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Nutrient stocks of short-term fallows on a high base status soil in the humid tropics of Papua New Guinea

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Abstract

In order to understand nutrient dynamics in tropical farming systems with fallows, it is necessary to assess changes in nutrient stocks in plants, litter and soils. Nutrient stocks (soil, above ground biomass, litter) were assessed of one-year old fallows with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. The experiment was conducted on a high base status soil (Typic Eutropepts), and in Papua New Guinea such soils are intensively used for agriculture. Soil samples were taken prior to fallow establisment and after one year when the fallows were slashed and above ground biomass and nutrients measured. The above ground and litter biomass of piper was 13.7 Mg dry matter ha^{-1}, compared to 23.3 Mg ha^{-1} of gliricidia and 14.9 Mg ha^{-1} of imperata. Gliricidia produced almost 7 Mg ha^{-1} wood. Total above ground biomass returned to the soil when the fallows were slashed was the same for piper and gliricidia (8 Mg ha^{-1}). Gliricidia accumulated the largest amounts of all major nutrients except for K, which was highest in the above ground piper biomass. Imperata biomass contained the lowest amount of nutrients. The largest stocks of C, N, Ca and Mg were found in the soil, whereas the majority of P was found in the above ground biomass and litter. Almost half of the total K stock of piper and gliricidia was in the biomass. During the fallow period, soil organic C significantly increased under gliricidia fallow whereas no net changes occurred in piper and imperata fallows. The study has shown large differences in biomass and nutrient stocks between the two woody fallows (piper, gliricidia) and between the woody fallows and the non-woody fallow (imperata). Short-term woody fallows are to be preferred above grass (imperata) fallows in the humid lowlands of Papua New Guinea because of higher nutrient stocks.

Introduction

Shifting cultivation is practiced in many places in the humid tropics. It is a sustainable farming system provided the cropping period is relatively short and there is a long fallow period during which the soil fertility is restored. Due to increased land use pressure, fallow periods have shortened which inevitably results in the collapse of the system. For more permanent cropping systems inorganic fertilisers are essential to sustain crop yields but such inputs are often too expensive for subsistence farmers or may be uneconomical or difficult to obtain. In the past decade, much research has focussed on the use and effects of short-term fallows as a step towards more permanent cropping systems (Sanchez 1999; Young 1997). Considerable progress has been made on how fallows work and what are suitable species for different agro-ecological zones (Nair et al. 1999). Relatively much work has been done on the effects of different cropping systems on poor fertility and acid soils (Sanchez and Benites 1987) but high base status soils (exchangeable Ca > 10 mmol$_c$ kg^{-1}, pH > 5.0) have received far less attention.

High-base status soils may have low levels of available P or N, or both. Fallow species on high base status soils should therefore supply N through biological fixation or deep capture, suppress weeds and/or should supply P through chemical transformations and through a reduction of the P complexation (Buresh and Cooper 1999). In order to understand these nutrient dynamics in tropical farming systems with fallows, it is necessary to assess changes in nutrient stocks in plants, litter and soils (Szott et al. 1999). It is generally perceived that fallows with trees (i.e., woody fallows) have a larger capacity to enhance nutrient availability on high base status soils than on low base status soils.

In Papua New Guinea, shifting cultivation systems were commonly practiced in the humid lowlands. Soils are relatively young and base-rich soils (Inceptisols) cover about 60% of Papua New Guinea. Such soils are the most intensively used soils for agriculture (Freyne and McAlpine 1987). A study was conducted on a Typic Eutropepts (Inceptisols) located in a shifting cultivation area. The system consists of a short fallow period (1 to 5 yr) alternated with a cropping period of about one year. Common fallow species in the area are *Piper aduncum*, which is a native shrub of South America (Hartemink 2001), and *Imperata cylindrica* (hereafter named piper and imperata). Piper is a woody fallow which is not burned after slashing, and which is often found as monospecific stands in the humid lowlands. At the end of the fallow period, piper is coppiced at 0.2 to 0.5 m above the ground with bushknives. The vegetation debris is left to dry for some weeks whereafter the woody parts (stems) are removed from the field, and are used for firewood and sometimes for constructing hutroofs. Burning the vegetation debris is uncommon. Imperata fallows are common in areas with frequent bushfires and these usually occur when there is a short dry spell, which takes place in most years. Fires hinder the regrowth of woody vegetation.

Plots were planted with *Piper aduncum*, *Imperata cylindrica* and *Gliricidia sepium* (hereafter named gliricidia). Piper and imperata are considered native or traditional fallows whereas gliricidia is an improved fallow which is generally assumed to be more efficient than traditional fallows in restoring fertility (Buresh and Cooper 1999). The fallows were grown for one year whereafter the above ground biomass and nutrient content were determined. The objectives of the study were to quantify above ground biomass and nutrient stocks of the three fallow species, and the amounts of nutrients returned to the soil when the fallows are slashed. The study also aimed to compare two woody fallows (piper and gliricidia) to a non-woody fallow (imperata), and to compare traditional fallows (piper, imperata) to an improved fallow (gliricidia).

Materials and methods

Experimental site

The experiment was conducted between November 1996 and November 1997 near Hobu village (6°34'S, 147°02'E), which is 25 km N of the city of Lae in the Morobe Province. The site is located at an altitude of 405 m a.s.l. at the footslopes of the Saruwaged mountain range. Total rainfall during the experimental period was 1,828 mm. The end of 1997 was an exceptionally dry period and this was caused by the El Niño/Southern Oscillation climatic event. Total rainfall in 1997 was 1,897 mm compared to 3,667 mm of rain for 1998. Temperatures were not available for the experimental site but average daily temperatures at the University of Technology, which is situated about 15 km to the North of Hobu village, are 26.3 °C. The climate classifies as Af (Köppen).

The Hobu experimental site is located on an uplifted alluvial terrace with a slope of less than 2%. Soils are derived from a mixture of alluvial and colluvial deposits dominated by sedimentary rocks and coarse to medium grained, basic, igneous rocks. The soils have water-worn gravelly and stony horizons below 0.2 m depth; effective rooting depth is over 0.7 m. Chemical and physical properties of air-dried and sieved (< 2 mm) soil is given in Table 1. The soils are fertile with moderately high organic C contents and high levels of exchangeable cations. The topsoils are clayey and have bulk densities between 0.6 and 0.8 Mg m^{-3}. Soils in the area are not enriched by volcanic ashes which has occurred in many parts of Papua New Guinea (Bleeker 1983). The low bulk density is probably related to the high soil organic carbon contents (Manrique and Jones 1991). The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base).

Table 1. Soil chemical and physical properties of a Typic Eutropepts at the experimental site in the humid lowlands of Papua New Guinea.

Sampling depth m	pH H_2O 1:5	Organic C g kg^{-1}	Total N g kg^{-1}	P Olsen mg kg^{-1}	CEC pH7 $mmol_c$ kg^{-1}	Exchangeable cations $mmol_c$ kg^{-1}			Base saturation %	Particle size fractions g kg^{-1}			Bulk density Mg m^{-3}
						Ca	Mg	K		clay	silt	sand	
0-0.12	6.2	54.6	5.0	9	400	248	78	16.9	86	480	160	360	0.82
0.12-0.23	6.3	25.4	2.3	2	155	220	84	1.9	100	620	110	270	0.85
0.23-0.39	6.6	13.7	1.3	1	338	200	105	1.4	91	600	140	260	0.97
0.39-0.99	7.4	2.1	0.3	4	357	189	99	1.4	82	340	110	550	1.30

Samples were taken in a soil pit near the experimental plots in February 1997 and the site had been fallow since 1992.

Experimental set-up

An area of about 0.5 ha secondary vegetation was slashed manually at the beginning of November 1996. The vegetation consisted mainly of *Piper aduncum* and to a lesser extent by *Homolanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Rogers and Hartemink 2000). The site was previously used for growing foodcrops (sweet potato, taro, sugar cane) but had been fallow since 1992. All vegetation debris was removed and no burning was practised, which follows the land-clearing practices of local farmers.

Plots of 6.0 by 6.0 m each were laid out and treatments were assigned to the plots in a randomised complete block design with four replications. On 27 and 28 November 1996, four plots were planted with seedlings (0.2 m height) of *Piper aduncum* obtained from a nearby roadside. Four plots were planted with *Gliricidia sepium* cuttings (0.4 m length) obtained from a nearby cocoa plantation. Piper and gliricidia fallows were planted at distances of 0.75 by 0.75 m (17,778 plants ha^{-1}). These spacings are often observed in natural piper fallows (Hartemink 2001). During the first months, piper and gliricidia plots were manually weeded but thereafter the canopy had closed and no more weeding was necessary. At the same time four plots were left fallow. Woody regrowth was removed from this plot and within four weeks the vegetation was dominated by *Imperata cylindrica*. Some minor weeds in the imperata fallow were *Ageratum conyzoides, Sphaerostepanos unitus*, *Rottboellia exalta*, *Sida rhombifolia*, *Polygala paniculata*, *Euphorbia hirta* and *Emilia sonchifolia*.

Soil sampling and analysis

Soil samples for chemical analysis were taken when the fallows were planted (27-28th November 1996) and one day before the fallows were slashed (19th November 1997). Soil samples were collected with an Edelman auger (diameter 0.05 m) at 12 random locations in a plot, mixed in a 20 L bucket and a subsample of about 1 kg was taken. Air-dried samples were ground and sieved (2 mm) and were sent for analysis to the National Analytical Chemistry Laboratories in Port Moresby. The procedures for soil analysis were as follows: pH H_2O (1:5 w/v); organic C and total N by Leco CNS-2000 dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH_4OAc percolation (pH 7.0); particle size analysis by hydrometer. The soil data in Table 1 and Table 5 are based on these analytical methods.

In order to express soil nutrient content in kg ha^{-1}, bulk density of the soil was measured. In each plot, the 0-0.05 and 0.10-0.15 m soil horizons were sampled using two 100 mL cores per depth and measurements were duplicated in each plot. Bulk density was measured one day before soil samples for chemical analysis were taken. Cores were oven-dried at 105 °C for 72h. Topsoil chemical properties (C, N, P, K, Ca, Mg) were multiplied with average bulk density values of the 0-0.05 and 0.10-0.15 m soil horizons to obtain nutrient pools in kg ha^{-1}.

Plant sampling and analysis

After one year of growth (20-24 November 1997), the fallow vegetation was cut at ground level. Piper plants were separated into stems, branches, and leaves whereas gliricidia plants were separated into stems and leaves. The litterlayer was carefully removed from the entire plots and placed in paper bags. As there was virtualy no weed growth and the plants were harvested in a dry spell it was relatively easy to gather together the litter layer from the soil surface. For the imperata fallow there was virtually no litter. In each plot, total fresh matter was weighed of the different plant parts, and subsamples were taken to the laboratory for dry matter determination and nutrient analysis. Roots were not sampled in this study.

In the laboratory, all plant samples were rinsed with distilled water and ovendried at 70 °C for 72h. Samples were ground (mesh 0.2 mm) and sent for nutrient analysis to the laboratories of the School of Land and Food of the University of Queensland. One subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca, and Mg using ICP AES (Spectro Model P). A second subsample was digested according to the Kjeldahl procedure and analysed for C and N on an Alpkem Rapid Flow Analyser Series 300. Nutrient stocks in the above ground biomass were calculated by multiplying dry mass with the nutrient concentration.

Statistical analysis

For the above ground biomass, nutrient concentration and content, and nutrient removal standard deviations were calculated. An ANOVA was conducted to investigate statistical differences in soil chemical properties and in the discussion of the results the statistically significant difference was set at 5% ($P < 0.05$). All statistical analysis has been conducted with Statistix 8 for Windows.

Results

Above ground biomass

One-year-old piper had produced 13.7 Mg dry matter (DM) ha^{-1}, compared to 23.3 Mg ha^{-1} produced by gliricidia and 14.9 Mg ha^{-1} by imperata fallow (Table 2). The stem biomass of gliricidia was almost three times larger than that of piper. Gliricidia also produced more litter and leaves than piper. Average rate of above ground biomass accumulation in kg DM ha^{-1} d^{-1} was about 38 for piper, 64 for gliricidia and 41 for imperata. In the study area, farmers commonly remove the stems when the fallows are slashed and small branches and leaves are returned to the soil as surface mulch. Above ground biomass that would be returned to the soil was about 8 Mg ha^{-1} for piper and gliricidia, and 14.9 Mg ha^{-1} for imperata.

Table 2. Above ground biomass production one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea.

	Biomass in Mg dry matter ha^{-1} ± 1 SD		
	Piper	Gliricidia	Imperata
Stems	5.9 ± 1.0	15.2 ± 0.6	
Branches	1.6 ± 0.2		
Leaves	4.2 ± 0.4	5.2 ± 0.3	14.9 ± 2.0
Litter	2.0 ± 0.4	2.9 ± 0.9	
Total	13.7 ± 1.3	23.3 ± 1.6	14.9 ± 2.0

Nutrient stocks – carbon, nitrogen and phosphorus

Carbon and nutrient concentrations of the various plant parts are given in Table 3. Gliricidia leaves contained relatively high N concentrations compared to the leaves of piper and imperata. Phosphorus concentrations were low in most plant parts and little difference was found between the fallow species. Potassium concentrations were high in piper leaves and branches, and also the piper stems and litter had relatively high K concentrations. Concentrations of Ca and Mg were highest in the litter of piper and gliricidia. Imperata had low concentrations of all major nutrients.

Nutrient concentrations were multiplied with the dry biomass in order to calculate nutrient stocks. Total organic C in the above ground biomass of the piper fallow was 5.8 Mg ha^{-1} of which almost half was found in the stems (Table 4). Gliricidia fixed two times more C and about two-thirds of the plant organic C was found in the stems. Total above ground C accumulation by imperata was larger than that of piper and equalled the amount of C fixed in gliricidia stems.

In all three fallows, the amount of C in the above ground biomass was only a fraction of the organic C in the topsoil. Above ground biomass C averaged 7% of the total C stock (biomass, litter, soil) for piper and imperata, and about 11% for gliricidia (Figure 1). This slightly larger fraction for the gliricidia is caused by the larger wood production of gliricidia as compared to piper (Table 2).

Above ground biomass of gliricidia contained 356 kg N ha^{-1} of which half was found in the stems. Nitrogen contents of the gliricidia leaves exceeded the

Table 3. Carbon and nutrient concentration of the biomass of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea.

		% ± 1 SD					
Fallow species	Compartment	C	N	P	K	Ca	Mg
Piper aduncum	Stems	45.2 ± 0.1	0.4 < 0.1	0.1 < 0.1	1.6 ± 0.2	0.2 < 0.1	0.1 < 0.1
	Branches	41.8 ± 0.6	0.7 ± 0.1	0.3 ± 0.1	3.7 ± 0.5	0.6 ± 0.1	0.4 ± 0.1
	Leaves	41.2 ± 1.3	1.6 ± 0.3	0.2 < 0.1	3.0 ± 0.2	1.8 ± 0.1	0.5 ± 0.1
	Litter	35.4 ± 0.8	0.9 ± 0.1	0.1 < 0.1	1.2 ± 0.2	2.9 ± 0.2	0.5 ± 0.1
Gliricidia sepium	Stems	45.4 ± 0.4	1.1 ± 0.2	0.2 < 0.1	1.0 ± 0.1	0.6 ± 0.1	0.1 < 0.1
	Leaves	45.9 ± 0.4	2.8 ± 0.2	0.2 < 0.1	1.6 ± 0.2	2.4 ± 0.3	0.5 ± 0.1
	Litter	39.6 ± 2.9	1.6 ± 0.1	0.1 < 0.1	0.3 < 0.1	3.4 ± 0.5	0.6 ± 0.1
Imperata cylindrica	Whole plant	44.7 ± 0.4	0.5 ± 0.1	0.1 < 0.1	0.6 < 0.1	0.4 ± 0.1	0.2 < 0.1

Table 4. Carbon and nutrient content of the topsoil and above ground biomass of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea, partly after Hartemink (2003).

		Mg ha^{-1}	kg ha^{-1}				
Fallow species	Compartment	C	N	P	K	Ca	Mg
Piper aduncum	Stems	2.7 ± 0.4	23 ± 2.8	7.4 ± 0.6	92 ± 7.9	10 ± 1.6	5 ± 1.4
	Branches	0.6 ± 0.06	11 ± 2.1	4.5 ± 1.2	58 ± 9.1	10 ± 1.7	6 ± 1.2
	Leaves	1.7 ± 0.1	67 ± 8.6	8.2 ± 1.5	125 ± 13.8	78 ± 7.0	23 ± 3.7
	Litter	0.7 ± 0.1	19 ± 3.8	1.7 ± 0.3	23 ± 3.0	59 ± 15.5	11 ± 3.4
	Total vegetation	5.8 ± 0.6	120 ± 11.5	21.8 ± 1.7	299 ± 24.6	157 ± 19.8	45 ± 8.2
	Soil (0-0.15 m)	80.3 ± 7.8	8081 ± 642	5.9 ± 1.0	377 ± 163	4981 ± 790	879 ± 265
	Total	86.1 ± 7.4	8201 ± 638	27.7 ± 2.5	675 ± 150	5138 ± 771	924 ± 258
Gliricidia sepium	Stems	6.9 ± 0.3	164 ± 24.0	24.2 ± 4.5	159 ± 11.3	90 ± 22.4	23 ± 3.5
	Leaves	2.4 ± 0.2	145 ± 11.9	8.6 ± 0.6	81 ± 11.2	127 ± 13.9	24 ± 6.9
	Litter	1.1 ± 0.3	47 ± 11.7	3.0 ± 1.2	8 ± 2.0	95 ± 16.4	17 ± 6.2
	Total vegetation	10.4 ± 0.7	356 ± 10.6	35.9 ± 4.1	248 ± 14.7	312 ± 37.7	64 ± 12.3
	Soil (0-0.15 m)	86.2 ± 9.6	8059 ± 776	4.7 ± 1.1	327 ± 147	4600 ± 533	868 ± 162
	Total	96.6 ± 9.1	8415 ± 780	40.6 ± 3.8	575 ± 157	4912 ± 549	932 ± 170
Imperata cylindrica	Whole plant	6.7 ± 0.9	76 ± 23.9	11.9 ± 3.7	89 ± 15.5	56 ± 17.5	29 ± 8.5
	Soil (0-0.15 m)	85.7 ± 8.9	8311 ± 911	5.2 ± 1.8	508 ± 148	5329 ± 472	871 ± 192
	Total	92.4 ± 8.6	8387 ± 913	17.1 ± 3.0	597 ± 149	5385 ± 458	900 ± 197

The soil content of Ca, Mg, K and P is based on extraction and not on total analysis.

total N content of the piper biomass. Imperata had accumulated the lowest amount of N and the concentrations in its leaves were on average below 6 g N kg^{-1}. Total N in the topsoils (0-0.15 m) under the three fallows was high (about 8200 kg N ha^{-1}). Similar to what was found for organic C, stocks of N in the topsoil largely exceeded N in the above ground biomass. The fraction of N in the biomass from the total N stocks was less than 2% for piper and imperata, and about 4% for gliricidia (Figure 1).

Soil available P stocks at the end of the fallows were very low and around 5 kg ha^{-1} under each of the three fallow species. Piper biomass contained about four times more P than the available P in the topsoils and most P was found in the piper leaves. Seven times more P was found in the above ground gliricidia biomass than in the soil. Most of the P in

Table 5. Soil chemical properties before and after one-year fallow with *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. Sampling depth 0-0.15m (except for bulk density), partly after Hartemink (2003).

Fallow species	Sampling time	pH H_2O 1:5 w/v	Organic C g kg^{-1}	Total N g kg^{-1}	Olsen P mg kg^{-1}	CEC pH7 $mmol_c$ kg^{-1}	Exchangeable cations $mmol_c$ kg^{-1}			Base saturation %	Bulk density ^{1} (Mg m^{-3})	
							Ca	Mg	K		0-0.05	0.10-0.15
Piper aduncum	Before the fallow	6.2	68.4	6.2	8.4	407	242	60	12.5	77	0.61	0.71
	After the fallow	5.8	71.0	7.2	5.2	440	219	63	8.4	67	0.70	0.81
	Difference	$P < 0.01$	ns	ns	ns	ns	ns	ns	$P < 0.01$	ns		
Gliricidia sepium	Before the fallow	6.2	67.8	6.2	5.9	393	252	63	9.5	83	0.57	0.64
	After the fallow	5.9	82.2	7.7	4.5	416	220	68	7.9	71	0.64	0.75
	Difference	ns	$P < 0.05$	$P < 0.05$	ns	ns	ns	ns	ns	ns		
Imperata cylindrica	Before the fallow	6.3	70.1	6.7	6.5	409	279	60	11.6	86	0.59	0.74
	After the fallow	5.7	76.9	7.5	4.6	450	239	65	11.6	71	0.67	0.81
	Difference	$P < 0.01$	ns	ns	ns	ns	ns	ns	ns	ns		

ns – no statistical significant difference ($P > 0.05$); ^{1}for bulk density there were insufficient data to conduct a t-test.

the gliricidia was found in the stems. Imperata leaves had very low P concentrations (< 0.8 g P kg^{-1}) but two times more P was found in the imperata biomass than in the topsoil. Overall, gliricidia fallows had the largest P stock, which was more than two times the P stock of imperata fallows.

Nutrient stocks – cations

Piper biomass contained large amounts of K (Table 4) due to the high K concentration of its leaves (Table 3). More than 40% of the total K-stock of piper fallows was found in the above ground biomass (Figure 1). Gliricidia biomass contained also high amounts of K of which about two-third was found in the stems. Imperata contained the lowest amount of K, but had the highest soil K stocks. Gliricidia biomass contained 312 kg Ca ha^{-1} of which 127 kg ha^{-1} was found in the leaves (Table 4). Piper biomass contained two-time less Ca than gliricidia whereas imperata had accumulated only 56 kg Ca ha^{-1}. For piper most of the Ca was found in the leaves. For all three fallow species, Ca stocks in the topsoil largely exceeded the Ca in the above ground biomass and for piper and gliricidia less than 7% of the total Ca was found in the above ground biomass (Figure 2). The amounts of Mg in leaves of piper and gliricidia were similar but total Mg accumulation by gliricidia was almost 20 kg ha^{-1} higher. One-third of the Mg in the above ground biomass of the gliricidia was found in the litter. Less than 7% of the Mg stocks of gliricidia and piper were found in the above ground biomass whereas less than 3% of the Mg stock was in the imperata biomass.

Changes in soil properties

Soil properties were measured before the fallows were planted and after one year when the fallows were slashed. Statistical analysis revealed that the pH H_2O had significantly ($P < 0.01$) declined under piper and imperata fallow by 0.4 to 0.5 pH unit (Table 5). The smaller pH change under gliricidia fallow was not significant. Levels of organic C and total N were both significantly ($P < 0.05$) increased under gliricidia but had not changed significantly under the other two fallow species. No significant changes were found in available P, CEC, exchangeable Ca and Mg and base saturation under the three fallows. Exchangeable K was significantly ($P < 0.01$) reduced by 4.1 $mmol_c$ K kg^{-1} in the topsoils under piper but no changes were apparent after gliricidia or imperata fallows. Soil bulk densities had slightly increased un-

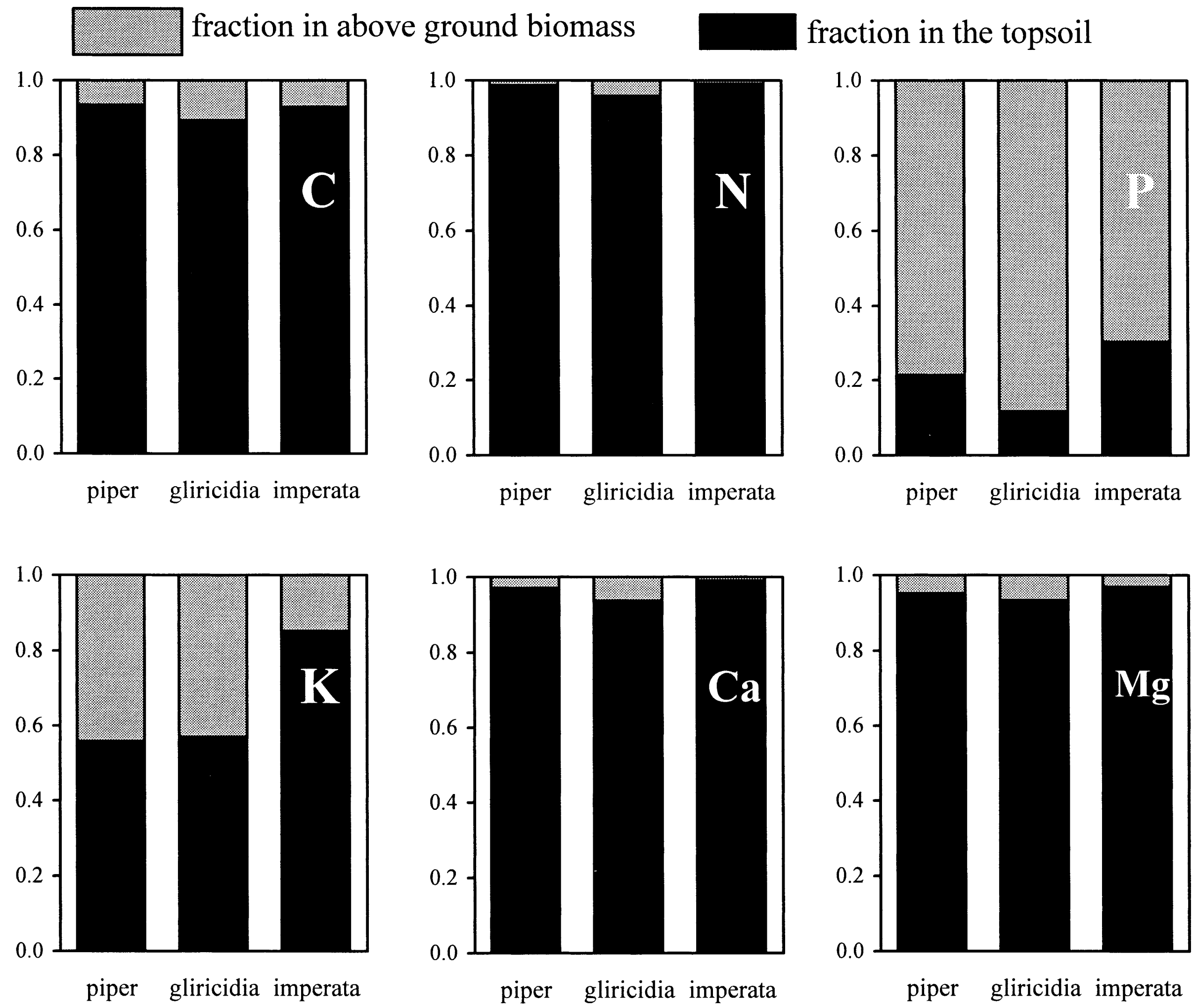

Figure 1. Fraction of nutrients in the above ground biomass of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallows and in the topsoil (0-0.15 m) in the humid lowlands of Papua New Guinea. The soil content of Ca, Mg, K and P is based on extraction and not on total analysis.

der all three fallow species but data were insufficient for a statistical comparison.

Nutrient cycling

Although the above ground biomass of gliricidia was almost two times higher than that of piper, the amount of C returned to the soil is the same for piper and gliricidia due to the removal of large quantities of glircidia stems (Figure 2). Imperata biomass returns the highest amounts of C to the soil because no biomass is removed from the plots. Gliricidia had accumulated large amounts of N and returned almost 200 kg N ha^{-1} with the leaf and litter biomass. Little N was removed with the piper wood and one-year old piper fallows returned almost 100 kg N ha^{-1}. The amount of P returned to the soil was around 13 kg P ha $^{-1}$ for the three fallow species. Piper accumulated the largest amount of K and returned more than 200 kg ha^{-1} with its leaves, litter and small branches; gliricidia and imperata returned less than half of the piper. Large amounts of Ca were returned with the gliricidia leaves, intermediate amounts with piper and relatively little Ca was returned with the imperata biomass. Similar amounts of Mg were returned with the piper and gliricidia biomass. Figure 2 clearly shows that considerable amount of all major nutrients are removed with the wood of the gliricidia wood

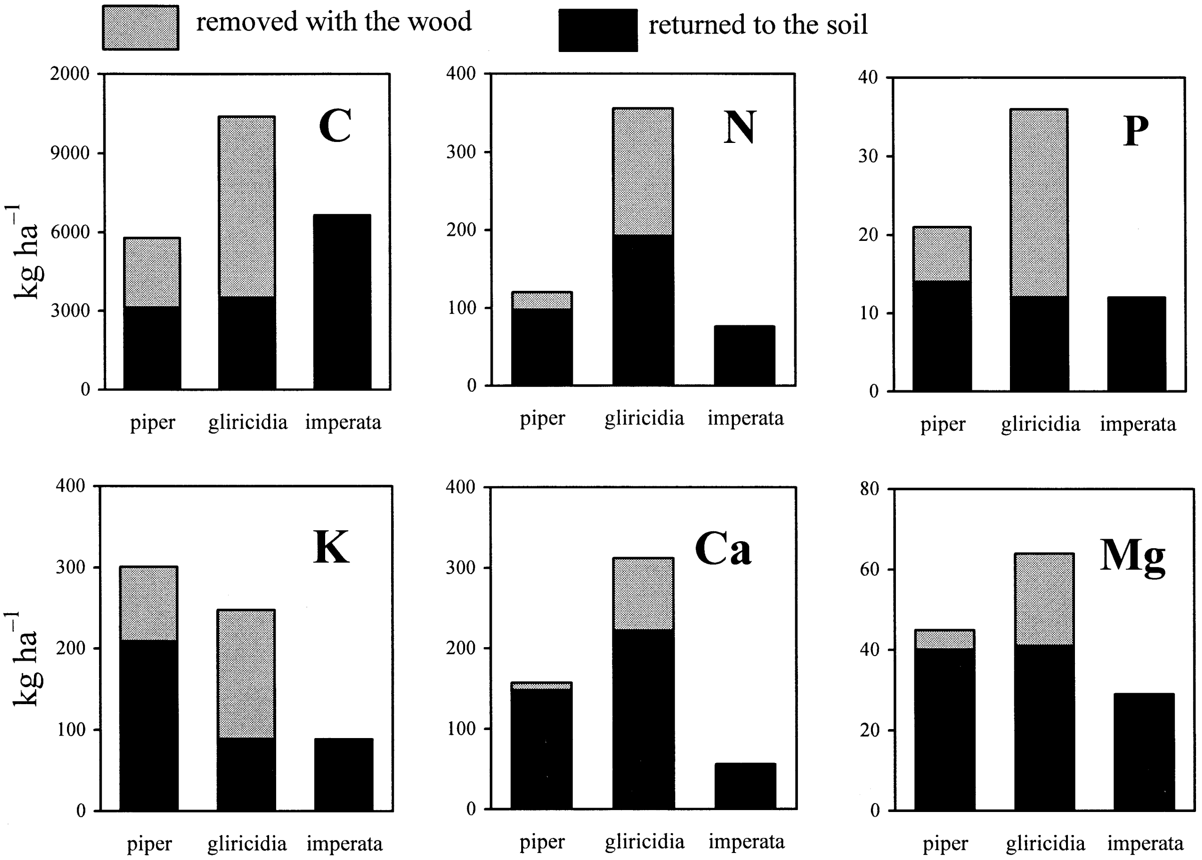

Figure 2. Carbon and nutrients removed with the wood and returned to the soil of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea.

(stems). Less nutrients were removed with the piper wood compared to the gliricidia wood.

Discussion

There were considerable differences in biomass and nutrient stocks between the two woody fallows (piper, gliricidia) and between the woody fallows and the non-woody fallow (imperata). This discussion focuses on biomass and nutrient stocks, changes in soil properties and the cycling of nutrients and the implications for cropping systems on high base status soils in the humid lowlands of Papua New Guinea.

Biomass

Total above ground biomass accumulation (including litter) ranged from 13.7 Mg DM ha^{-1} yr^{-1} (piper) to 23.3 Mg ha^{-1} yr^{-1} (gliricidia). These are relatively high rates of biomass accumulation. In the humid tropics, accumulation of above ground biomass during the first ten years of fallow growth generally ranges between 4 and 15 Mg DM ha^{-1} yr^{-1} (Szott et al. 1999). High rates of biomass accumulation result in high nutrient accumulation and quick soil cover, which helps to reduce nutrient losses, and may also result in high N gains by leguminous crops and trees. The high rates found in this experiment are influenced by the high base status of the soils, but more biomass could have been produced. In another experiment at the same experimental site it was found that *Piper aduncum* biomass accumulation was linearly related to the amount of rain. In that experiment piper had accumulated 48 Mg ha^{-1} after 23 mo (average 25 Mg DM ha^{-1} yr^{-1}). Total rain during the 23 mo was 5,323 mm (mean 231 mm mo^{-1}) compared to 1,828 mm of rain (mean 152 mm mo^{-1}) during the experimental period reported in this paper. In the experiment reported in this paper, growth of *Piper aduncum* was retarded due to the relatively dry conditions. The data confirm the general trend that fallow biomass accumulation increases in the tropics with increasing rainfall (Szott et al. 1999).

Total biomass accumulation of the fallows was higher as below ground biomass was not assessed due to the stoniness of the soils which makes quantification difficult (Hartemink 2001). Szott and Palm (1996) based on the work of Uhl (1987) and others, worked with a ratio below ground/above ground biomass of 0.1 to 0.2 for natural and improved fallows. Assuming a ratio of 0.15, total biomass (including litter) is 15.8 Mg ha^{-1} for piper, 26.8 Mg ha^{-1} for gliricidia, and 17.1 Mg ha^{-1} for imperata. Again, these are large amounts of biomass accumulated in a short period and that is exactly what a fallow in the tropics should do (Sanchez 1999).

Nutrient stocks and cycling

In all three fallow types, the bulk of the C, N, Ca and Mg was present in the soil and only a small fraction was found in the above ground biomass. In the humid tropics it is mostly found that more C is found in the soil than in vegetation (Houghton 1995), and the data reported here confirm this. It is partly due to the fact that the soils have relatively high C concentrations (around 50 g kg^{-1}). The bulk of N was present in the soil (1 to 4% of the total) and not in the above ground biomass, which is also commonly found in tropical rainforests. Contrary, most of the P and a considerable part of the K stocks of these short-term fallows is found in the above ground biomass. These findings suggest that the transfer of nutrients in fallow-cropping systems should be differently appraised for different nutrients.

Total nutrient stocks in the fallows is higher because (i) nutrients in roots were not measured, (ii) only nutrients in the 0-0.15 m soil horizon were measured, (iii) only extractable P and cations were measured whereas total contents of these nutrients is higher. Organic C and total N are the total Figures but P is extracted by bicarbonate and Ca, Mg and K by an NH_4-acetate so P and cations are a fraction of the total amounts present in the soil. The soil nutrient data for P and the cations are thus lower than the total nutrient stocks (Hartemink 2003). On the other hand, the data give a fair quantification of the amounts of nutrients that are potentially available for crop production. Due to the stoniness of the subsoil most roots were found in the top 0.15 m, deep capture of nutrients which is important in many fallow systems (Hartemink et al. 2000a), is not relevant for this study site. Therefore, nutrient stocks reported for the topsoil are more or less equal to the amount of nutrients available (Hartemink 2003).

Gliricidia had accumulated the largest amounts of all major nutrients (except for K) and more than 350 kg N ha^{-1} was accumulated in the above ground biomass of gliricidia. Giller (2001) summarised estimates of N content of one-year old gliricidia prunings and values ranged from 19 to 204 kg N ha^{-1}. Although the roots of N fixing trees may contain large amounts of N it was found that gliricidia contains little N below ground (Giller 2001; Schroth and Zech 1995) so that most of the N is found in the above ground biomass. Much of the N in the gliricidia leafs and litter (192 kg ha^{-1}) is rapidly mineralised when the gliricidia fallow is slashed and becomes available to the succeeding crop (Hartemink and O'Sullivan 2001).

The major function of fallows is to recycle and conserve nutrients rather than to cause net increases in ecosystem nutrient stocks (Buresh and Cooper 1999). Gliricidia and piper fallow recycled larger amounts of nutrients than imperata which may induce greater losses. Hartemink (2003) compared nutrient budgets of the fallow-crop systems with changes in soil nutrient contents. It was found that more N and Ca were lost from the soil than could be explained by the input-output budgets and it is likely that leaching losses were high (Hartemink 2003).

Soil changes

The observational period was only one year and changes in soil chemical properties using conventional analytical techniques are not always found within such period (Young 1997). Nonetheless some interesting changes in soil properties and differences between the fallow species were found. Exchangeable K decreased significantly under piper fallow which reflected the high K uptake by piper. Soil organic C significantly increased under gliricidia fallow which is related to the high biomass and litter production compared to the other two fallow vegetations. Restoration of soil organic matter is one of the main function of fallows (Greenland and Nye 1959) and apparently gliricidia fallows can relatively quickly increase soil organic C contents. On the other hand, reports from the literature have shown that there is often a decrease in soil C-stock during first 8 months of a fallow period and then and increase in the remainder (Szott et al. 1994). Juo et al. (1995) observed an increase in newly established fallows during the first year and the data reported in this paper confirm this observation.

There were also some significant soil physical changes during the fallow period. Soil moisture meaasured directly after one-year piper fallow was significantly lower than under gliricidia fallow. Soil moisture content in the topsoil under piper was 0.29 $m^3\ m^{-3}$ as compared to 0.36 $m^3\ m^{-3}$ under gliricidia (Hartemink and O'Sullivan 2001). This effect lasted for several weeks after the fallows were slashed and a sweet potato crop was planted. The lower soil moisture contents after piper is an advantage since high rainfall depresses sweet potato yield (Hartemink et al. 2000b; Hartemink 2003).

Implications

Although piper biomass production was high, growth was depressed due to the relatively dry conditions. As a result, gliricidia produced much more biomass and accumulated more nutrients than piper. Imperata produced lowest amounts of biomass and nutrients. The imperata fallow is not preferable as its nutrient accumulation is limited, fixes no N and is also difficult to clear and yields no additional products (firewood). Farmers might not consider improved fallows unless they provide functions and products in addition to soil fertility restoration (Buresh and Cooper 1999). However, for most farmers the effects of the short-term fallow vegetations on subsequent crop yield may be an overriding factor. Piper returned largest amounts of nutrients (particular K) to the soil and as most of the cropping systems in the humid lowlands of Papua New Guinea are dominated by root and tuber crops which are large K-consumers (Hartemink 2003), it is a suitable fallow species.

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