates and finer soil fractions could be easily transported away. Greater runoff and soil loss have been reported in agricultural land use compared to forest and grasslands under the lowland climatic conditions of PNG (Cornelio & Killur 2011).

Land use types varied significantly ($p < 0.05$) regarding

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Table 1 Soil bulk density and textural composition in two soil depths (0–0.15 m and 0.15–0.30 m) under different land use types. Factorial ANOVA results for the interactions between land use types and soil depths were non-significant for all parameters

Soil depth (m)	Land use type	Bulk density (mg m^{-3})	Particle size distribution		
			Sand (%)	Silt (%)	Clay (%)
0–0.15	Secondary forest	0.56c	59.7	18.7abc	21.7
	Plantation forest	1.09b	52.0	22.7abc	25.3
	Grassland	1.31a	51.3	29.7a	19.0
	Agriculture	0.61c	61.7	14.0bc	24.3
0.15–0.30	Secondary forest	0.66c	65.7	14.7bc	19.7
	Plantation forest	1.17b	57.3	18.3abc	24.3
	Grassland	1.37a	56.3	26.7ab	17.0
	Agriculture	0.68c	73.7	11.0c	15.2
F test significance		*p* value			
Land use type		0.0008	0.0966	0.0145	0.2479
Soil depth		0.0398	0.1095	0.2485	0.1550

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

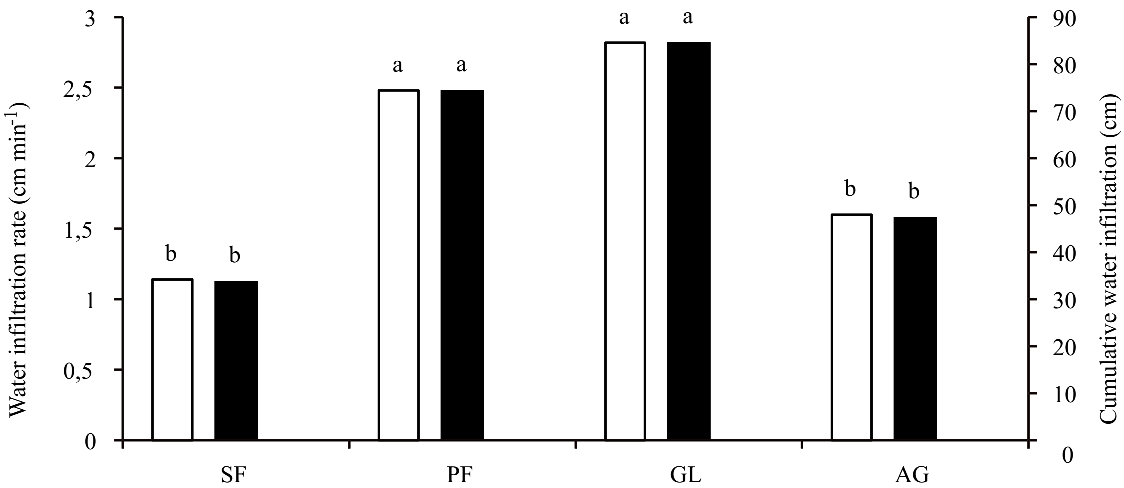

Figure 1 Water infiltration rate and cumulative water infiltration in the surface soil of different land use types. SF secondary forest; PF: plantation forest; GL: grassland; AG: agricultural garden. Bars with same letter are not significantly different from each other. Infiltration rate (cm min^{-1}) (■), cummulative infiltration (cm) (□).

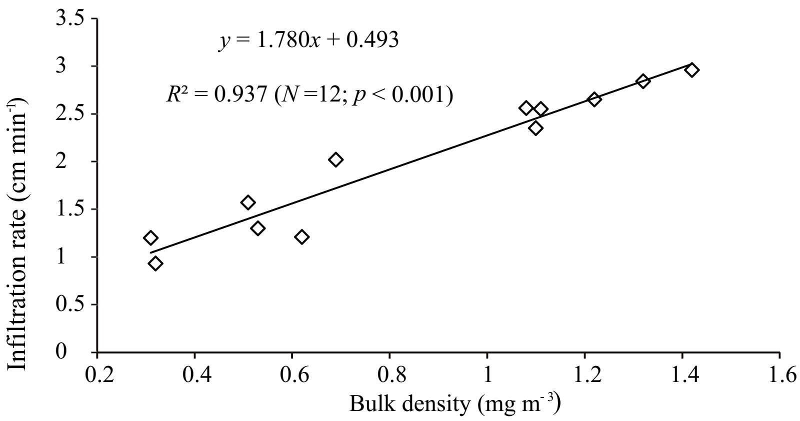

Figure 2 Relationship between water infiltration rate and soil bulk density in the surface soil of different land use types.

Table 2 Fertility parameters in 2 soil depths (0–0.15 m and 0.15–0.30 m) under different land use types. Factorial ANOVA results for the interactions between land use types and soil depths were non-significant for all parameters

Soil depth (m)	Land use types	pH	Soil organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Bray's phosphorous	Extractable potassium
0–0.15	Secondary forest	5.23bc	24.9a	1.6a	11.8	0.94a
	Plantation forest	5.10c	25.4a	1.8a	19.9	0.62ab
	Grassland	5.43ab	21.1b	1.5ab	6.7	0.47ab
	Agriculture	5.20bc	28.9a	1.7a	14.6	0.45ab
0.15–0.30	Secondary forest	5.33bc	11.4c	0.8c	11.9	0.95a
	Plantation forest	5.34abc	6.2c	0.7c	8.8	0.47ab
	Grassland	5.60a	10.5c	0.8c	8.4	0.32b
	Agriculture	5.27bc	13.4c	0.9bc	10.7	0.25b
F test significance				*p value*		
Land use type		0.0323	0.3034	0.9681	0.2053	0.0272
Soil depth		0.0656	0.0000	0.0001	0.1715	0.3848

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

Table 3 Pearson's correlation coefficients (r) between various soil properties under different land use systems

	BD	Sand %	Silt %	Clay %	pH	SOC	TN	Bray's -P
Sand %	-0.289							
Silt %	0.403	-0.891**						
Clay %	-0.031	-0.688**	0.283					
pH	0.388	-0.095	0.324	-0.315				
SOC	-0.278	0.001	-0.125	0.199	-0.438*			
TN	-0.080	-0.246	0.089	0.378	-0.422*	0.909**		
Bray's-P	-0.301	0.120	-0.187	0.046	-0.457*	0.427*	0.255	
Exctr K	-0.484*	0.079	-0.059	-0.073	-0.129	0.172	0.035	0.521*

BD: bulk density; SOC: soil organic carbon; TN: total nitrogen; Extr K: extractable potassium
* indicates that correlation is significant at $p < 0.05$
** indicates that correlation is significant at $p < 0.01$

water infiltration rates (Figure 1). Water infiltration rate was greatest (2.82 cm min^{-1}) in grassland, followed by plantation forest (2.48 cm min^{-1}), agricultural garden (1.60 cm min^{-1}), and least in secondary forest (1.14 cm min^{-1}). Akin to this trend, cumulative water infiltration also significantly differed between land uses. BD values of top soils across different land use types were positively and significantly correlated ($r = 0.968$; $p < 0.01$) to the infiltration rate (Figure 2). Infiltration rates were expected to decrease with the increase in compaction or increasing BD values. On the contrary, in our study we noticed that infiltration rates increased with the increase in BD values. One of the reasons could be that the BD values for most of the samples covering 3 land use types were very low (except for the grasslands). Besides, according to Lichner *et al.* (1994) grass roots can affect infiltration rates in topsoil directly by inducing the preferred flow through macro-pores or indirectly by their influence on soil structure.

Among the various chemical properties studied, land use significantly ($p < 0.05$) influenced the soil reaction (pH) and extractable K content (Table 2). Surface soils in all land use types were strongly acidic, plantation forest showing the lowest pH (5.23). Maximum soil pH was recorded under grass lands (5.43). With the increase in soil depth, soil pH values increased in all four land use types. Soil organic carbon and total nitrogen contents significantly ($p < 0.05$) decreased with the soil depth. Higher pH in grasslands could be due to the better recycling and conservation of basic cations in these soils. Spatial comparisons of areas historically dominated by trees and grasses indicate that soil pH and base saturation tend to be lower under forests with similar parent materials and climates. Under forest stand, soils are prone to acidification and leaching of basic cations and hence a lower pH value (Ugolini *et al.* 1988). However, afforestation studies on grasslands have revealed that in many instances cation cycling and redistribution by trees, rather than cation leaching by organic acids or enhanced carbonic acid production in the soil, is the dominant mechanism of acidification (Jobbagy & Jackson 2003). Commonly followed practices of slash and burn can add ash material thus increasing the soil pH under agricultural gardens and grassland soils (Sanchez 1976), which affects the availability of nutrients. Highest soil organic carbon (SOC) content (28.9 g kg^{-1}) was recorded in agricultural soil, while lowest SOC content was noticed under grasslands (21.1 g kg^{-1}). The SOC concentration in a soil depends on balance between primary productivity, amount of biomass recycled to soil (Bulluck *et al.* 2002) and the rate of biologically-mediated organic matter decomposition processes. Soil conditions such as pH can influence decomposition rates of SOC. Studies conducted (van Noordwijk *et al*. 1997; Schroth *et al*. 2002) elsewhere found a decrease in organic carbon with time when forested areas were shifted to agriculture or secondary forest or mixed forests. However, our results contradicted such observations. Agricultural gardens in PNG are fallowed after few production cycles rather than continuously cultivated (Hanson *et al*. 2001) thus providing opportunity for SOC build up. Another important reason could be that farmers in PNG collect and use leaf composts to fertilize their agricultural gardens. Such practices could supply additional biomass and organic carbon in the agricultural soil.

Soil chemical properties showed degradation trend particularly regarding phosphorous and potassium availability. Land uses with standing trees (secondary forest and plantation forest) had a positive effect on phosphorous and potassium fertility. Bray's phosphorous (6.7–19.9 mg kg^{-1}) and extractable potassium (0.25–0.94 c mol kg^{-1}) were within medium range of availability (London 1991). Bray-P contents were lower in grasslands and agricultural gardens. Consistent with our findings, inorganic P contents of the soils have been reported to be greater under forest systems compared to grasslands of New Zealand mainly due to nutrient pumping and stratification in the top layers (Belton *et al.* 1996). Efficiency of nutrient extraction and stratification increases with increase in biodiversity or in mixed stand of grassland vegetation (Oelmann *et al.* 2011). Nevertheless, in our study lower Bray's- P concentrations (8.8 mg kg^{-1}) was noticed in plantation forest than that of secondary forest (11.9 mg kg^{-1}) and possibly such explanation could hold good for forest systems.

Extractable K content was 2-fold lower in surface soils due to the conversion of secondary forests to agricultural garden. K content was almost four-fold lower in subsurface soils (0.15–0.30 m) due to agricultural activities. Empirical critical limit of soil in Indonesia was 0.20 c mo kg^{-1} (Nursyamsi *et al*. 2008), whereas at ultisols lampung and oxisols sitiung for maize were 0.41 and 0.72 c mol kg^{-1}, respectively with neutral normal ammonium acetate (Sulaeman *et al.* 2000). However no such information is available for the crops and soils of PNG. Depletion of K under agricultural gardens could be due to mining of nutrients in crop produce and off take of nutrients. The results show an evidence for the lack of nutrient cycling in agricultural gardens compared secondary and plantation forests. Variations in concentration of K due to land use changes have been reported in ultisols of Peru and alfisols of Ghana (Sanchez 1976). Land use variations could be also due to the textural changes among different land uses. For example, the secondary forest land had greater amounts of silt (p < 0.05) and clay content than those under agricultural gardens. Available potassium content in soils depends on soil texture and types of soil minerals and is directly proportional to quantity of finer fractions viz., silt, and clay content (Nursyamsi *et al.* 2008).

Results in Table 3 shows that soil pH had a negative but significant relationship (p < 0.05) with SOC content (r = -0.438*), total N (r = 0.422*), and Bray's phosphorous contents (r = -0.457*). As the land use changed from secondary forest to other types, pH tended to increase, thus affecting other soil chemical properties. Such increase in pH specifically under grasslands and agricultural gardens could have increased organic matter decomposition in soil and hence promote greater mineralization and leaching losses of soluble N from the soil system.

Conclusion

Conversion of natural vegetation into other land covers considerably affects soil physical and chemical properties. Therefore land conversion to other uses must be managed carefully to retain soil fertility and continuous productivity. Conversion of natural forest land into agricultural and grassland is of particular risk; however, conversion of grasslands into agricultural gardens could improve soil physical and chemical properties due to increase of above ground biomass, traditional tillage, mineralization of plant residues, and nutrient input by legume plants from atmosphere. Furthermore, management strategies such as fallowing periods of slash and burn systems should be long enough to allow nutrient replenishment and stabilization of soil physical properties.

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